Safety Study of Artificial Turf Containing Crumb Rubber Infill Made From Recycled Tires: Measurements of Chemicals and Particulates in the Air, Bacteria in the Turf, and Skin Abrasions Caused by Contact with the Surface

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Executive Summary

Introduction

The new generation of artificial turf athletic fields often contains crumb rubber infill made from recycled tires. Crumb rubber infill serves as an artificial soil, supporting the artificial blades of grass, softening the surface, improving drainage, and helping to provide a high-quality playing surface for a variety of sports. However, tire rubber is a complex material, containing many naturally-occurring and man-made chemicals. Crumb rubber made from recycled tires has the potential to release a variety of chemicals and particles into the air. It also represents a potential site of bacterial growth and transmission to athletes using the fields (including methicillin-resistant *Staphylococcus aureus*, MRSA). Therefore, OEHHA has evaluated the following aspects of artificial turf safety for fields constructed with recycled crumb rubber infill.

Study Goals

Determine whether the new generation of artificial turf athletic field containing recycled crumb rubber infill is a public health hazard with regard to:

1. **Inhalation**: Do these fields release significant amounts of volatile organic compounds (VOCs) or fine particulates of aerodynamic diameter less than 2.5 microns ($PM_{2.5}$ and associated metals) into the air? If so, are the levels harmful to the health of persons using these fields?

2. **Skin infection**: Do these fields increase the risk of serious skin infections in athletes, either by harboring more bacteria or by causing more skin abrasions (also known as turf burns) than natural turf?

Methods

1. **Inhalation hazard**
   a. Measure $PM_{2.5}$ and bound metals in air sampled from above artificial turf fields during periods of active field use. Compare to concentrations in the air sampled upwind of each field.
   b. Measure VOCs in the air sampled from above artificial turf fields during hot summer days. Compare to concentrations in the air sampled from above nearby natural turf fields.

2. **Skin infection hazard**
   a. Measure bacteria on components (infill/soil and blades) of existing artificial and natural turf fields.
   b. With the cooperation of athletic trainers from colleges and universities in California and Nevada, measure skin abrasion rates for varsity soccer players competing on artificial and natural turf fields.

Results and Conclusions

1. **Inhalation hazard**
   a. $PM_{2.5}$ and associated elements (including lead and other heavy metals) were either below the level of detection or at similar concentrations above artificial turf athletic fields and upwind of the fields. No public health concern was identified.
   b. The large majority of air samples collected from above artificial turf had VOC concentrations that were below the limit of detection. Those VOCs that were detected were usually present in only one or two samples out of the eight samples collected per field. There was also little consistency among the four artificial turf fields with regards to the VOCs detected. Nevertheless, seven VOCs detected above artificial turf were evaluated in a screening-level estimate of health risks for both chronic and acute inhalation exposure scenarios. All exposures were below health-based screening levels, suggesting that adverse health effects were unlikely to occur in persons using artificial turf.
   c. There was no correlation between the concentrations or types of VOCs detected above artificial turf and the surface temperature.

2. **Skin infection hazard**
   a. Fewer bacteria were detected on artificial turf compared to natural turf. This was true for MRSA and other *Staphylococci* capable of infecting humans. This would tend to decrease the risk of skin infection in athletes using artificial turf relative to athletes using natural turf.
   b. The rate of skin abrasions due to contact with the turf was two- to three-fold higher for college soccer players competing on artificial turf compared to natural turf. This was observed for both female and male teams. Skin abrasion seriousness was similar on the two surfaces. The higher skin abrasion rate would tend to increase the risk of skin infection in athletes using artificial turf relative to athletes using natural turf.
   c. The sum of these effects on the skin infection rate for artificial turf relative to natural turf cannot be predicted from these data alone. Measuring the skin infection rates in athletes competing on artificial and natural turf might determine if there is a significant difference.

Recommendations

1. **Inhalation hazard**
   a. There was no relationship between surface temperature and the concentrations of VOCs detected above artificial turf fields. Therefore, there is no reason for recommending that field usage in the summer be restricted to cooler mornings as a strategy for avoiding exposure to VOCs.

2. **Skin infection hazard**
   a. Preventing skin abrasions should be given the highest priority for preventing skin infection. Protective clothing and equipment should be considered, especially when games take place on artificial turf.
   b. Treating skin abrasions should be given the next highest priority. Clean, disinfect and cover abrasions as soon as possible. Keep wounds clean and protected as they heal.
   c. Disinfecting artificial turf fields should be the lowest priority. Such efforts may have little effect given the lower numbers of bacteria detected on artificial turf relative to natural

turf (based on the results of this study) and the extensive literature suggesting that body-to-body contact is the primary mode of MRSA transmission.

d. It is not known if the abrasiveness of the new generation of artificial turf is primarily determined by the infill or by the blades of grass. Such information would be valuable for engineering new types of turf with decreased abrasiveness. Creating artificial turf with decreased abrasiveness for athletes, while still retaining its strength and durability relative to natural turf, represents a challenge in materials engineering.

Uncertainties and Data Gaps Remaining

1) **Inhalation hazard**
   a. It is not known if the following variables influence $PM_{2.5}$ and VOC release from artificial turf fields containing crumb rubber infill: field age, processing of tire rubber at cryogenic versus ambient temperatures, source of tire stocks (automobile versus truck tires, tire age at the time of processing).
   b. This study only measured $PM_{2.5}$ and VOCs above outdoor fields. Indoor fields have received much less attention. Since $PM_{2.5}$ and VOCs have the potential to accumulate in indoor venues, future testing indoors should be considered.

2) **Skin infection hazard**
   a. The skin abrasion rate for artificial turf may vary according to age group and type of sport.
   b. The skin abrasion rate may be different for fields containing crumb rubber processed at cryogenic temperatures compared to ambient temperatures.
   c. The skin abrasion rate may vary with field age.
   d. It is not known if skin abrasions caused by artificial and natural turf heal at similar rates.
   e. Few data exist to evaluate whether the bacterial populations of artificial and natural turf vary according to the weather or season

Chapter 1

A Screening-Level Evaluation of the Human Health Risks Posed by Volatile Organic Compounds in the Air Over Outdoor Artificial Turf Fields Containing Recycled Crumb Rubber Infill

Abstract

Air from above four artificial turf athletic fields containing recycled crumb rubber infill was analyzed for volatile organic compounds (VOCs). Nearby natural turf fields were analyzed for comparison. The fields, located in California's Central Valley, were sampled multiple times throughout summer days, from the cool early morning to the heat of the day in the afternoon. Air and field surface temperatures were also monitored.

Few VOCs were detected (most detection limits were around 1 $\mu g/m^3$). Most VOCs detected over artificial turf were present in only one or two of the eight air samples collected per field, demonstrating little consistency over time within each field. There was also little consistency between artificial fields with regard to the VOCs detected. In addition, VOC concentrations over artificial turf did not increase as the surface temperature increased by as much as 55°F over the course of the day.

Comparing artificial turf to natural turf, seven VOCs met the following two criteria, suggesting that they originated from the artificial turf:

- Detected in at least two of the eight air samples collected from above an artificial field.
- Detected at a higher average concentration over that artificial field compared to the nearby natural field.

Chronic and acute exposure scenarios were constructed to estimate the exposure of soccer players to these seven VOCs via inhalation. A screening-level assessment of health risks was performed by comparing the estimated exposures to health-based screening levels. All exposures were lower than the screening levels, indicating that adverse health effects were unlikely in athletes using these fields. Uncertainties and limitations of this analysis are also presented.

Introduction

Rubber used to manufacture car and truck tires is a complex material, containing a variety of man-made and naturally occurring substances. Some of these are volatile. Therefore, it is not surprising that rubber made from recycled tires emits a number of chemicals. For example, in two studies conducted by the California Integrated Waste Management Board (CIWMB, 2003 and 2006), tire-derived indoor rubber flooring emitted 21 and 31 different volatile organic compounds (VOCs). Sections of artificial turf containing crumb rubber infill made from recycled tires were allowed to off-gas in chambers for 28 days (Moretto, 2007). A total of 112 VOCs were detected. In several independent studies, recycled crumb rubber was heated under laboratory conditions to determine what chemicals volatilize from the rubber at high temperature. A number of chemicals (VOCs and semi-volatile organic compounds, or sVOCs) were detected: Plesser and Lund, 2004, 12 chemicals; EHHI, 2007, 4 chemicals; New York State, 2009, up to 60 chemicals; Li et al., 2010, 11 chemicals.

Crumb rubber infill made from recycled tires is a major component of the new generation of artificial turf athletic fields. Given the findings that chemicals volatilize from crumb rubber, it is important to determine whether any of these VOCs reach high enough levels over these fields to constitute a health hazard to athletes using the fields. This question can be addressed by sampling the air over these fields, identifying the VOCs present, measuring their concentrations, and comparing those concentrations to health-based screening levels.

A number of air sampling studies have recently been conducted that focused on the new generation of artificial turf containing recycled crumb rubber infill. These are summarized in Table 1 along with the OEHHA study that is the subject of this report. All of these studies concentrated on outdoor fields except for the study by Simcox et al. (2010), which also included a single indoor field.

Using method TO-15 for VOC identification (U.S. EPA, 1999), TRC (2009) detected three VOCs from the TO-15 target list that were in the air over artificial turf but not upwind: 2-butanone, n-hexane, and chloroform. Four tentatively identified compounds (TICs) were also detected over artificial turf: isobutane, pentane, 2-methyl-1,3-butadiene, and 2-methylbutane. TICs are compounds that were not on the method TO-15 target list and therefore their identities and concentrations were estimated. Due to the low levels of these chemicals, none was judged by the authors to be a health hazard. Furthermore, the report stated that since the pattern of detection of these chemicals was not consistent, they were probably not released by these fields.

A total of 85 VOCs and 65 sVOCs were detected in the air over two fields comprising the New York State (2009) study. However, most of these were TICs with GC/MS peaks that only partially matched the reference scans. Therefore, their identities and quantities could not be determined with confidence. Since air samples were taken at various heights above each field and at various locations upwind and downwind of each field, both vertical and horizontal chemical concentration profiles could be constructed from the data. Correlations between height above or position across these fields and chemical concentration were not observed, suggesting that the fields were not the source of these chemicals. Nonetheless, 15 chemicals detected from above one field and 16 detected from above the other field were evaluated for noncancer risks to athletes using these fields. Eight chemicals were also evaluated for cancer risks. All evaluations considered the inhalation route of exposure only. The report concluded that there were no serious public health risks associated with the use of these fields.

In a recent study by U.S. EPA (2009a), most of the VOCs detected over three artificial turf fields were also detected in the upwind samples. From among the 56 VOCs analyzed, the only VOC that was detected over artificial turf but not upwind was methyl isobutyl ketone (MIBK, also known as 4-methyl-2-pentanone).

The air sampling studies discussed above, as well as the OEHHA study reported here, utilized stationary air samplers placed on the fields. In a study reported earlier this year (Simcox et al., 2010), both stationary air samplers and personal air samplers worn by study personnel were used. Possible contamination issues discussed in the report suggest that the personal air samples were not reliable. Therefore, considering only the data from the stationary samplers for the four outdoor artificial turf fields in that study, only two VOCs from the method TO-15 target list were substantially above background: cyclohexane over one field and acetone over another.

Table 1. Summary of VOC sampling parameters for five studies of outdoor artificial turf fields containing recycled crumb rubber infill.

Study	# of outdoor fields measured	# of air samples, per field/total all fields	# of air samples upwind of artificial field	Air collection method	VOC analysis method (# of target chemicals)	Were TICs identified?	Air sampling height above surface	Air sampling duration	Ambient air temperature range during sampling
TRC, 2009	2 artificial, 1 natural	4/16	2	6-L SUMMA canisters	EPA TO-15 (69)	Yes	3 feet	1 hour	79-94°F
New York State, 2009	2 artificial (same fields as in TRC, 2009)	8/18	1	Sorbent media in cartridges	EPA 5041A/8260B	Yes	At surface, 3 feet and 6 feet	2 hours	77-84°F
U.S. EPA, 2009a	3 artificial	3 or 6/12	1	6-L SUMMA canisters	EPA TO-15 (56)	No	3.3 feet	20 seconds	82-95°F
Simcox et al., 2010	4 artificial[1], 1 natural	1-2/13[2]	1	6-L SUMMA canisters	EPA TO-15 (60)	Yes	3 feet (all fields) and 0.5 feet (3 fields)	1 hour	68-87°F
OEHHA, 2010	4 artificial, 4 natural[3]	8/64	0*	6-L SUMMA canisters	EPA TO-15 (94)	Yes	4 feet	45 minutes	63-98°F

[1] Does not include one indoor artificial turf field.
[2] Does not include air collected via personal samplers.
[3] In each of four municipalities the artificial field and natural field were located at the same school or sports complex. In two cases the fields were adjacent, in one case they were separated by a parking lot, and in one case they were separated by a natural turf field.

In addition, one TIC was specific to a single artificial turf field: 2-methyl butane. The levels of total volatile organic compounds (TVOCs) were also evaluated. For three out of four outdoor artificial turf fields, the concentration of TVOCs was lower in air sampled from above the field than in the air sampled upwind of the field. The average TVOC concentration for the four artificial turf fields was 18 $\mu g/m^3$ compared to 26 $\mu g/m^3$ for four samples collected upwind of these fields and one sample from above a grass field. A human health risk assessment based on these data (Connecticut Department of Public Health, 2010) did not identify any elevated inhalation health risks to athletes using these outdoor fields.

It is well-established that the release of VOCs from a variety of materials increases with increasing temperature. This was demonstrated recently in a laboratory study in which the recycled crumb rubber infill used in the construction of artificial turf fields was heated to 77, 117 or 158°F (New York State, 2009). The VOCs released at the three temperatures were identified. Thirteen chemicals were detected at a greater frequency as the temperature increased. No chemicals showed the opposite relationship; i.e., fewer detects as the temperature increased.

A study is needed in intact athletic fields containing recycled crumb rubber, performed over the range of temperatures encountered during summer days, to quantify the relationship between field temperature and VOC concentration above the field. While the earlier studies listed in Table 1 did record surface and ambient temperatures, they did not measure VOCs at different temperatures on the same field. This was one goal of the present study.

The Office of Environmental Health Hazard Assessment (OEHHA), in consultation with CalRecycle, has performed air sampling to measure the concentrations of VOCs over artificial turf athletic fields in California. New generation artificial turf containing crumb rubber infill made from recycled tires was specifically targeted. Air samples were also collected from above adjacent/nearby natural turf athletic fields for comparison. Field locations were selected in California's Central Valley and sampling was conducted during the summer of 2010. In order to study the relationship between temperature (both ambient and surface) and VOC concentration, air samples were collected from early in the morning through late afternoon, alternating between artificial turf and natural turf. Throughout this period temperature measurements were also made at each field's surface and four feet above each field. This yielded a total of 64 air samples from eight fields, evenly divided between artificial and natural turf (Table 1), along with temperature data. These data allowed us to test the relationship between temperature and VOC concentrations over artificial turf, as well as estimate whether the chemicals constitute an inhalation risk to persons using these fields.

Methods

Air sampling

Schools and municipalities with artificial turf fields containing crumb rubber infill were identified from lists available on artificial turf installers' websites. Locations in California's Central Valley were chosen based on the probability that summer daytime temperatures would exceed the target temperature for air sampling of 90°F. Permission was obtained prior to sampling. Four separate schools or municipalities were sampled between June 8 and August 4, 2010. Each school or town sports complex had an artificial turf athletic field and an adjacent or nearby natural grass athletic field within a few hundred meters of each other (Table 2). Artificial field ages ranged from eight months to five years.

Table 2. Field characteristics

Town #	Venue	Configuration	Artificial field age
1	Town sports complex	An artificial turf and a natural turf field separated by a parking lot approximately 100 meters wide	1 year
2	Town sports complex	An artificial and a natural turf field 25 meters apart, separated by a concrete walkway and natural landscaping	8 months
3	High school	Artificial field in outdoor stadium and natural turf field 300 meters apart, separated by bleachers and another natural turf field	5 years
4	High school	Artificial turf field in outdoor stadium almost adjacent to natural turf field, separated by bleachers	2 years

Air samples were collected alternately on each artificial and natural turf field, beginning at approximately 8 a.m. and ending at approximately 5 p.m. Gas regulators allowed sampling over 45-minute intervals (flow rate of approximately 125 milliliters per minute). Samples were collected in six liter SUMMA canisters following a leak check to verify that each canister had the correct vacuum and did not leak after being connected to a regulator. The same two regulators were used for the entire study. All sampling was performed with duplicate canisters placed next to each other at the same spot on the artificial or natural turf field. Air intake occurred at four feet above each surface. Canisters were shipped by ground express to the analyzing laboratory within 1-2 days of sampling. Analysis was completed within the 30-day time limit recommended for sample storage (U.S. EPA, 1999).

Surface temperatures, as well as temperatures at four feet above each surface (ambient temperature), were monitored throughout the day. Wind speed and wind direction also were recorded.

Each day following air sampling at the athletic fields, two additional samples were collected within a few hundred meters of the Pacific Ocean at Fort Funston, in San Francisco. This location generally has strong onshore winds during the summer. These so-called “beach” samples were assumed to contain very low amounts of VOCs and were used as an additional check (in addition to the laboratory method blanks) for possible false positives in the samples collected from above the artificial and natural turf athletic fields.

Air samples were analyzed for VOCs according to U.S. EPA method TO-15. All analyses were performed by Environmental Analytical Services (San Luis Obispo, CA). The method TO-15 target list of chemicals used by this laboratory contains 94 target VOCs that can be reliably detected and quantified. These are shown in the Appendix along with representative method detection limits (MDLs; most around 1 $\mu g/m^3$) and reporting limits (RLs). The MDL was the lowest concentration of the chemical that could be detected. Concentrations from the MDL to just below the reporting limits were estimated by the analyzing laboratory and are indicated by a “J” qualifier in the tables. The reporting limits were the lowest concentration of the chemical that

could be quantified with confidence. It coincided with the lowest point on the calibration curve. Exact MDLs and reporting limits varied slightly with each sample. Quality control tests were run every day that samples were analyzed. These tests included method blanks to detect false positives, duplicate control samples to measure relative percent differences, and laboratory control spikes to measure percent recoveries.

The laboratory also measured TICs. These were VOCs not on the U.S. EPA method TO-15 target list of 94 compounds. The identities and amounts of TICs were estimated, unlike the 94 chemicals on the target list (see above). Six were tentatively identified. However, the six TICs were ubiquitous in both artificial and natural turf field samples, as well as in the samples collected at the beach. Therefore, they were considered to be contaminants and are not evaluated in this assessment.

Soccer coaches survey

Permission was obtained from the California Youth Soccer Association (CYSA, northern division) to circulate a survey request to its member coaches via its newsletter. The coaches were asked to access an online survey form at their convenience. The survey questions included how many hours per year the different age groups engage in organized soccer play (school or club teams), and at what ages organized soccer play typically begins and ends. The survey was conducted in September 2009. There were 236 coaches who responded to the survey. The coaches were asked to tailor their responses towards enthusiastic soccer players, who tend to play the most soccer per year for many years.

Results

Concentrating field emissions to identify additional target chemicals

Our first priority was to sample the air above artificial turf to screen for TICs not on our target list of 94 VOCs (see Appendix). To concentrate the emissions from these fields, and thereby increase our chances of detecting TICs, a new, clean (with detergent and water) garbage can made of galvanized steel was inverted on an artificial turf field for 20 minutes. Then, the garbage can was tilted as little as possible and the SUMMA canister was placed inside and allowed to fill for 45 minutes inside the inverted can. The process was repeated with a second canister. The temperature inside the garbage can ranged between 96° and 106°F during sampling on artificial turf, while the outside ambient temperature ranged between 84° and 88°F. For comparison, two air samples were collected in a similar manner within a few hundred meters of the Pacific Ocean during a day with strong onshore winds (temperature usually in the high 50°s to mid 60°s). VOC concentrations were expected to be very low in these “beach” samples (see methods section). Table 3 shows the results for this phase of the study.

Six TICs were detected in the air above artificial turf: butanal, pentanal, hexanal, hexamethylcyclotrisiloxane, 2,3-dimethylnonane, and nonanal (data not shown). They are not among the 94 target VOCs (U.S. EPA method TO-15). However, they were ubiquitous in subsequent samples from artificial turf, natural turf, and the beach. Therefore, they were considered to be contaminants and were not evaluated in this assessment.

Among the 94 VOCs on the target list, five were also ubiquitous in samples taken from above artificial turf, natural turf, and at the beach: dichlorodifluoromethane, chloromethane, ethanol, acetone, and 2-butanone. Therefore, these five chemicals probably represent contamination rather than emissions from artificial turf. These chemicals were not evaluated in this assessment.

Table 3 shows 10 chemicals from the VOC target list that were detected above their MDLs. Only 4-methyl-2-pentanone (a.k.a., methyl isobutyl ketone) was detected in both artificial turf air samples and absent from both beach samples. In both cases the concentrations were above the reporting limit. This was the only instance in the entire VOC sampling study (apart from the five probable contaminants discussed above) that a VOC was present above its reporting limit in both duplicate samples. As mentioned in the introduction, 4-methyl-2-pentanone was the only artificial turf-specific VOC in a recent study (U.S. EPA, 2009). That only a single chemical became concentrated inside the garbage can to a level above its reporting limit suggested that subsequent sampling in the absence of the garbage can would detect few target list VOCs. This turned out to be the case (see below).

Table 3. Volatile organic compounds accumulating *inside a steel garbage can* inverted on artificial turf at town #2 [1]

Compound	Art[2]	Art	Beach[3]	Beach
Dichlorodifluoromethane	4.4	2.1 J	3.1 J	2.8 J
Chloromethane	2	0.9 J	1.3 J	1.7 J
Bromomethane	1.3 J	*	*	*
Ethanol	3.4 J	*	*	*
Acetone	44.5	15.8	17.2	15.9
2-Propanol	*	*	2.1 J	*
2-Butane	14.7	1.9 J	3.2	3
Cyclohexane	*	*	1.2 J	*
Benzene	*	1.3 J	*	*
4-Methyl-2-pentanone (methyl isobutyl ketone)	7.8	21	*	*

[1] All concentrations are in micrograms per cubic meter of sampled air.
[2] Art = artificial turf athletic field
* Indicates compound was not detected (i.e., was below the method detection limit, MDL).
J Indicates the value was estimated because the concentration detected was between the method detection limit (MDL) and the reporting limit (RL).
[3] Beach samples are described in the methods section.
Shaded values indicate concentrations of chemicals that were detected in both artificial turf samples and absent from both beach samples.
Another 84 volatile organic compounds from the target list were below their MDLs.

Monitoring field temperatures throughout the day

One goal of this study was to determine whether VOC concentrations above artificial turf fields were sensitive to field temperature. Therefore, each field was monitored for surface temperature and ambient temperature (measured at four feet above the surface) beginning early in the morning, when the day was cool, until the heat of the day in the afternoon. The artificial and

natural turf fields chosen for monitoring at each town were either adjacent or within a few hundred meters of each other (Table 2).

Temperature profiles for the four artificial turf fields and four natural turf fields are shown in Figures 1-4. The data are consistent from town to town. Comparing the artificial turf to the natural turf at each town indicates the following:

- The ambient temperatures measured at four feet above each field were similar for the two surfaces.
- The surface temperature of the artificial field was always higher than the surface temperature of the natural turf field.
- The difference between the surface temperature of the artificial and natural turf was least early in the morning and greatest later in the afternoon.

Thus, the higher temperature of artificial turf relative to natural turf was evident on the surface, but not in the breathing zone (four feet above the surface) of young athletes using the fields. This has been reported previously for artificial and natural turf fields in New York State (New York State, 2009).

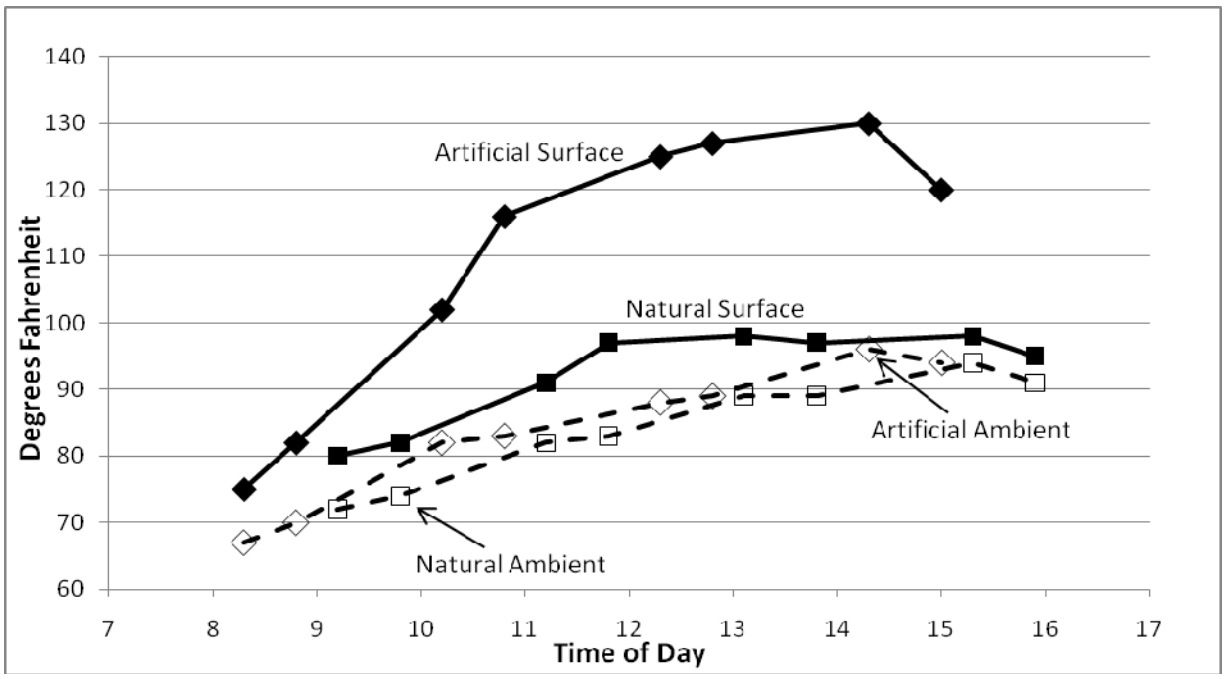

Figure 1. Surface and ambient temperatures of an artificial and natural turf field at town #1 during the day. Solid symbols: temperature of the indicated surface measured with a temperature probe. Open symbols: temperature measured at four feet above the indicated surface using a hand-held meter. Diamonds: data collected from artificial turf field. Rectangles: data collected from natural turf field.

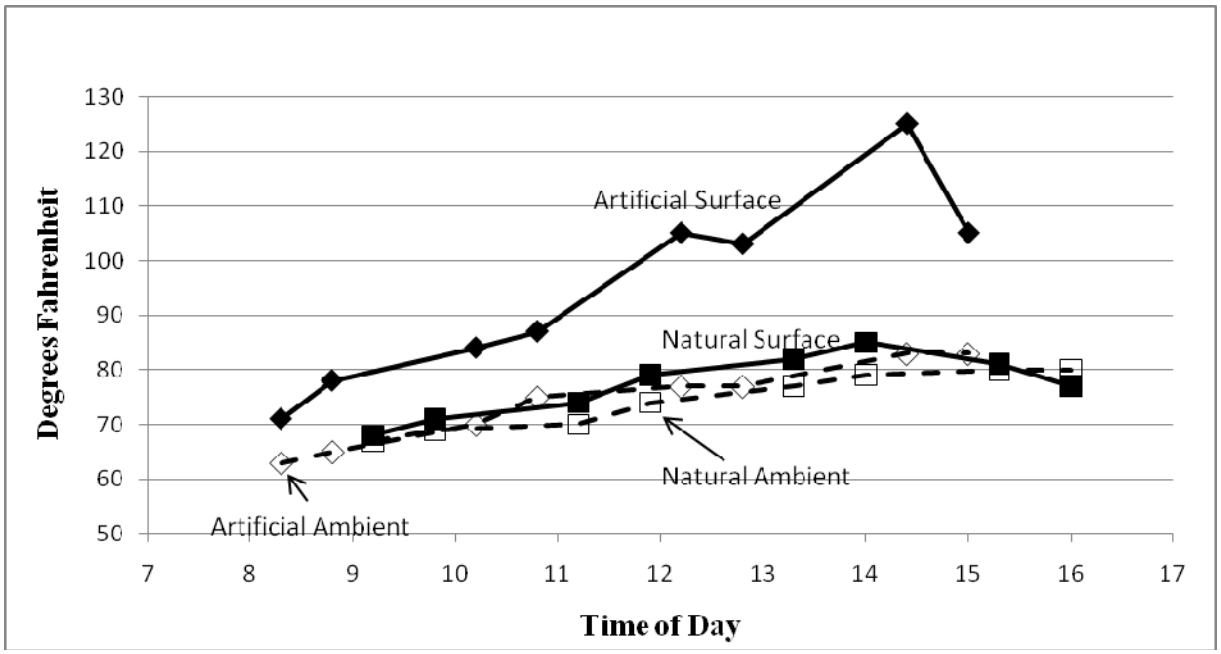

Figure 2. Surface and ambient temperatures of an artificial and natural turf field at town #2 during the day. Solid symbols: temperature of the indicated surface measured with a temperature probe. Open symbols: temperature measured at four feet above the indicated surface using a hand-held meter. Diamonds: data collected from artificial turf field. Rectangles: data collected from natural turf field.

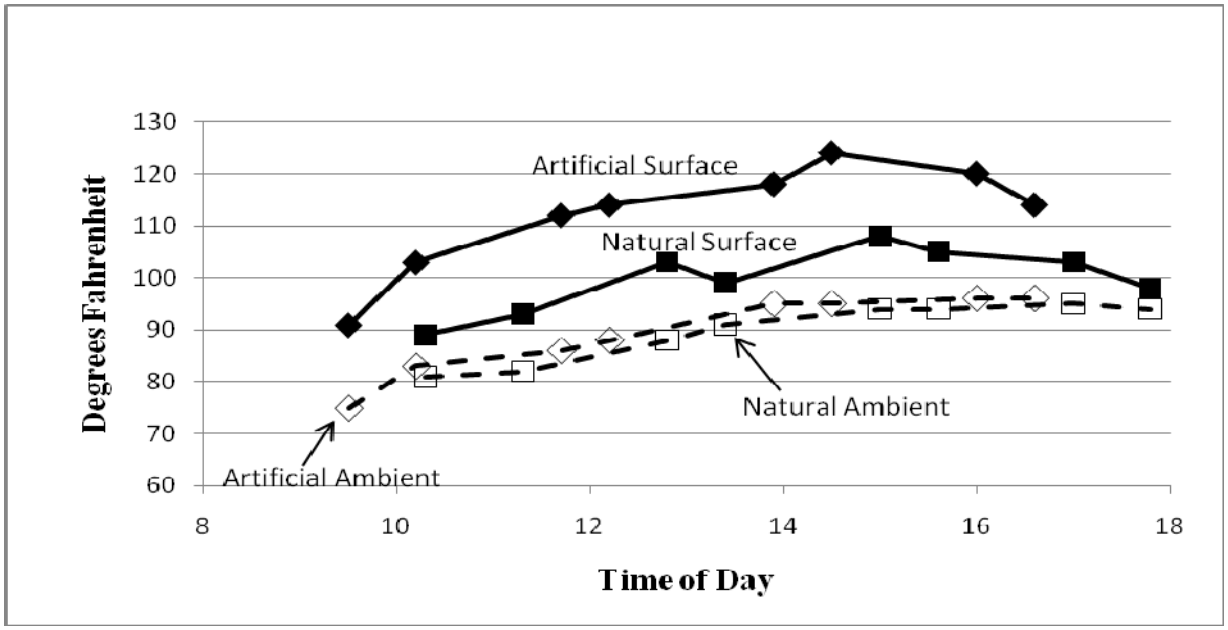

Figure 3. Surface and ambient temperatures of an artificial and natural turf field at town #3 during the day. Solid symbols: temperature of the indicated surface measured with a temperature probe. Open symbols: temperature measured at four feet above the indicated surface using a hand-held meter. Diamonds: data collected from artificial turf field. Rectangles: data collected from natural turf field.

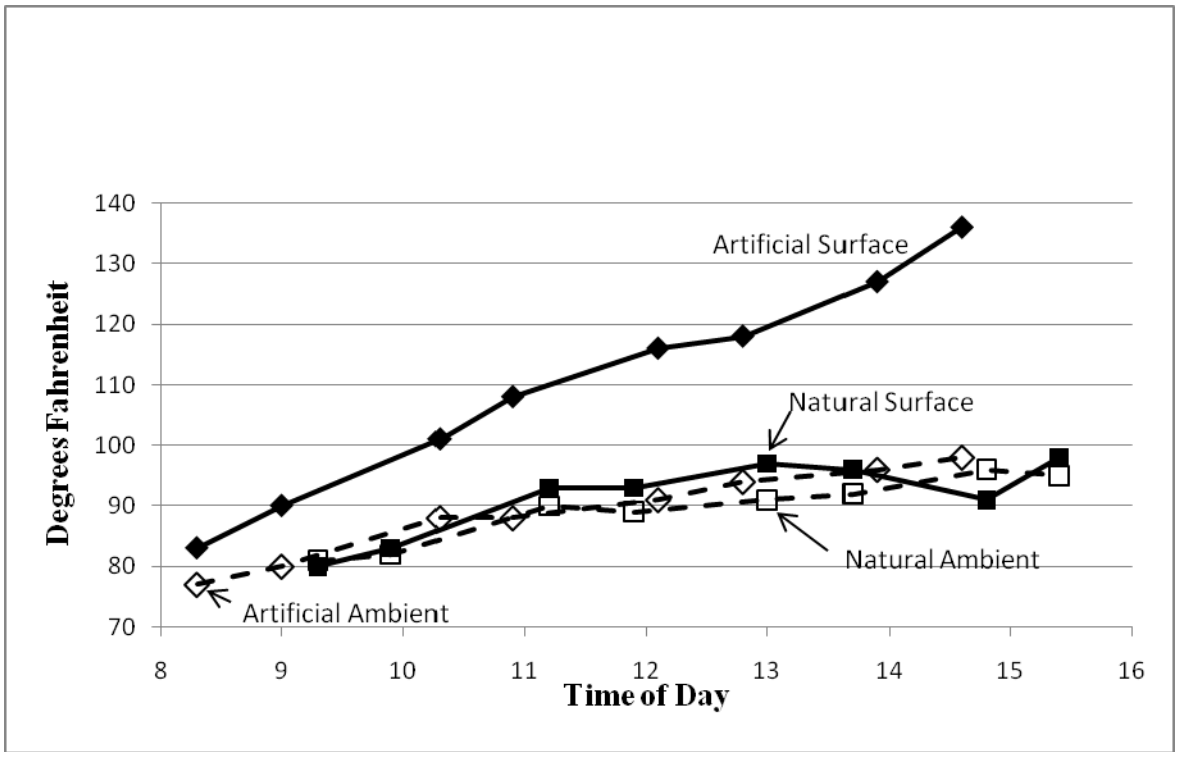

Figure 4. Surface and ambient temperatures of an artificial and natural turf field at town #4 during the day. Solid symbols: temperature of the indicated surface measured with a temperature probe. Open symbols: temperature measured at four feet above the indicated surface using a hand-held meter. Diamonds: data collected from artificial turf field. Rectangles: data collected from natural turf field.

Table 4. Summary of the temperature data collected from four artificial and four natural turf fields.[1]

Field type	Time interval	Ambient temp. range	Surface temp. range	Surface temp. change	Surface temp. change per ambient degree change[2]
Town #1					
Art field	8:15-15:00	68-96°	75-130°	55°	2.0°
Nat field	9:10-16:00	72-95°	80-98°	18°	0.8°
Town #2					
Art field	8:20-15:00	63-83°	71-125°	54°	2.7°
Nat field	9:15-16:00	68-80°	69-86°	17°	1.4°
Town #3					
Art field	9:20-16:30	75-97°	91-125°	34°	1.5°
Nat field	10:15-17:50	80-96°	89-109°	20°	1.3°
Town #4					
Art field	8:20-14:40	78-98°	83-137°	54°	2.7°
Nat field	9:20-15:20	81-96°	80-98°	19°	1.2°

[1] All measurements are in degrees (°) Fahrenheit.
[2] Calculated as follows: surface temperature change/ambient temperature change.

Table 4 above summarizes the results from Figures 1-4. The following conclusions can be drawn about the temperature sensitivity of artificial turf relative to natural turf:

- The maximum ambient temperatures at four feet above artificial turf and natural turf were similar (within 3°F).
- The maximum surface temperature of artificial turf was from 16-39°F higher than the maximum surface temperature of natural turf.
- For three of the artificial turf fields, the increase in surface temperature per increase in ambient °F was about twice that of the natural turf field (column six in Table 4), while for the artificial turf field in town #3 the increase on artificial turf was only slightly greater than the increase on natural turf (1.5 vs. 1.3°F).

Our goal in monitoring ambient and surface temperatures was to measure their influence on VOC concentrations. In this regard, the data in Table 4 show:

- The target ambient temperature of 90°F was achieved in three out of four towns.
- The increases in the temperature of the artificial surfaces (34, 54, 54 and 55°F) were relatively large. Given what is known about the relationship between temperature and VOC release from recycled crumb rubber (New York State, 2009), these increases are large enough to allow a robust test of the effect of temperature on VOC concentrations over artificial turf.

Air sampling: Town #1

Town #1 had a sports complex containing a new generation artificial turf field with crumb rubber infill, along with a number of natural turf fields. Air was collected from above the artificial turf field and one natural turf field. The temperature of the artificial turf surface increased 55°F during the period of air sampling (Table 4).

Table 5 shows the VOCs detected over the artificial and natural turf fields in town #1. As discussed above, some chemicals were ubiquitous, appearing in most samples from both surfaces and from samples collected at the beach. Therefore, they were considered contaminants and are not evaluated in this assessment. For this data set those chemicals were dichlorodifluormethane, chloromethane, acetone, and 2-butanone. Another nine chemicals were detected; seven were specific to the artificial turf field and two were specific to the natural turf field. Six of these nine were detected in only one of eight air samples taken from above artificial or natural turf. The remaining three chemicals, 2-propanol, cyclohexane, and toluene, were detected in two of eight air samples taken from above artificial turf. For all nine chemicals detected over the two fields, most concentrations were between the MDL and reporting limit for each chemical. Comparing Table 5 to Figure 1, there was no pattern of increasing frequency of detection or increasing concentration with increasing temperature, despite the 55°F increase in the temperature of the artificial surface over the monitoring interval.

Air sampling: Town #2

Town #2 had a sports complex containing multiple artificial (crumb rubber infill) and natural turf fields. Air was sampled from above one artificial turf field and one natural turf field. The temperature of the artificial turf surface increased 54°F during the period of air sampling (Table 4).

Table 6 shows the VOCs detected over the artificial and natural turf fields in town #2. Five of the chemicals detected were ubiquitous (including method blanks) and therefore were considered to be contaminants and are not evaluated further: dichlorodifluoromethane, chloromethane, ethanol, acetone, and 2-butanone. Another 24 chemicals were detected; 18 were specific to artificial turf, three were specific to natural turf, and three were detected over both surfaces. From among the 18 artificial turf-specific chemicals, 13 were detected in only one of the eight air samples collected from above artificial turf. The other five were detected in two (m,p-xylene, o-xylene, 1,2,4-trimethylbenzene) or three (isopropylbenzene, 4-ethyltoluene) air samples from above artificial turf.

Benzene was noteworthy since it was detected in five of eight air samples from above artificial turf, compared to only one air sample from above natural turf. However, it was also detected at 0.75 $\mu g/m^3$ in one of the method blanks for this batch of air samples (canisters containing purified air samples). U.S. EPA (2009b) suggests that for chemicals detected in method blanks, field detects should be at least five to ten times greater; otherwise, they should be considered nondetects. Since these benzene field concentrations (all "J" qualified) were less than five times the concentration measured in the method blank, they were considered nondetects. Benzene was not detected over the fields in towns #1 and #3, and was detected at the same frequency (three of eight samples) over the artificial and natural turf fields in town #4.

Consistent with the data from town #1, most chemical concentrations in air samples from town #2 were between the MDL and the reporting limit (Table 6). The xylene isomers were exceptions in this regard, since all four detected concentrations were above the reporting limits.

Lastly, there was no pattern suggesting that the artificial surface released more chemicals as it heated up. Rather, more chemicals were detected earlier in the day, when the temperatures were lower. A possible reason for this may have been the winds, which were somewhat lighter on that date in the morning compared to the afternoon (varying between approximately 5 and 10 mph out of the southwest for most of the day).

Air sampling: Town #3

Town #3 had a high school with an artificial turf field in an outdoor stadium. Air was sampled from above that field and a nearby natural turf field. The temperature of the artificial turf surface increased 34°F during the period of air sampling (Table 4).

Table 7 shows the VOCs detected over the artificial and natural turf fields. Consistent with the data collected from towns #1 and #2, Five VOCs were ubiquitous and are not evaluated further: dichlorodifluoromethane, chloromethane, ethanol, acetone, and 2-butanone. Another 11 chemicals were detected; seven were specific to artificial turf, one was specific to natural turf, and three were found over both surfaces. Eight of the 11 chemicals detected were present in only a single air sample per field. Toluene was detected in four samples from above artificial turf and four samples from above natural turf. As found for the other towns, most of the chemicals that were detected were present at concentrations above the MDL but below the reporting limit. Once again, there was no indication that the detection frequencies or chemical concentrations increased as the artificial surface heated up throughout the day.

Air sampling: Town #4

Town #4 had a high school with an artificial turf field in an outdoor stadium. Air was sampled from above that field and an adjacent natural turf field. The temperature of the artificial surface increased 54°C during the period of air sampling (Table 4).

For this group of air samples (Table 8), acetone, benzene, and toluene were all detected in the method blanks. In addition, acetone and toluene were present in the air sampled at the beach. Therefore, these chemicals were considered contaminants in the air samples from this field.

For the other four chemicals detected on these fields, two were specific to artificial turf, one was specific to natural turf, and one was detected over both fields. All were detected in only one out of eight air samples per field, and in all cases the concentrations were below the reporting limit. There was no apparent surface temperature effect for these four chemicals.

Table 5. Volatile organic compounds detected in air sampled from above an artificial and natural turf field at town #1 during the day.[1]

	8:34[5]		9:33		10:33		11:33		12:32		13:28		14:40		15:37			
Compound	**Art[2]**	**Art**	**Nat[3]**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Beach[4]**	**Beach**
Dichlorodifluoromethane	3.3J	2.1J	2.8J	2.4J	1.9J	2.3J	2.4J		1.9J	1.8J	2.9J	2.0J	3.2J	2.4J	2.3J	2.4J	2.1J	2.5J
Chloromethane	1.2J	1.0J	1.3J	1.0J	1.0J	1.0J	1.7J	1.0J	1.1J	1.0J	1.1J	0.8J	1.1J	1.2J	1.2J	1.2J	1.0J	1.1J
Ethanol	*	2.5J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Acetone	8.8	7.9	28.6	10.9	9.3	9.5	12.8	9.3	13.4	9.1	13.5	8.4	11.7	14.6	19.6	22.2	6.6	5.5
2-Propanol	*	*	*	*	*	*	*	*	*	*	*	*	2.1J	1.6J	*	*	*	*
2-Butanone	1.2J	1.7J	6.2	1.9J	1.6J	1.6J	2.3J	2.2	2.6	1.4J	3.3	1.1J	1.5J	2.3J	2.7	3.7	2.7	1.0
Hexane	*	1.2J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Tetrahydrofuran	*	*	*	*	*	*	*	*	3.1	*	*	*	*	*	*	*	*	*
Cyclohexane	*	1.9J	*	*	*	*	*	*	*	*	*	*	1.3J	*	*	*	*	*
n-Heptane	*	2.7	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Toluene	1.2J	11.6	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
m,p-Xylenes	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	2.6J	*	*
Isopropylbenzene	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	1.7J	*	*

[1] All concentrations are in micrograms per cubic meter of sampled air.
[2] Art = artificial turf athletic field
[3] Nat = natural grass athletic field
* Indicates compound was not detected (i.e., was below the method detection limit, MDL).
J Indicates the value was estimated, registering between the method detection limit (MDL) and the reporting limit (RL).
[4] Beach samples are described in the methods section.
[5] Midpoints of 45-minute sampling intervals are shown in the table.
Another 81 volatile organic compounds from the target list were not detected in any sample (i.e., were below their MDLs).

Table 6. Volatile organic compounds detected in air sampled from above an artificial and natural turf field at town #2 during the day.[1]

	8:34[5]		9:33		10:33		11:31		12:30		13:44		14:43		15:43			
Compound	**Art[2]**	**Art**	**Nat[3]**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Beach[4]**	**Beach**
Dichlorodifluoromethane	4.1	3.5J	3.6J	3.6J	3.6J	3.5J	4.5	3.5J	3.4J	3.6J	3.0J	3.3J	3.7J	3.0J	3.2J	3.7J	2.9J	3.1J
Chloromethane	5.1	1.4J	1.6J	1.3J	1.5J	1.6J	1.7J	1.4J	1.2J	1.5J	1.8	1.4J	1.9	1.1J	1.3J	1.3J	1.2J	1.2J
Chloroethane	1.7J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Ethanol	*	*	3.6J	*	*	4.6J	*	*	*	4.9J	13.9	3.2J	11.9	*	*	*	*	*
Acetone	263	17.6	16.6	14.4	7.8	80	15.2	12.6	9.7	15.7	227	17.3	30.2	10.3	16.6	14.1	8.8	9.9
2-Propanol	*	*	*	1.3J	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2-Butanone	14.1	3.2	3.9	1.7J	1.4J	6.0	3.3	1.3J	*	2.4J	44	2.2J	5.0	1.1J	2.5	1.9J	1.3J	1.5J
Tetrahydrofuran	1.2J	*	*	*	*	*	*	*	*	*	3.3	*	*	*	*	*	*	*
Cyclohexane	0.9J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Benzene	1.7J	*	*	*	1.6J	1.2J	*	*	1.8J	*	*	1.5J	1.7J	*	*	*	*	*
n-Heptane	2.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
4-Methyl-2-pentanone	*	*	*	*	*	*	*	*	*	3.5	1.4J	*	*	*	*	*	*	*
Toluene	4.6	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2-Hexanone	*	*	*	*	*	*	*	*	*	*	2.3	*	*	*	*	*	*	*
Octane	2.5	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Chlorobenzene	23.9	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Ethylbenzene	3.5J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
m,p-Xylenes	26.2	*	*	*	*	14.5	*	*	*	*	*	*	*	*	*	*	*	*
Nonane	0.9J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

	8:34[5]		9:33		10:33		11:31		12:30		13:44		14:43		15:43			
Compound	**Art[2]**	**Art**	**Nat[3]**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Beach[4]**	**Beach**
o-Xylene	7.1	*	*	*	*	60	*	*	*	*	*	*	*	*	*	*	*	*
n-Propylbenzene	2.1J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Isopropylbenzene	3.2	1.5J	*	*	*	22.6	*	*	*	*	*	*	*	*	*	*	*	*
4-Ethyltoluene	1.6J	1.2J	*	*	*	12	*	*	*	*	*	*	*	*	*	*	*	*
1,3,5-Trimethylbenzene	*	*	*	*	*	38	*	*	*	*	*	*	*	*	*	*	*	*
Decane	8.9	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
1,2,4-Trimethylbenzene	4.1J	*	*	*	*	20	*	*	*	*	*	*	*	*	*	*	*	*
sec-Butylbenzene	1.9J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Isopropyltoluene	2.6J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
1,2,4-Trichlorobenzene	*	*	*	*	*	*	*	*	*	*	2.7J	*	*	*	*	*	*	*

[1] All concentrations are in micrograms per cubic meter of sampled air.
[2] Art = artificial turf athletic field
[3] Nat = natural grass athletic field
* Indicates compound was not detected (i.e., was below the method detection limit, MDL).
J Indicates the value was estimated, registering between the method detection limit (MDL) and the reporting limit (RL).
[4] Beach samples are described in the methods section.
[5] Midpoints of 45-minute sampling intervals are shown in the table.
Another 65 volatile organic compounds from the target list were not detected in any sample (i.e., were below their MDLs)

Table 7. Volatile organic compounds detected in air sampled from above an artificial and natural turf field at town #3 during the day.[1]

	9:51[5]		10:59		12:00		13:07		14:13		15:20		16:19		17:22			
Compound	**Art[2]**	**Art**	**Nat[3]**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Beach[4]**	**Beach**
Dichlorodifluoromethane	2.1J	2.8J	3.1J	2.4J	2J	2.6J	2J	2.5J	2.5J	3.2J	2.7J	2.8J	3.2J	2.5J	2.2J	2.7J	2.2J	2.2J
Chloromethane	0.7J	0.9J	1.2J	1.1J	1.0J	1.0J	0.9J	1.5J	0.8J	1.6J	1.1J	1.7J	1.1J	0.9J	1.2J	1.4J	2.5	0.8J
Ethanol	2.7J	3.3J	2.7J	*	*	*	3.5J	7.9	*	6.1	33.5	4.1J	3.6J	*	*	*	4.7J	*
Acetone	10.4	14.5	10.8	12.4	39.1	12	16.3	20.2	15.4	72.5	19	24.7	15.8	12	15.7	15.2	113	6.1
Allyl chloride	*	*	*	3.5	*	*	*	*	1.6J	1.1J	*	*	*	*	*	*	*	*
Vinyl acetate	*	*	*	*	*	*	*	3.4J	*	9J	*	*	*	*	*	*	*	*
2-Butanone	2.7	1.7J	*	*	2.8	2.8	3.3	2.2J	3	39.4	8	31.7	2.1J	1.2J	2.5	1.7J	5.6	5.2
Tetrahydrofuran	*	*	*	*	*	*	1.6J	*	*	*	1.4J	6.9	*	*	*	*	*	*
Toluene	*	2J	*	2.3J	*	2.6	2.6	*	3	*	3.1J	*	4	*	*	2.7J	*	*
2-Hexanone	*	*	*	*	*	*	*	*	*	1J	*	*	*	*	*	*	*	*
Chlorobenzene	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	5.1	*
m,p-Xylenes	*	*	*	*	6.2J	*	*	*	*	*	*	*	*	*	*	*	7.9	*
o-Xylene	*	*	*	*	24.5	*	*	*	*	*	*	*	*	*	*	*	1.9J	*
4-Chlorotoluene	*	*	*	*	1.2J	*	*	*	*	*	*	*	*	*	*	*	*	*
Isopropylbenzene	*	*	*	*	7.2J	*	*	*	*	*	*	*	*	*	*	*	*	*
4-Ethyltoluene	*	*	*	*	8.9J	*	*	*	*	*	*	*	*	*	*	*	*	*
1,3,5-Trimethylbenzene	*	*	*	*	20.1	*	*	*	*	*	*	*	*	*	*	*	*	*

[1] All concentrations are in micrograms per cubic meter of sampled air.
[2] Art = artificial turf athletic field
[3] Nat = natural grass athletic field

* Indicates compound was not detected (i.e., was below the method detection limit, MDL).
J Indicates the value was estimated, registering between the method detection limit (MDL) and the reporting limit (RL).
[4] Beach samples are described in the methods section.
[5] Midpoints of 45-minute sampling intervals are shown in the table.
Another 77 volatile organic compounds from the target list were not detected in any sample (i.e., were below their MDLs).

Table 8. Volatile organic compounds detected in air sampled from above an artificial and natural turf field at town #4 during the day.[1]

	8:41[5]		9:38		10:36		11:32		12:27		13:20		14:14		15:07			
Compound	**Art[2]**	**Art**	**Nat[3]**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Beach[4]**	**Beach**
Acetone	*	*	*	*	*	*	*	*	*	*	*	*	7.9	12.7	3.2	10.9	*	5.8
2-Propanol	*	*	*	*	*	*	*	*	1.2J	*	*	*	*	*	*	*	*	*
Vinyl acetate	*	*	*	*	*	*	*	*	*	*	*	*	*	5.9J	*	*	*	*
2-Butanone	1.2J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	2.1J	*	*
Isobutyl alcohol	*	*	*	*	*	*	*	*	*	*	*	2.9J	*	*	*	*	*	*
Benzene	3.9J	2.9J	*	*	*	*	2.7J	4.8J	*	7.6J	3.2J	*	*	*	*	*	*	*
Toluene	5	3.2J	3.1J	2J	2.8J	2J	2.1J	2.6J	2.2J	6.5J	3.4J	2.5J	2.5J	2J	2.9J	2.4J	1.7J	3.8J

[1] All concentrations are in micrograms per cubic meter of sampled air.
[2] Art = artificial turf athletic field
[3] Nat = natural grass athletic field
* Indicates compound was not detected (i.e., was below the method detection limit, MDL).
J Indicates the value was estimated, registering between the method detection limit (MDL) and the reporting limit (RL).
[4] Beach samples are described in the methods section.
[5] Midpoints of 45-minute sampling intervals are shown in the table.
Another 87 volatile organic compounds from the target list were not detected in any sample (i.e., were below their MDLs).

Comparing towns

The data from all four artificial turf fields in the four different towns can be compared to determine whether any VOCs were consistently detected above artificial turf. To do this, we first identified the VOCs that were reproducibly detected above any one of the four artificial turf fields; i.e., were measured in at least two of the eight samples collected from any artificial turf field. Those VOCs are shown in Table 9. Nine VOCs met this criterion (the probable contaminants discussed above are not included). Eight of these were reproducibly detected over only a single field. Toluene was reproducibly detected over two fields. It should be noted that at town #3, the natural turf field had as many toluene detects (4/8) as the artificial turf field. Taken together, these data demonstrate little field-to-field consistency with regards to the VOCs detected over artificial turf. One possible explanation is that the batches of recycled crumb rubber infill used to construct each field emitted different VOCs. Another possibility is that the small amounts of VOCs emitted by these fields usually did not accumulate to measurable concentrations in the open air. It may also be that the low levels detected in a few samples reflected concentrations of the ambient air.

Table 9. VOCs that were detected in at least two of eight air samples collected from above an artificial turf field (i.e., reproducibly detected in that field).

VOC	Artificial turf field where VOC detected in ≥ 2 samples	Artificial turf field where VOC detected in 1sample or not detected
2-Propanol	Town #1	Towns #2,3,4
Cyclohexane	Town #1	Towns #2,3,4
Toluene	Towns #1 and #3	Towns #2 and #4
m,p-Xylene	Town #2	Towns #1,3,4
Isopropylbenzene	Town #2	Towns #1,3,4
o-Xylene	Town #2	Towns #1,3,4
4-Ethyltoluene	Town #2	Towns #1,3,4
1,2,4-Trimethylbenzene	Town #2	Towns #1,3,4
Allyl chloride	Town #3	Towns #1,2,4

Each chemical in Table 9 can also be tracked in each individual artificial turf field to assess the consistency of its detection during the sampling day. Tables 5-8 show that there was little consistency over the sampling day. Most VOCs were detected in only a few samples per field and were below the MDL in the majority of samples. A low frequency of detection such as observed here suggests that if these chemicals are released by these fields, they are released at low levels. Such low level release might also help explain the relatively poor agreement between many duplicate samples (Tables 5-8).

It is also worth comparing the concentrated air samples collected from inside the garbage can inverted on the artificial field at town #2 (Table 3) to the samples collected from four feet above that field in the open air (Table 6). Among the VOCs detected inside the garbage can, 4-methyl-2-pentanone was the only one detected in both samples that was not detected in either beach control. Both samples were above the reporting limit: the concentrations detected were 14.8 and 21 $\mu g/m^3$. In contrast, 4-methyl-2-pentanone was only detected in one of eight open air samples collected from the same artificial turf field, at a concentration of 3.5 $\mu g/m^3$. A possible explanation is that the rate of 4-methyl-2-pentanone emission by this field was insufficient to reproducibly raise its concentration in the open air to above its MDL. Since this compound concentrated to a higher level inside the garbage can than any other VOC (contaminants such as acetone excluded), it was to be expected that few if any other VOCs would be reproducibly detected in the open air samples for this field. This turned out to be the case for all the fields in all four towns (Table 9).

Most of the VOCs shown in Table 9 were detected over field #1 (one year old) or field #2 (eight months old). These were also the newest fields in the study. Since VOC emissions from crumb rubber infill decreased over time in a laboratory study (Xi et al., 2010), it might be expected that more VOCs would be detected over newer fields.

Estimating the amount of organized soccer played on artificial turf fields

A number of managers of parks with artificial turf athletic fields mentioned that by far the heaviest use of their fields was for organized soccer leagues. This suggests that, currently, the athletes most heavily exposed to chemicals emitted by artificial turf fields are those playing organized soccer. To estimate the maximum time (worst-case scenario) children and adults spend each year playing soccer on artificial turf, we conducted a survey to estimate the time they spend each year playing organized soccer on all fields, artificial and natural.

Soccer coaches are in the best position to give accurate estimates of soccer playing time. Therefore, we obtained permission from the California Youth Soccer Association (CYSA, northern division) to circulate a survey to its member coaches via its newsletter. The survey was conducted in September 2009. There were 236 coaches who responded to the survey. The coaches were asked to concentrate their responses on the enthusiastic soccer players who tend to play the most soccer per year for many years.

Table 10 shows the coaches' estimates of how much time ardent soccer players spend in organized league play (including organized practices) as a function of age. The large standard deviations indicate the estimates varied widely. Organized league play peaks during high school. For all ages, the 95th percentile values are approximately two- to three-fold greater than the average values. Since the coaches were asked to focus their estimates on enthusiastic players, we consider the average values to be the most appropriate values for estimating the exposure of each age group to VOCs. As shown in Table 10, high school players have the highest average usage hours per year, at 222 hrs./year. This value is used to adjust chemical concentrations in air in the following sections.

Table 10. California Youth Soccer Association (CYSA) coaches' survey of hours per year enthusiastic soccer players spend in organized practices and games[1]

School or adult years	Age in years inclusive	Average hours per year (standard deviation)[2]	95th percentile hours per year
Preschool/Kindergarten	4-5	31 (18)	64
Grammar	6-11	95 (100)	280
Middle School	12-14	147 (108)	320
High School	15-18	222 (152)	475
College	19-22	186 (151)	430
Adult	23-29	116 (103)	359
Adult	30-39	83 (52)	158
Adult	40-49	73 (55)	189
Adult	50-59	74 (83)	222

[1] Survey conducted in September 2009. There were 236 coaches who responded to the survey. Coaches were asked to concentrate on enthusiastic soccer players.
[2] Hours spent in organized soccer practices and games as part of an organized league (youth, school or adult) held on any type of athletic field.

Estimating VOC exposures to persons using artificial turf fields

The VOCs detected over the fields in Tables 5-8 were screened to determine whether any fulfilled the following two criteria:

- Detected in at least two of the eight samples collected from above one of the artificial turf fields, indicating their detection at that field was reproducible.
- Detected in the same artificial turf field at an average concentration (average of eight samples per field) that was greater than the average concentration of the nearby natural turf field (suggesting the artificial turf released the chemical into the air).

Seven chemicals satisfied the above two criteria. Two types of exposure estimates were made covering these seven chemicals, as shown in Table 11. The first was for chronic exposure and assumed that athletes use these fields for at least one year. However, we also assumed that field use is intermittent within any year. Therefore, the average chemical concentration detected over an artificial turf field was prorated for an exposure period of 222 hours/year (column five) as shown in footnote three of the table.

The second set of estimates in Table 11 address acute, one-time exposures. To estimate the highest acute exposure likely to occur, the highest VOC concentration measured on the field is selected (column three) without any time adjustment.

Table 11. VOC exposure concentrations for persons using artificial turf fields (all concentrations in µg/m^3).

VOC	Town with artificial field with highest average VOC concentration	Highest VOC concentration over indicated artificial turf field (acute exposure) [1]	Average VOC concentration over indicated artificial turf field[2]	Value from column four averaged over 222 hrs of artificial turf field use per year (chronic exposure) [3]
2-Propanol	Town #1	1.9	0.9	0.02
Cyclohexane	Town #1	1.2	0.7	0.02
Toluene	Town #1	6.4	2.1	0.05
m,p,o-xylenes	Town #2	44.3	15.3	0.38
Isopropylbenzene	Town #2	11.6	3.8	0.10
4-Ethyltoluene	Town #2	6.3	2.2	0.06
1,2,4-Trimethylbenzene	Town #2	10.7	4.3	0.11

[1] The highest value from among the four time points per field. Each time point was an average of the two duplicate samples collected for that time point. For example, for m,p-xylene the 8:34 time point had values of 26.2 and 1.6 (1/2 the MDL), yielding an average value for the time point of 13.9. For o-xylene, the 10:33 time point had values of 60 and 0.8 (1/2 the MDL), yielding an average value of 30.4. Adding these two averages gives 44.3 for the three xylene isomers.
[2] To calculate the average chemical concentration over each field, nondetects were given the value of one-half the MDL, and the values for the eight air samples per field were averaged. For example, for m,p-xylene the average of the eight air samples (26.2+1.6+1.6+14.5+1.4+1.6+1.6+1.6) was 6.3. Similarly, the average for o-xylene was 9.0. Adding these two averages gives 15.3 for the three xylene isomers.
[3] Multiply values in the fourth column by 222/8760. The value of 222 is hours of artificial turf field use per year, and was taken from Table 10. It represents the age group playing the most organized soccer in a year (15-18 year-olds). The value of 8760 is the number of hours in a year.

Table 11 shows that the VOC exposure concentrations are approximately 100-fold lower for chronic exposures compared to acute exposures. Xylene exposures are the highest, at 0.38 µg/m^3 and 44.3 µg/m^3 for the chronic and acute scenarios, respectively.

A screening-level estimate of inhalation health risks to persons using artificial turf athletic fields

Two kinds of screening-level health risk estimates are presented below in Table 12. The first covers chronic exposures, in which average chemical concentrations over artificial turf fields prorated for an exposure period of one year (column four) are compared to chronic health-based screening values (column five). The second covers acute exposures in which the maximum chemical concentrations detected over artificial turf fields (column two) are compared directly to acute screening values (column three). Acute screening values were not available for

isopropylbenzene, 4-ethyltoluene or 1,2,4-trimethylbenzene. Subchronic screening values were used instead, as described in the footnotes to the table. Screening values are published by authoritative bodies, usually governmental. They indicate the concentrations of chemicals in the air below which adverse human health effects are not expected.

None of the seven VOCs is on the California Proposition 65 List of Chemicals Known to the State to Cause Cancer. Therefore, cancer risks were not calculated.

Table 12. Screening-level estimates of health risks to persons breathing VOCs in the air above artificial turf (all concentrations in µg/m^3).

VOC	Highest VOC concentration over artificial turf[1]	Acute health-based screening value	VOC concentration over artificial turf averaged over one year[2]	Chronic health-based screening value
2-Propanol	1.9	3,200[3]	0.02	7,000[3]
Cyclohexane	1.2	10,300[4]	0.02	80,000[5]
Toluene	6.4	3,700[3]	0.05	300[3]
m,p,o-xylenes	44.3	22,000[3]	0.38	700[3]
Isopropylbenzene	11.6	4,000[6]	0.10	400[6]
4-Ethyltoluene	6.3	850[7]	0.06	85[7]
1,2,4-Trimethylbenzene	10.7	70[8]	0.11	7[8]

[1] Third column in Table 11.
[2] Fifth column in Table 11.
[3] OEHHA, 2010.
[4] A human study by Hathaway et al. (1991) yielded a lowest observed adverse effect level (LOAEL) of 1,030 mg/m^3. Dividing by a factor of 10 to extrapolate to a no observed adverse effect level (NOAEL) and dividing by another 10 for inter-individual variability yields an acute screening value of 10.3 mg/m^3.
[5] ACGIH, 1994. 8 hr time weighted average (TWA) occupational exposure limit of 350 mg/m^3 multiplied by 8 hr/day X 250 days/year X 1/(8760 hrs/year).
[6] IRIS, 2010. The acute screening value in the table above was derived from the chronic RfC by omitting the factor of 10 used to extrapolate from subchronic to chronic exposure.
[7] A study in the rat by Swiercz et al. (2000) yielded a no observed adverse effect level of 477 mg/m^3 for a four week exposure at 6 hrs per day and 5 days per week. Multiplying by (6 hr/24 hr) and (5 days/7 days) adjusts for exposure duration, giving an adjusted value of 85 mg/m^3. Dividing by 10 for rat to human extrapolation and 10 for interindividual variability gives a subchronic screening value of 850 µg/m^3. This value is used in the table above for the acute screen. Dividing by 10 for subchronic to chronic extrapolation yields a chronic screening value of 85 µg/m^3.
[8] U.S. EPA, 2007. The citation provided a subchronic and chronic provisional reference concentration (p-RfC). The subchronic p-RfC was used for the acute screen and the chronic p-RfC was used for the chronic screen.

The chronic exposure concentrations in column 4 range from approximately 64-fold (1,2,4-trimethylbenzene) to 4 million-fold (cyclohexane) lower than the corresponding chronic health-based screening values in column five. These large differences suggest that these chemicals do not pose serious inhalation health risks to athletes using these fields over extended time periods.

The acute exposure concentrations in column two are also lower than the corresponding acute screening values in column three. However, the differences are less than for the chronic screen, ranging from 6.5-fold in the case of 1,2,4-trimethylbenzene to almost 8,600-fold in the case of cyclohexane. It should be noted that a subchronic screening value was used to estimate the acute risk to 1,2,4-trimethylbenzene. If an acute screening value was available, the margin of safety would probably be significantly greater. Nonetheless, the differences between the VOC concentrations above these fields and their acute health-based screening values (Table 12) indicate that acute health effects are also unlikely to result from breathing the air over these fields.

Conclusions

Air sampling was conducted at a height of four feet above four artificial turf fields containing recycled crumb rubber infill. Nine VOCs from a target list of 94 chemicals were detected in at least two of eight air samples collected from above an artificial field throughout the sampling day (Table 9). Six of these were also detected over natural turf or in control "beach" samples.

The VOC concentrations above any one field, sampled at the same location on each field, exhibited little consistency over the course of the day (Table 5-8). There was also little consistency between artificial turf fields in different towns. Toluene was the only VOC that was detected in at least two of eight samples per field in two artificial fields (Table 9). A possible explanation for these findings is that artificial turf emits VOCs at low levels, such that their concentrations above the field are usually too low to be detected (i.e., below the MDL).

The surface temperatures of the artificial turf fields increased from 34 to 55°F over the course of the day. This allowed a robust test of the effect of temperature on VOC concentrations over artificial turf. No effect of temperature was observed on the concentrations of VOCs over any of the fields, artificial or natural. Since in laboratory studies recycled crumb rubber infill emitted more VOCs as the temperature increased (New York State, 2009), the absence of a temperature effect in the field is consistent with the hypothesis that usually the VOCs were emitted at levels too low to be measured in the open air. Alternatively, the VOCs detected may have already been in the ambient air or may have been due to occasional laboratory contamination.

Despite the inconsistent detection of VOCs over artificial turf, the data were screened to identify chemicals that were detected in at least two of eight samples collected from an artificial field, and to determine whether the average concentration over that field was greater than the average concentration over the nearby natural turf field. The seven chemicals meeting these criteria were screened for acute and chronic health risks.

Acute exposures to persons using these fields were the unadjusted, highest VOC concentration detected over the artificial field (Table 11). Chronic exposures were calculated using the average VOC concentration over the field on the sampling day, averaged over 222 hours of artificial turf field use per year. These usage hours represent the time enthusiastic soccer players 15-18 years of age spend in organized practices and games in a year. The acute and chronic exposures were compared to health-based screening values in a screening-level estimate of health risks (Table 12).

For both the acute and chronic exposure scenarios, the large differences between the estimated exposure concentrations and the screening values suggest that adverse health effects are unlikely to occur in persons using these fields. Similar conclusions were reached in two other studies conducted within the past two years (New York State, 2009; Connecticut Department of Public Health, 2010).

Uncertainties

There are a number of uncertainties associated with our screening-level risk estimates presented in Table 12. Uncertainties that would tend to overestimate the health risks include:

- The chronic exposure scenario assumes that athletes play 100 percent of their organized soccer on artificial turf with crumb rubber infill. This is unlikely and therefore overestimates the risk.
- Air sampling during cold weather might detect fewer and lower levels of VOCs than detected during the hot summer weather in this study. If so, then using the data collected during the summer to estimate exposure for a year overestimates the exposure.
- Subchronic screening values were used to estimate the risks of acute adverse health effects for three VOCs. This would likely lead to an overestimation of risk.

Uncertainties that lead to underestimations of the health risks posed by the VOCs in the air over artificial turf containing crumb rubber infill include:

- The chronic exposure scenario assumes that athletes only play soccer on these artificial surfaces. However, athletes may participate in other organized sports that commonly take place on artificial turf fields such as football, baseball, and lacrosse. Participation in multiple sports would increase the exposures estimated here.
- Recycled tire rubber emits hundreds of VOCs (CIWMB, 2003). Our target list of VOCs contained 94 chemicals (U.S. EPA Method TO-15). Therefore, it was not possible to screen for all of the VOCs emitted by recycled crumb rubber. Since many remain unidentified, their concentrations above artificial turf, as well as their potential health effects, are unknown. However, the recent study by Simcox et al. (2010) suggests that the concentrations of unidentified VOCs over artificial turf are very low. This may be inferred from the finding that the levels of total volatile organic compounds (TVOCs) over artificial turf fields were no higher than the levels upwind of the fields and over natural turf.
- Another uncertainty relates to the chronic screening level developed here for cyclohexane (Table 12). An occupational standard was used to develop the screening level. Occupational standards may not be sufficiently protective for the general public, including the elderly and children. However, occupational standards are useful for screening-level risk estimates. In addition, the 4 million-fold difference between the cyclohexane screening level and the estimated exposure concentration suggests that the risk of health effects from exposure to cyclohexane is very low.

Study limitations

- The method used to calculate exposures (Table 11) assumed that samples with a chemical concentration below the detection limit (nondetects) contained that chemical at a

concentration of one-half the MDL. Since either five or six of the eight field samples used to calculate each exposure concentration were nondetects, this has the potential to introduce significant bias into the calculation (Helsel, 2005). Development of more sensitive methods for reducing the number of nondetects in future studies will help reduce this source of bias.

- The artificial turf fields comprising this study were sampled from eight months to five years after installation. Since the emission of many VOCs from crumb rubber infill decreased over time in laboratory tests (Xi et al., 2010), it is likely that VOC release would be greatest shortly after field installation. Whether VOCs emitted by newly installed fields accumulate to measurable concentrations in the air can be tested by sampling the air above new fields.
- This study covered outdoor fields made of artificial turf. However, artificial turf is also being used in indoor sports stadiums. VOCs released by indoor fields have the potential to accumulate, depending on the building's ventilation rate. A recent study by Simcox et al. (2010) found significantly higher concentrations of VOCs and sVOCs over an indoor artificial turf field compared to outdoor fields. However, some complications discussed in that report (such as no building ventilation on the day of air sampling) suggest that additional indoor fields should be sampled to determine if VOC levels over indoor artificial turf fields pose health risks. A Norwegian study (Dye et al., 2006) of artificial turf fields in indoor stadiums concluded that health risks were unlikely to result from the VOC and sVOCs in the stadium air.
- Our study analyzed VOCs in the air above four artificial turf fields. This is a small number compared to the number of artificial fields already in use and those to be installed in the near future. It remains possible that different lots of recycled crumb rubber emit different VOCs. Recent laboratory measurements by Simcox et al. (2010) demonstrated fairly good agreement between different samples of crumb rubber of similar age and the VOCs they emitted. However, some differences were detected.
- The new generation of artificial turf contains other materials in addition to crumb rubber infill, including synthetic blades of grass, backing material, and various types of adhesives. It is possible that some of the VOCs we detected may have originated from these materials rather than from the crumb rubber.

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Chapter 2

Is the New Generation of Artificial Turf Containing Recycled Crumb Rubber Infill a Significant Source of Airborne Particulate Matter (PM2.5)?

Abstract

Outdoor athletic fields made of the new generation of artificial turf containing crumb rubber infill from recycled tires were analyzed to determine if they release significant amounts of airborne particulate matter of aerodynamic diameter less than 2.5 microns ($PM_{2.5}$). Air above three fields was sampled for three-hour intervals during periods of active field use (soccer games or practices). For comparison, the ambient air was analyzed by sampling upwind of the fields. $PM_{2.5}$ was collected on pre-weighed Teflon filters followed by gravimetry to determine its weight. X-ray fluorescence (XRF) was performed on the filters from two of the fields to measure the elemental content of the $PM_{2.5}$. The weight of $PM_{2.5}$ in the air above two fields was below the limit of detection. For the third field, the weight of $PM_{2.5}$ was similar in the air above and upwind of the field (from 12 to18 $\mu g/m^3$). In the two fields analyzed by XRF, five elements were detected in the $PM_{2.5}$ at levels above the limits of detection: sodium, calcium, potassium, chlorine, and sulfur. Therefore, these elements could serve as markers for the $PM_{2.5}$ collected on the filters. The concentrations of all five elements were similar above and upwind of the fields, suggesting that the concentrations of $PM_{2.5}$ at both locations were also similar. Another 32 elements, including heavy metals such as lead, cadmium, mercury, nickel, arsenic, manganese, and chromium, were below the limits of detection. These data indicate that the new generation of artificial turf containing crumb rubber infill is not a significant source of airborne $PM_{2.5}$ or heavy metals associated with $PM_{2.5}$

Introduction

Airborne particulate matter with a mass median aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$) is a potential source of human toxicity via the inhalation route. Due to their small size, upon inhalation these particles penetrate deeply into the lungs, into the region where gas exchange occurs. If these particles are deposited in this region, chemicals or metals they contain have the potential to pass quickly into the bloodstream. Increased $PM_{2.5}$ concentrations of 10 $\mu g/m^3$ correlated with increased incidences of human disease, including respiratory and cardiovascular disease (Ostro et al., 2006; Ostro et al., 2007; Peng et al., 2009; Zanobetti and Schwartz, 2009). Hospital admissions and mortality also increased with increased concentrations of $PM_{2.5}$. Importantly, the increases in hospital admissions, mortality and $PM_{2.5}$ occurred during time frames as short as one or two days, suggesting that acute exposure to elevated levels of $PM_{2.5}$ is sufficient to cause human toxicity. This is supported by studies of mice exposed via intratracheal instillation of $PM_{2.5}$ collected from ambient air, where it was acutely toxic to lung tissue (Wegesser et al., 2009). Thus, data from both laboratory studies of animals and epidemiological studies of humans indicate that $PM_{2.5}$ in the ambient air can be acutely toxic. The $PM_{2.5}$ discussed above was emitted into the air largely through combustion. Two examples are emissions from vehicles (particularly diesel) and emissions from wood fires. More recently, specific components of the $PM_{2.5}$ in the ambient air were shown to be particularly toxic. These included elemental carbon and organic carbon, both of which correlated with increased risks of hospital admissions for cardiovascular and respiratory diseases (Peng et al., 2009) and increased

mortality (Ostro et al., 2007). Whether the $PM_{2.5}$ potentially generated by artificial turf fields containing crumb rubber infill would contain chemicals as toxic as those in the $PM_{2.5}$ generated by combustion, is not known.

The new generation of artificial turf often contains infill composed of recycled tire rubber. The rubber is processed (at ambient or cryogenic temperatures) into millimeter-sized pieces of rubber crumb that simulate natural soil. The process of mechanical grinding of rubber generated measurable levels of airborne PM_{10} (airborne particulate matter with mass median aerodynamic diameter of less than 10 µm; Chien et al., 2003). Both $PM_{2.5}$ and PM_{10} were detected in the air above ***indoor*** artificial turf fields containing rubber crumb (Dye et al., 2006), although the particulate matter in the ambient air was not measured for comparison. Recent measurements of PM_{10} (U.S. EPA, 2009) and both PM_{10} and $PM_{2.5}$ (New York State, 2009; TRC, 2009) over ***outdoor*** artificial turf fields suggest that these fields do not release significant amounts of particulate matter in either size class. In the case of $PM_{10,}$ the amounts of 12 elements (including seven heavy metals) in these particles were similar whether the air was sampled from above or upwind of these fields (U.S. EPA, 2009). These studies suggest that outdoor artificial turf containing rubber crumb does not release significant amounts of $PM_{2.5}$, PM_{10}, or PM_{10}-associated metals into the air. We have been unable to locate any data on the metals content of $PM_{2.5}$ sampled from above outdoor artificial turf fields. Therefore, our goal was to determine whether ***outdoor*** artificial turf fields containing rubber crumb are point sources for the release of $PM_{2.5}$ and $PM_{2.5}$-associated metals into the air. To accomplish this we visited three such fields and sampled the air both above and upwind of each field.

Methods

Permission was obtained from three San Francisco Bay Area cities to perform air sampling at city fields during soccer games or practices. One city manager estimated that 80-90 percent of field usage was for soccer. Air samples were collected during periods of active field use, since $PM_{2.5}$ generation or release into the air, if they occurred at all, were expected to be maximal at those times.

All three fields consisted of new generation artificial turf containing crumb rubber infill made from recycled tires. Fields #1, #2 and #3 were 26, 8 and 3 months old, respectively, at the time of air sampling. Each artificial turf field contained a marked soccer field. The artificial turf extended past the boundaries of each soccer field by at least three to five meters on every side. The air sampling equipment was placed about one meter from a sideline or endline of the marked soccer field, on the downwind side of the field. Wind speed and direction were monitored continuously with a wind meter and weather vane (Nielsen-Kellerman, PA). The prevailing winds in the San Francisco Bay Area tend to be out of the west or northwest during the spring and summer. Such was the case during all air sampling. There was no significant precipitation on the day preceding sampling or the day of sampling. Immediately before or after air sampling at each artificial turf field, air was sampled in an identical manner at a location a few hundred meters upwind of each field (see below).

Air sampling for $PM_{2.5}$ and associated metals was performed with a MiniVol Tactical Air Sampler from Airmetrics (Eugene, OR). This device pumps air through two impactors in series followed by a 47 mm Teflon filter. The first impactor removes particles with a mass median aerodynamic diameter of greater than 10 µm. The second impactor removes particles greater than 2.5 µm. The remaining particles less than 2.5 µm in diameter ($PM_{2.5}$) were collected on the pre-weighed Teflon filters (weighed at Chester LabNet in Tigard, OR, after equilibrating at the

correct temperature and humidity for 24 hours). Filters were returned to the lab for weighing a second time (gravimetry) and measurement of metals by X-ray fluorescence (XRF).

For each of the three artificial turf fields, one air sample was collected from above the field (during active field use) and one sample from upwind of the field during consecutive three hour sampling periods. The next day this was repeated at the same two locations, again during active field use, yielding two "field" samples and two "upwind" samples per field. Air sampling was performed at a height of four feet above the ground to approximate the breathing height of children. The flow rate of pumped air was adjusted to five liters per minute, including correction for temperature and pressure according to the manufacturer's instructions. At this flow rate, 0.9 m^3 of air was sampled during each three hour period. A single-point flow rate check was performed with a calibrated manometer. The measured flow rate of the MiniVol Tactical Air Sampler differed from the calculated flow rate by less than one percent. Sample "blanks" were included for both gravimetry and XRF analysis. Sample "blanks" were filters that were treated exactly like the filters used for air sampling (i.e., all filters were weighed at the lab), but upon receipt by us were never removed from their packaging, prior to being sent back to the lab to be weighed for the second time.

Results

Table 1 shows the gravimetric data for air sampling above the three artificial turf fields. Filter net weights above the limit of detection (LOD) of 26 µg per filter were only collected at one of the fields (field #2). This suggests that the $PM_{2.5}$ concentrations in the air above and upwind of field #1 and field #3 were too low to measure by the gravimetric method used here. Extending the sampling period to 24 hours most likely would have increased the filter net weights to above the LOD; however, this also would have extended sampling to periods when the fields were not in use, complicating interpretation of the data.

Focusing on field #2, $PM_{2.5}$ concentrations ranged from 12 to 18 $\mu g/m^3$. There was good agreement between the two "field" samples (16 and 18 $\mu g/m^3$) and between the two "upwind" samples (12 and 16 $\mu g/m^3$). The "field" and "upwind" values were similar, indicating that the field was not a point source for the release of significant amounts of $PM_{2.5}$ into the air. Unfortunately, since only these four filter net weights (from among the 12 samples collected at the three fields) were above the LOD, statistical analysis of the difference between "field" and "upwind" values was not possible. However, the XRF data presented below indicate that the $PM_{2.5}$ collected from above or upwind of the fields had the same elemental composition, suggesting it originated from the same source.

Following gravimetric analysis, the filters from fields #2 and #3 were analyzed by XRF. This procedure allowed quantification of 37 elements associated with the airborne $PM_{2.5}$. The LODs for some elements were more than 1,000-fold lower than the gravimetric LOD. Thus, the XRF data allowed detection of $PM_{2.5}$ at much lower concentrations than gravimetry.

Table 2 shows the XRF data. The mass of sulfur (S) associated with $PM_{2.5}$ collected from above and upwind of both fields ranged from 13- to 35-fold higher than the LOD. These high sulfur levels relative to the LOD provide more confidence in the accuracy of the sulfur data compared to the gravimetric data presented in Table 1. The mass of $PM_{2.5}$-associated chlorine (Cl) collected from field #3 was even higher, ranging from 352- to 496-fold higher than the LOD. Potassium (K), calcium (Ca), and sodium (Na) collected from above field #2 were also higher than the corresponding LOD, although the sodium values were less than two-fold higher than the LOD (Table 2).

Table 1. $PM_{2.5}$ air concentrations above three artificial turf fields: gravimetric data.

Artificial turf field	Date sampled	[1]Sample type	[2]Net weight of each filter (µg)	[3]$PM_{2.5}$ air concentration (µg/m^3)
#1	4/29/09	Upwind	12	NC
#1	4/29/09	Field	19	NC
#1	4/30/09	Upwind	19	NC
#1	4/30/09	Field	13	NC
#1	4/30/09	Blank	12	NA
#2	5/9/09	Upwind	30	16
#2	5/9/09	Field	30	16
#2	5/10/09	Upwind	27	12
#2	5/10/09	Field	32	18
#2	5/10/09	Blank	13	NA
#2	5/10/09	Blank	20	NA
#2	5/10/09	Blank	14	NA
#3	6/6/09	Upwind	25	NC
#3	6/6/09	Field	12	NC
#3	6/7/09	Upwind	18	NC
#3	6/7/09	Field	16	NC
#3	6/7/09	Blank	16	NA
#3	6/7/09	Blank	19	NA
#3	6/7/09	Blank	11	NA
LOD (see footnote 2) = 26 µg/filter				

[1] "Upwind" samples were collected a few hundred meters upwind of each field; "field" samples were collected along the field's sideline or endline on the downwind side of the field during soccer games or practice; "blank" samples were filters that were never removed from their packaging prior to being returned to the laboratory for weighing.
[2] Filter net weights (filter weight after sampling minus filter weight before sampling) reported by the analyzing laboratory. Four values for field #2 were above the limit of detection (LOD) of 26 µg per filter [LOD = average of the seven "blank" net weights + (3.14 x standard deviation) = 15 + (3.14 x 3.5) = 26; (Keith, 1991)]
[3] Concentrations calculated by subtracting the field #2 average "blank" net weight (16) from each "upwind" or "field" net weight and dividing by 0.9 m^3 to correct for the amount of air sampled. NC = not calculated, since filter net weights were below the LOD. NA = not applicable.

The XRF data in Table 2 also allow a comparison between the "field" and "upwind" concentrations of these elements. Surveying all five elements, the concentration ranges of the "field and "upwind" samples were similar, indicating that the fields were not significant sources for the release of $PM_{2.5}$ containing these elements. These results compliment the gravimetric results.

Table 2. Air concentrations of elements associated with $PM_{2.5}$ collected from above two artificial turf fields.

Artificial turf field	Date sampled	[1]Sample type	[2]Na	[2]S	[2]Cl	[2]K	[2]Ca
#2	5/9/09	Upwind	3.95/3.82	0.61/0.67	4.96/5.51	0.12/0.13	0.18/0.18
#2	5/9/09	Field	3.70/3.54	0.51/0.56	4.66/5.18	0.11/0.12	0.14/0.14
#2	5/10/09	Upwind	2.25/1.93	0.65/0.71	3.52/3.91	0.07/0.08	0.12/0.12
#2	5/10/09	Field	2.92/2.68	0.70/0.77	3.55/3.94	0.09/0.10	0.15/0.15
#2	5/10/09	Blank	0.84/	0.01/	0.00/	0.00/	0.01/
#2	5/10/09	Blank	0.17/	0.00/	0.00/	0.00/	0.02/
#3	6/6/09	Upwind	[4]	0.35/0.39	[4]	[4]	[4]
#3	6/6/09	Field	[4]	0.32/0.36	[4]	[4]	[4]
#3	6/7/09	Upwind	[4]	0.27/0.25	[4]	[4]	[4]
#3	6/7/09	Field	[4]	0.25/0.28	[4]	[4]	[4]
#3	6/7/09	Blank	1.15/	0.00/	0.00/	0.00/	0.00/
#3	6/7/09	Blank	0.19/	0.00/	0.01/	0.00/	0.02/
[3]LOD			2.13	0.02	0.01	0.00	0.04

[1] "Upwind" samples were collected a few hundred meters upwind of each field; "field" samples were collected along the field's sideline or endline on the downwind side of the field during soccer games or practices; "blank" samples were filters that were never removed from their packaging prior to being returned to the laboratory for analysis.

[2] Concentrations of elements associated with $PM_{2.5}$. Each value to the left of the slash is the amount of element (in µg) detected on each filter by X-ray fluorescence (XRF). Each value to the right of the slash is the final air concentration (in $\mu g/m^3$) calculated by subtracting the average blank value for that field from the measured amount of element and dividing by 0.9 m^3 to correct for the amount of air sampled. Only those elements are shown where the amounts of both "field" samples were above the limit of detection (LOD, see footnote 3) and above the laboratory's 99.7 percent confidence minimum detectable limit (MDL). Another 32 elements (including lead) were measured but not included in the table since the values were below the LOD and/or MDL.

[3] Each limit of detection (LOD) was determined using the four sample "blanks" from the two artificial turf fields. A sample "blank" was a filter that was never removed from its packaging prior to being returned to the laboratory for analysis by XRF. The calculation was: LOD = average "blank" value + [(3.14) x (standard deviation)].

[4] Amount of element in one or both "field" samples was below the LOD and/or MDL.

Another 32 elements analyzed by XRF were below the LOD and/or laboratory MDL (minimum detectable limit, as reported by the analyzing laboratory, see footnote 1 to Table 3) (data not shown), and therefore were not detected in the $PM_{2.5}$ collected from either upwind or above the artificial turf fields. Some of the toxicologically important elements not detected were arsenic, cadmium, chromium, lead, manganese, mercury, and nickel (Table 3). The LOD for lead was 0.12 µg/m^3. Zinc was also below its detection limits (Table 3).

Table 3. Laboratory MDLs and calculated LODs for X-ray fluorescence (XRF) performed to detect selected elements in the $PM_{2.5}$ fraction collected from above or upwind of artificial turf fields.

Element	Laboratory 99.7 percent confidence minimum detectable limit (MDL[1]) in µg/m^3	Limit of detection (LOD[2]) in µg/m^3
Arsenic	0.057	0
Cadmium	0.15	0.26
Chromium	0.021	0.0024
Lead	0.09	0.12
Manganese	0.031	0.04
Mercury	0.011	0.14
Nickel	0.065	0.06
Zinc	0.076	0.02

[1] MDLs, reported by the laboratory performing the XRF, were based on uncertainties associated with calibration, counting statistics, peak overlap correction, and absorption correction.
[2] LODs were calculated as described in footnote 3 of Table 2.

Discussion

Once particles with a mass median aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$) become airborne, they can travel for days over many miles. Their small size permits inhalation deep into the lungs, into the alveolar region where gas exchange occurs. If these particles are deposited in this region, they become a potential health concern, depending on their chemical composition.

The ground rubber infill used in the new generation of artificial turf is a potential source of $PM_{2.5}$. It has been reported that the grinding process itself generates particles of rubber in the 10 µm range (Chien et al., 2003; $PM_{2.5}$ was not analyzed in this study). It is not known if cryogenic processing of recycled tires into rubber crumb does the same. In addition, it is not known whether the mechanical forces produced by athletes running on these fields generate $PM_{2.5}$.

Prior to our study, some air sampling had been performed over indoor and outdoor artificial turf fields to measure $PM_{2.5}$ levels. In the case of **indoor** fields enclosed in covered stadiums (Dye et al., 2006), $PM_{2.5}$ was detected at concentrations up to 19 µg/m^3, about 50 percent of which consisted of rubber. However, in this study, $PM_{2.5}$ levels in the air outside of the stadiums were

not measured, making it difficult to pinpoint the source of the indoor $PM_{2.5}$. Two studies showed that the $PM_{2.5}$ concentrations in the air over **outdoor** fields were not different from concentrations upwind of the fields, indicating that the fields were not significant sources of $PM_{2.5}$ release (TRC, 2009; New York State, 2009). The results of our study, covering three **outdoor** fields, are consistent with the two earlier **outdoor** studies.

Measurement of total $PM_{2.5}$ by gravimetry yielded values above the LOD at one of three fields (Table 1). This was not unexpected since a relatively small volume of air (0.9 m^3) was filtered during the three hour sampling intervals. Three-hour intervals were chosen to ensure that each sampling interval covered a period of constant and intensive field use, when $PM_{2.5}$ generation and/or release was expected to be maximal.

Looking specifically at the gravimetry for field #2, the $PM_{2.5}$ concentrations ranged from 12 to 18 $\mu g/m^3$. This range agrees well with mean concentrations reported for other U.S. cities and populous counties (Liu et al., 2009; Peng et al., 2009; Zanobetti and Schwartz, 2009). The gravimetric data for the three fields indicate the $PM_{2.5}$ concentration was above the LOD at one field and below the LOD at the other two. Comparing the two "field" values to the two "upwind" values for field #2, the concentrations are similar, suggesting the field was not a source of airborne $PM_{2.5}$. Therefore, for the three fields monitored for airborne $PM_{2.5}$, two had levels that were below the LOD and one had levels similar to the ambient level. These data suggest that the artificial turf fields are not significant sources of $PM_{2.5}$ release.

One possible explanation for our finding of similar $PM_{2.5}$ concentrations over and upwind of these fields is that these fields may not contain rubber particles in this size class. This possibility was tested by wipe sampling and vacuum sampling two artificial turf fields in New York State (New York State, 2009). The collected material was analyzed by light and electron microscopy to determine particle size. The chemical content of the particles was measured by Fourier Transform Infrared (FITR) spectroscopy. Particles fell into two size classes: a large size class in the millimeter range that contained rubber particles, and a small size class that averaged 5-7 microns in diameter composed of minerals such as quartz and calcite, along with biological material such as pollen and mold. Rubber particles were not present in the smaller (respirable) size class. This work suggests that crumb rubber infill does not contain significant amounts of rubber particles in the size class capable of becoming airborne $PM_{2.5}$.

The XRF measurements presented here were significantly more sensitive than the gravimetry. LODs were more than 1,000-fold lower for some elements compared to the gravimetry. Sulfur values from both fields ranged from 13- to 35-fold higher than their LOD (Table 2), providing a sensitive marker for the sulfur-containing fraction of the $PM_{2.5}$ collected from above and upwind of these fields.

The concentrations of sulfur associated with $PM_{2.5}$ ranged from 0.25 to 0.77 $\mu g/m^3$. This range is similar to the median value of 0.9 $\mu g/m^3$ for sulfur (as sulfate) reported for populous U.S. counties (Peng et al., 2009). Five elements including sulfur were measured at levels above their LODs, allowing their use as markers for $PM_{2.5}$ (Table 2). Comparing "field" to "upwind" concentrations of these five elements, the concentrations were consistently similar, indicating that field #2 and field #3 were not significant sources of $PM_{2.5}$. Combining the XRF and gravimetric results, the data indicate that these artificial turf fields do not release measurable amounts of $PM_{2.5}$ into the air.

Artificial turf also contains synthetic blades of grass that represent another potential source of $PM_{2.5}$. Green-colored dust has been detected in some older fields by wipe sampling, presumably

caused by wear to the blades. In some cases this dust contained relatively large amounts of lead due to the use of lead-containing paint (NJDHSS, 2008). Crumb rubber made from recycled tires also contains lead, some of which is bioavailable (OEHHA, 2007; U.S. EPA, 2009). Lead-containing dust is a potential source of inhalation toxicity to athletes using these fields if the dust is in the $PM_{2.5}$ size range. Therefore, we performed XRF on the $PM_{2.5}$ collected from above these fields to measure its content of lead and other metals. All heavy metals analyzed, including cadmium, chromium, lead, manganese, mercury, and nickel, were below their LOD and/or laboratory MDL (Table 3). Arsenic and zinc were also below their detection limits (Table 3). Since the zinc content of crumb rubber made from recycled tires can exceed 1 percent by weight (U.S. EPA, 2009), our finding that zinc was below its LOD is consistent with the conclusion that crumb rubber particles were not included in the airborne $PM_{2.5}$.

Our XRF analysis of $PM_{2.5}$ had an LOD for lead of 0.12 $\mu g/m^3$. The 30-day average California Ambient Air Quality Standard for total lead is 1.5 $\mu g/m^3$, while the federal standard is 0.15 $\mu g/m^3$ for a three-month rolling average (CARB, 2008). Since lead and other heavy metals have a low volatility at the temperatures encountered on these fields, any metals released into the air by these fields would be bound to particulate matter. We did not detect lead or other heavy metals in the $PM_{2.5}$. Levels of PM_{10}-associated heavy metals were the same in air sampled from above and upwind of two artificial turf fields containing crumb rubber infill (U.S. EPA, 2009). Together, these two sets of data indicate that these surfaces do not release significant amounts of lead or other heavy metals bound to particulate matter in the respirable range.

This study has a number of limitations. Only three artificial turf fields were tested, and only two air samples were collected from above each field. The oldest field (field #2) was 26 months old at the time of testing. This is considerably less than the advertised lifespan for these fields of from 8 to 15 years. In addition, it is not known whether the $PM_{2.5}$ content of a batch of crumb rubber varies depending on the lot of tires or the particular tire recycling facility. Keeping these limitations in mind, our study, together with the studies from New York State (New York State, 2009; TRC, 2009), did not detect the release of $PM_{2.5}$ from a total of five fields containing crumb rubber infill. In addition, four fields (two fields also analyzed for $PM_{2.5}$) also were negative for PM_{10} release (New York State, 2009; TRC, 2009; U.S. EPA, 2009). Thus, the data collected to date from a total of seven different fields indicate that these fields are not significant point sources for the release of respirable particulate matter.

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Chapter 3

Identification and Quantification of Bacteria Cultured from Components of Artificial and Natural Turf Athletic Fields

Abstract

Outdoor athletic fields made of the new generation of artificial turf containing crumb rubber from recycled tires were analyzed for bacteria. Five artificial turf fields located at high schools, colleges, and universities in the San Francisco Bay Area were measured. Two natural turf fields were analyzed for comparison. Samples of crumb rubber infill from artificial turf or soil from natural turf were collected, along with blades of artificial or natural grass. Samples were cultured in the laboratory for bacterial identification and quantification according to the three most prominent species assay, along with quantification of methicillin-resistant *Staphylococcus aureus* (MRSA).

Artificial turf yielded from four to 10 different species of bacteria per field, compared to 11 to 14 species per natural turf field. Artificial turf also yielded fewer bacterial colony forming units (according to the three most prominent species analysis) per gram of material than natural turf, ranging from 0 to 53,000 CFUs (colony forming units) per gram of crumb rubber infill or artificial blades compared to 637,000 to 305,000,000 CFUs per gram of soil or natural blades from natural turf. Two of 30 samples (7 percent) from artificial turf were positive for a species of *Staphylococci* compared to six of 12 samples (50 percent) from natural turf (p=0.004 by Fisher's Exact Test). No MRSA was detected on artificial turf, while a single sample of blades from natural turf was positive for MRSA (p=0.3). These data indicate that the new generation of artificial turf containing crumb rubber infill harbors fewer bacteria than natural turf, including *Staphylococci* and MRSA. Environmental factors contributing to this difference may be the low moisture content and high temperature of artificial turf relative to natural turf.

Introduction

Staphylococcus is a genus of gram-positive bacteria commonly found on the surface of human skin. Normally, these skin bacteria cause no infection or health problems. However, under the proper conditions these bacteria can infect the skin, causing diseases such as impetigo and boils. *Staphylococcus aureus* (*S. aureus*) is a species that is particularly pathogenic to humans. If a skin infection of *S. aureus* moves internally, it can cause serious organ damage and death.

The methicillin antibiotics were originally very effective for treating *S. aureus* infections. However, over time strains developed that were resistant to this class of antibiotics, termed methicillin-resistant *S. aureu* (MRSA). Currently, these strains cause serious infections in hospitals, known as hospital-associated MRSA. The targets of hospital-associated MRSA are usually persons with other diseases and weakened immune systems (Boucher and Corey, 2008).

MRSA outbreaks also occur in healthy persons outside of hospitals. Such outbreaks are called community-associated MRSA. Risk factors may be absent. Cases of community-associated MRSA have been increasing rapidly over the last decade (Buss et al., 2009; Klein et al., 2009; Many, 2009). A number of such outbreaks have occurred in sports settings, particularly among athletes engaged in contact sports (Begier et al., 2004; Romano et al., 2006; Benjamin et al., 2007; Kirkland and Adams, 2008; Buss et al., 2009; Hall et al., 2009; Redziniak et al., 2009).

Most of these outbreaks were among sports with high frequencies of player-to-player skin contact: American football, wrestling, and rugby (Turbeville et al, 2006).

While player-to-player contact is considered the most important mode of MRSA transmission in sports outbreaks, possible instances of transmission via fomites (inanimate objects) have been reported, including soap bars (Nguyen et al., 2005; Miller and Diep, 2008; Hall et al., 2009), sensor wires used in fencing (MMWR, 2003), towels (MMWR, 2009), and weight room equipment (Kirkland and Adams, 2008). Turf itself has also been suggested as a fomite for MRSA transmission, following the identification of turf burns (i.e., turf-induced skin abrasions) as a risk factor for MRSA infection in outbreaks in professional (Kazakova et al., 2005) and college (Begier et al., 2004) football. Both of these football teams had home fields made of artificial turf, raising the possibility that artificial turf causes abrasions that are particularly susceptible to infection. However, turf burns suffered by football players on natural turf have also been associated with bacterial skin infections (Bartlett et al., 1982; Sosin et al., 1989). It appears that skin trauma constitutes a risk factor for MRSA infection whether it is caused by the playing surface, chafing from uniforms or protective equipment, body shaving, wrestling mats, or sensor wires used in fencing competition.

There are at least two different explanations for an association between turf burns and infection by MRSA. First, the turf itself might harbor the bacteria, transferring it to the athlete's skin during player contacts with the turf that are forceful enough to cause a turf burn. Alternatively, the turf might not be a significant source of MRSA. Rather, turf burns may be efficient portals of entry for the bacteria during subsequent player-to-player contacts. This study addresses the possibility that the new generation of artificial turf containing crumb rubber from recycled tires is itself a significant source of MRSA and other *Staphylococci* species. Artificial turf and natural turf fields have both been sampled for bacterial culture to measure their content of bacteria in general, and *Staphylococci* (including MRSA) in particular. The possibilities that the new generation of artificial turf causes more and more serious turf burns than natural turf are addressed in a companion study in this report.

Methods

Seven soccer fields were analyzed for bacteria. Five were artificial turf and two were natural turf. All were on the grounds of colleges, universities, or high schools located in the San Francisco Bay Area. Fields #1-4 were sampled on September 29, 2009. Fields #5-7 were sampled on October 12, 2009. Weather on the earlier date was cloudy to sunny, breezy and in the lower 60s (^{o}F). Weather on the later date was cloudy, with lighter winds, and in a similar temperature range.

Two different components of the fields were collected: artificial infill or natural soil and blades of grass (artificial or natural). For artificial turf fields, the infill was a mixture of recycled crumb rubber and sand. Grass blades from artificial turf were most likely made of polyethylene.

Soil and infill samples were taken from the topmost inch of material. Therefore, some of the material was exposed to the sun and some was shielded. A stainless steel spatula was used to scoop up the soil or infill. The spatula was kept in a solution of 70 percent isopropyl alcohol, wiped with a sterile alcohol pad, and waved in the air to dry prior to sample collection. All artificial or natural blades of grass were taken from the layer that was exposed to the sun. A stainless steel scissors was used to cut and collect the blades. The scissors was cleaned as described above for the spatula. Disposable nitrile gloves were worn during sample collection. All infill, soil, and blade samples were placed into pre-weighed sterile polystyrene conical tubes

and then into a chest containing ice. Samples were shipped by overnight mail to the analyzing laboratory (LA Testing Inc., Pasadena, CA). Approximately 1-2 grams of soil or infill and approximately 0.30 to 0.90 grams of blades were collected per sample.

Each field was sampled in three different locations for both infill/soil and blades. The locations were just outside of each soccer penalty area at midfield, and inside of the circle at center field.

Samples were analyzed according to the following methods. The three most prominent bacterial colonies were quantified by culturing. Identification was through use of the API system (bioMerieux, Inc., Durham, NC) and other biochemical tests. Methicillin-resistant *Staphylococcus aureus* (MRSA) was also quantified by culture in selective medium containing the antibiotic.

Results

Table 1 shows the results of the assay for the three most prominent types of bacteria cultured from each sample. The soil and blades from natural turf yielded a greater variety and greater numbers of bacteria compared to infill and blades from artificial turf.

Table 1. Counts and identification of the three most prominent types of bacteria cultured from artificial or natural turf athletic fields.

Location on field	Field component	Sample weight (g)	Bacteria[1] in sample (^{4}CFU/g)	Analytical sensitivity (^{4}CFU/g)	Bacteria[1] identified
Field #1, artificial turf					
1	Infill[2]	2.2	5,510	46-455	*Brevibacterium* species, *Pseudomonas stutzeri, Rhodococcus* species
1	Blades[3]	0.034	0	2,940	None
2	Infill	1.75	57	57	*Bacillus pumilus C*
2	Blades	0.034	0	2,940	None
3	Infill	1.5	53,300	667	*Leifsonia aquatic, Pseudomonas fluorescens*
3	Blades	0.031	0	3230	None
Field #2, natural turf					
1	Soil	1.09	4,210,000	91,700	*Bacillus cereus, Pseudomonas putida, Staphylococcus* coagulase negative
1	Blades	0.062	305,000,000	1,610,000	*Arthrobacter, Pantoea dispersa, Pseudomonas luteola*
2	Soil	1.57	637,000	63,700	*Enterobacter cloacae,* presumptive *Bacillus* species
2	Blades	0.084	10,500,000	1,190-119,000	*Pantoea agglomerans, Staphylococcus* coagulase negative

Location on field	Field component	Sample weight (g)	Bacteria[1] in sample ([4]CFU/g)	Analytical sensitivity ([4]CFU/g)	Bacteria[1] identified
3	Soil	0.804	1,370,000	124,000	*Bacillus pumilus C, Staphylococcus lentus*
3	Blades	0.08	97,500,000	1,250,000	*Chryseobacterium meningosepticum, Staphylococcus aureus, Staphylococcus xylosus*
Field #3, artificial turf					
1	Infill	1.9	105	53	*Corynebacterium propinquum, Micrococcus luteus*
1	Blades	0.042	0	2,380	None
2	Infill	1.57	0	64	None
2	Blades	0.034	32,300	2,940-29,400	*Micrococcus luteus, Staphylococcus warneri*
3	Infill	2.0	50	50	*Micrococcus luteus*
3	Blades	0.026	11,500	3,850	*Arthrobacter* species
Field #4, artificial turf					
1	Infill	1.88	53	53	*Arthrobacter* species
1	Blades	0.03	0	3,330	None
2	Infill	1.38	73	73	*Pseudomonas oryzihabitans*
2	Blades	0.031	0	3,230	None
3	Infill	2.14	1,170	47	*Acinetobacter baumanni, Arthrobacter* species, *Microbacterium* species
3	Blades	0.036	2,780	2,780	*Bacillus* species
Field #5, artificial turf					
1	Infill	0.475	843	211	*Brevibacterium* species, *Micrococcus luteus, Sphingomonas paucimobilis*
1	Blades	0.036	0	2,780	None
2	Infill	1.64	854	61	*Micrococcus luteus, Rhodococcus* species
2	Blades	0.049	2,040	2,040	*Rhodococcus* species
3	Infill	1.93	1,760	52-518	*Aeromonas hydrophila/caviae, Micrococcus lylae*
3	Blades	0.034	0	2,940	None
Field #6, artificial turf					

Location on field	Field component	Sample weight (g)	Bacteria[1] in sample ([4]CFU/g)	Analytical sensitivity ([4]CFU/g)	Bacteria[1] identified
1	Infill	2.2	1,870	46	*Arthrobacter* species, *Brevundimonas vesicularis, Rhodococcus globerulus*
1	Blades	0.035	0	2,860	None
2	Infill	1.46	342	69	*Arthrobacter* species, *Kurthia sibirica, Staphylococcus hominis ss novobiosepticus*
2	Blades	0.028	0	3,570	None
3	Infill	1.57	255	64	*Curtobacterium albidum, Leifsonia aquatic*
3	Blades	0.023	17,400	4,350	*Cytophaga fermentans, Kurthia gibsonii, Microbacterium terregens*
Field #7, natural turf					
1	Soil	0.665	7,960,000	150,000	*Bacillus cereus/thuringiensis, Pantoea agglomerans, Rhizobium radiobacter*
1	Blades	0.133	56,400,000	752,000	*Brevibacterium* species, *Curtobacterium pusillum, Staphylococcus lentus*
2	Soil	1.04	2,500,000	96,300	*Aeromonas hydrophila/caviae, Pseudomonas luteola*
2	Blades	0.093	881,000	10,800	*Aeromonas hydrophila/caviae, Pantoea* species 3
3	Soil	0.653	14,100,000	153,000	*Pantoea* species 3, *Pseudomonas luteola, Staphylococcus sciuri*
3	Blades	0.08	192,000,000	1,250,000	*Aeromonas hydrophila/caviae, Microbacterium* species

[1] Bacteria were from among the three most prominent types.
[2] Infill was a mixture of recycled crumb rubber and sand in all cases.
[3] Blades refers to blades of grass, either artificial or natural.
[4] CFU = colony forming units.

The two natural turf fields averaged 12.5 different bacterial species per field (range: 11-14 species per field) compared to 6.2 species per field (range: 4-10 species per field) for the five artificial turf fields. This suggests that natural turf supports a more varied community of bacteria than artificial turf. Note that the two natural turf fields supported the growth of six different species of *Staphylococci* compared to two different *Staphylococci* species in the five artificial turf fields (Table 2). Two of these, *S. aureus* and *S. sciuri*, are well known human pathogens (Klein et al., 2009; Stepanovic et al., 2005). Both were detected on natural turf but not on artificial turf.

Table 2. Occurrence and pathogenicity of *Staphylococci* species cultured from components of artificial or natural turf athletic fields.

Staphylococcus species detected	Sample type	Pathogenic in humans?
***Artificial turf* (5 fields tested)**		
S. warneri	blades	Generally nonpathogenic
S. hominis ss novobiosepticus	infill	Possible opportunistic pathogen
***Natural turf* (2 fields tested)**		
Staphylococcus species (coagulase negative)	soil	Possible opportunistic pathogen
Staphylococcus species (coagulase negative)	blades	Possible opportunistic pathogen
S. lentus	soil	Generally nonpathogenic
S. aureus	blades	Pathogenic
S. sciuri	soil	Pathogenic
S. xylosus	blades	Generally nonpathogenic

With regard to the number of bacteria on these surfaces, the 12 samples of natural turf yielded between 637,000 and 305,000,000 bacteria per gram of material. The 30 samples of artificial turf yielded far fewer, ranging from 0 to 53,000 bacteria per gram of material. Eleven of the artificial turf samples contained no culturable bacteria at all: 10 of these were blades and one was infill (Table 1).

All samples were also cultured to determine whether they contained MRSA. A single blades sample from natural turf was positive for MRSA (Table 3). No MRSA was cultured from artificial turf components.

Table 3. Methicillin-resistant *Staphylococcus aureus* (MRSA) cultured from artificial or natural turf athletic fields.

Field # and type	Location on field	Field component	Sample weight (g)	[4]MRSA in sample ([3]CFU/g)	Concentration reporting limit ([3]CFU/g)
#1 artificial	1	Infill[1]	2.2	None detected	45
#1 artificial	1	Blades[2]	0.034	None detected	2,941
#1 artificial	2	Infill	1.75	None detected	57
#1 artificial	2	Blades	0.034	None detected	2,941
#1 artificial	3	Infill	1.5	None detected	67
#1 artificial	3	Blades	0.031	None detected	3,226

Field # and type	Location on field	Field component	Sample weight (g)	[4]MRSA in sample ([3]CFU/g)	Concentration reporting limit ([3]CFU/g)
#2 natural	1	Soil	1.09	None detected	92
#2 natural	1	Blades	0.062	None detected	1,613
#2 natural	2	Soil	1.57	None detected	64
#2 natural	2	Blades	0.084	None detected	1,190
#2 natural	3	Soil	0.804	None detected	124
#2 natural	3	Blades	0.08	1,250,000	1,250
#3 artificial	1	Infill	1.9	None detected	53
#3 artificial	1	Blades	0.042	None detected	2,380
#3 artificial	2	Infill	1.57	None detected	64
#3 artificial	2	Blades	0.034	None detected	2,941
#3 artificial	3	Infill	2.0	None detected	50
#3 artificial	3	Blades	0.026	None detected	3,846
#4 artificial	1	Infill	1.88	None detected	53
#4 artificial	1	Blades	0.03	None detected	3,333
#4 artificial	2	Infill	1.38	None detected	72
#4 artificial	2	Blades	0.031	None detected	3,226
#4 artificial	3	Infill	2.14	None detected	47
#4 artificial	3	Blades	0.036	None detected	2,778
#5 artificial	1	Infill	0.475	None detected	211
#5 artificial	1	Blades	0.036	None detected	2,778
#5 artificial	2	Infill	1.64	None detected	61
#5 artificial	2	Blades	0.049	None detected	2,041
#5 artificial	3	Infill	1.93	None detected	52
#5 artificial	3	Blades	0.034	None detected	2,941
#6 artificial	1	Infill	2.2	None detected	45
#6 artificial	1	Blades	0.035	None detected	2,857
#6 artificial	2	Infill	1.46	None detected	68
#6 artificial	2	Blades	0.028	None detected	3,571
#6 artificial	3	Infill	1.57	None detected	64
#6 artificial	3	Blades	0.023	None detected	4,348
#7 natural	1	Soil	0.665	None detected	150

Field # and type	Location on field	Field component	Sample weight (g)	[4]MRSA in sample ([3]CFU/g)	Concentration reporting limit ([3]CFU/g)
#7 natural	1	Blades	0.133	None detected	752
#7 natural	2	Soil	1.04	None detected	96
#7 natural	2	Blades	0.093	None detected	1,075
#7 natural	3	Soil	0.653	None detected	153
#7 natural	3	Blades	0.08	None detected	1,250

[1] Infill was a mixture of recycled crumb rubber and sand in all cases.
[2] Blades refers to blades of grass, either artificial or natural.
[3]CFU = colony forming units.
[4]MRSA = methicillin-resistant *Staphylococcus aureus*.

Table 4 summarizes the data from the two bacterial analyses (three most prominent bacteria and MRSA). Focusing first on the MRSA data (right-most column), the incidences of occurrence of this species on the two surfaces were low and not significantly different. However, when all *Staphylococcus* species were considered together (second column from the right), their incidence of occurrence on natural turf was significantly greater than on artificial turf.

Table 4. Summary data for the three most prominent bacteria and MRSA cultured from artificial turf and natural turf components.

Field type	# of fields sampled[1]	Bacteria species per field[2]	Bacteria per gram of infill/soil and blades[2]	Samples positive for *Staphylococci*[2]	Samples positive for MRSA[3]
Artificial	5	4-10	0 to 53,000	2/30[4]*	0/30[5]
Natural	2	11-14	637,000 to 305,000,000	6/12[4]*	1/12[5]

[1]As described in materials and methods, three soil/infill samples and three blades samples were collected per field.
[2]Three most prominent bacteria assay.
[3]MRSA assay.
[4]p=0.004 by Fisher's Exact Test
[5]p=0.3 by Fisher's Exact Test
*indicates statistical significance of $p \leq 0.05$

Discussion

The goal of this study was to determine whether the new generation of artificial turf harbors bacteria, including MRSA and other *Staphylococci*. Few data have been collected that address this topic. For a MRSA outbreak in a professional football team, wipe-sampling of the artificial turf (old-generation Astroturf®) in the parts of the field with the highest number of tackles did

not detect any MRSA (Kazakova et al., 2005). More recently, 20 new generation artificial turf fields were sampled at two locations per field (McNitt et al., 2008). Blades and rubber infill material were sampled separately for bacterial culture. Two samples of soil from natural turf fields were collected for comparison. No *S. aureus* was detected. Quantitative data were only presented for the soil/infill samples. Unidentified bacteria were detected at 0 to 80,000 colony forming units (CFUs) per gram of rubber infill compared to 260,000 to 310,000 CFUs per gram of natural soil. These data suggest that bacteria in general, and *S. aureus* in particular, colonize artificial turf no better than natural turf. A subsequent study in which *S. aureus* was inoculated on to components of artificial and natural turf and its growth measured supported this conclusion (Pennsylvania State University, undated).

The data we present indicate that fields made of the new generation of artificial turf containing recycled crumb rubber harbor fewer bacteria than fields made of natural turf. This was true both in terms of the numbers of CFUs detected per gram of field component and the variety of bacterial species.

The numbers of bacteria per gram of infill or blades from artificial turf ranged from 0 to 53,000 CFUs per gram of material (Table 4). Ten samples of infill and one of blades yielded no CFUs (Table 1). In contrast, natural turf components contained from 637,000 to 305,000,000 CFUs per gram of material. This large difference in CFUs per gram of material indicates that most, if not all, bacterial species survive and/or proliferate less well on artificial turf compared to natural turf. Some possible reasons for this are discussed below.

The number of different bacterial species that could be cultured from artificial turf was also less compared to natural turf. The bacterial species per field ranged from 4-10 on artificial turf compared to 11-14 on natural turf (Table 4). This pattern was also seen for MRSA, detected on 0/30 artificial turf samples compared to 1/12 natural turf samples (Table 3). These low MRSA incidences were not significantly different ($p=0.30$). However, when all *Staphylococcus* species were considered together (Table 2), their incidence of occurrence on artificial turf (2/30) was significantly lower than that on natural turf (6/12; $p=0.004$). Therefore, our data suggest that artificial turf fields harbor fewer *Staphylococci* in general, and fewer MRSA in particular, than natural turf fields.

That MRSA was only detected in one out of 42 turf samples (artificial and natural combined) was not unexpected, given that populations of MRSA have not been readily detected on the surfaces of potential fomites, including turf (Lindenmayer et al., 1998; Kazakova et al, 2005; Romano et al, 2006; Many, 2008; McNitt et al., 2008). In contrast, transmission of community-associated MRSA via body-to-body contact during contact sports is well-established (Begier et al., 2004; Turbeville et al., 2006; Benjamin et al., 2007; Cohen, 2008; Kirkland and Adams, 2008; Lindenmayer et al., 2008; Garza et al., 2009;), possibly due to the more hospitable environment that human skin provides for the survival and growth of this bacterium.

There are a number of possible reasons why *Staphylococci* might survive and/or multiply less well on artificial turf fields compared to natural turf. On the often-dry surface provided by artificial turf, a relative humidity in the ambient air of approximately 85 percent would be required for *Staphylococci* to grow (Atlas, 1984). The humidity in most of California is often below this value, especially in the dry season when the sampling for this study was performed. In addition, most bacteria pathogenic to humans grow best below approximately 104°F (40°C; Atlas, 1984). Temperatures on artificial turf fields can greatly exceed this value in the summer, reaching 160°F (New York State, 2009). Such high temperatures, coupled with low humidity, could be

lethal to many bacteria, and contribute to the lower bacterial count of artificial turf compared to natural turf (this study).

In conclusion, the bacterial population including *Staphylococci* was significantly smaller on artificial turf fields compared to natural turf fields. Considering the *Staphylococci* and MRSA data together, it is likely that artificial turf harbors fewer of these bacteria than natural turf, making fewer available for transmission to athletes during field use. However, other characteristics of artificial turf, such as abrasiveness, may influence the frequency of bacterial infections in athletes using these fields. The most definitive data would be the rates of bacterial infections in athletes using artificial turf compared to athletes using natural turf.

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Chapter 4

Comparing Skin Abrasion Due to Contact with Artificial Turf Versus Natural Turf During Intercollegiate Soccer Games

Abstract

Skin abrasion caused by contact with the playing field (also known as turf burn) is a risk factor for bacterial skin infection in athletes participating in contact sports. We have conducted a prospective study comparing the rate and seriousness of skin abrasions associated with the new generation of artificial turf containing crumb rubber infill to abrasions associated with natural turf. Athletic trainers for varsity soccer teams at more than 200 colleges and universities in California and Nevada were contacted by e-mail and telephone and asked to participate in this prospective study covering the 2008 fall season. Trainers from 33 of these schools participated, reporting skin abrasions that occurred during female and male intercollegiate games. A total of 524 games were reported. The overall abrasion rate was 19 abrasions per 1,000 player hours for all players on both surfaces combined. Dividing the abrasion rate for artificial turf by the abrasion rate for natural turf yielded the following abrasion rate ratios (95 percent confidence intervals): 3.0 (2.0-4.4) for females, 2.3 (1.4-3.7) for males, and 2.7 (2.0-3.7) for all players combined. While the abrasion rates were approximately two- to three-fold higher on artificial turf compared to natural turf, abrasion seriousness was similar on the two surfaces. The likelihood that a site of an abrasion was covered by clothing or equipment at the time of injury was similarly low for both surfaces. The leg (including thigh) was by far the most common site for an abrasion. We also discuss possible reasons for the higher abrasion rate on artificial turf, as well as the relationship between turf type and bacterial infection, for a better understanding of related issues.

Introduction

Turf burns are skin abrasions that occur when athletes fall onto a playing field surface during a practice or game. Most turf burns are treated by the team's athletic trainer or by the athlete herself/himself. Athletes usually lose little or no playing time after receiving a turf burn. As such, most turf burns are classified as zero time-loss injuries.

However, turf burn has been identified as a risk factor for serious bacterial skin infection, including infection by methicillin-resistant *Staphylococcus aureus* (MRSA) (Begier et al., 2004; Kazakova et al., 2005; Cohen, 2008). There are at least two possible reasons for this. The turf itself could be a reservoir of infectious bacteria that enter the wound at the time the turf burn is received. Alternatively, the turf burn may leave the athlete more susceptible to receiving bacteria from a second athlete during subsequent player-to-player contact. In either case, if turf burn frequency or seriousness is influenced by surface type, this information should be available to potential customers who must choose between artificial and natural surfaces. This information will also help in the development of best practices for preventing bacterial skin infections.

To evaluate the new generation of artificial turf playing field containing crumb rubber infill for skin abrasion frequency and seriousness, we needed a data set covering this type of field that included all skin abrasions (zero time-loss and time-loss) resulting from player-to-turf contact. We were unable to locate such a data set in the published literature. Therefore, we performed our own prospective study covering intercollegiate soccer played in California and Nevada during the summer and fall of 2008.

Methods

A list of the approximately 150 four-year colleges and universities in California and Northern Nevada was generated by an Internet search. No selection criteria were used other than that the schools were located in these geographic regions. Names and contact information for athletic trainers attending to each school's varsity soccer team (female and male) were collected from each school's website. A list of two-year community colleges in California with soccer teams (about 75) was generated using the website of the California Community College Athletic Trainers' Association. This list included the names and contact information for each team's athletic trainer. Athletic trainers were sent an e-mail describing our study of artificial turf safety. Telephone calls were then made to determine whether each athletic trainer was interested in participating during the 2008 season, running from August to December. Trainers from 41 schools, out of approximately 225 schools contacted, agreed to participate. Data were ultimately received from 33 schools. While trainers were asked to report the results of all games, many reported fewer than the school's full schedule. Trainers from 11 schools reported data from fewer than five games per school, eight reported between five and 15 games, and 14 trainers reported data from more than 15 games. All games were intercollegiate involving varsity teams. The typical college soccer schedule (not including post-season playoffs) includes from 15 to 25 intercollegiate games per season. The data covered 29 female and 24 male teams, and a total of 524 games.

All artificial turf fields belonged to the new generation of artificial turf containing artificial blades of grass and crumb rubber infill. In some cases the infill included sand in addition to the crumb rubber. The athletic trainers were asked to report only those abrasions that resulted from contact between the player and the field's surface.

The athletic trainers reported each abrasion they treated in an online survey form, accessible at any time. Each trainer typically reported data multiple times during the season, entering data from multiple games each time. The survey form asked for the following for each game:

1. School name
2. Date and time of the game
3. Whether the game was a home or away game
4. Whether the players were female or male
5. The kind of turf (artificial or natural)
6. If artificial, the type of infill (rubber, sand, rubber and sand, other)
7. Comments on field condition
8. Time during or after the game each abrasion was treated
9. Location of each abrasion on the body
10. Approximate dimensions of each abrasion
11. Seriousness of each abrasion (red only; pinpoints of bleeding; extensive bleeding)
12. Whether dirt or foreign bodies were present in the wound
13. Whether the site of each abrasion was covered by clothing or padding at the time of injury

Abrasion rates were calculated by dividing the total number of reported abrasions by the corresponding number of player hours and multiplying by 1,000 (Ekstrand et al., 2006). Each game was considered to contain 16.5 player hours per team (11 players per team multiplied by 90 minutes per game). Abrasion rate ratios were calculated by dividing the abrasion rate for artificial turf by the abrasion rate for natural turf. Confidence intervals for abrasion rate ratios were calculated according to Rothman (2002).

Results

Table 1 shows the skin abrasion rates for intercollegiate soccer played on the new generation of artificial turf compared to natural turf. As described in the methods section, these were abrasions caused by player contact with the playing surface. All abrasions were subsequently treated by the team's athletic trainer. As described below, the majority of abrasions were probably not serious enough to have caused significant loss of playing or practice time. The abrasion rates are shown in the second to last column in the table. The rates range from 12 to 39 abrasions per 1,000 player hours.

The abrasion rate ratios (artificial turf/natural turf) are in the last column of the table. For women there were 3.0 abrasions on artificial turf for every one abrasion on natural turf. For men there were 2.3 abrasions on artificial turf for every one abrasion on natural turf. For women and men combined there were 2.7 abrasions on artificial turf for every one abrasion on natural turf. The 95 percent confidence intervals for these abrasion rate ratios are also shown in the last column. They are all greater than 1.0, indicating that these abrasion rate differences are statistically significant.

The same data also were analyzed by calculating a surface-specific abrasion rate for each team individually, followed by calculation of a grand average rate for all games played on artificial or natural turf. A t-test comparison of the grand average rates for women, men and combined on the two surfaces yielded significantly higher abrasion rates for artificial turf that were similar to the differences in abrasion rate ratios shown in Table 1 (data not shown).

To further test whether skin abrasions were more common for soccer games played on artificial turf, we tabulated the games in which a team suffered multiple abrasions (Table 2). The great majority of games played on either surface produced only one abrasion that was treated by the athletic trainer. However, 20 of 158 games played on artificial turf produced multiple abrasions (two, three or four), compared to five of 366 games played on natural turf. This corresponds to 12.7 percent of games played on artificial turf and 1.4 percent of games played on natural turf. Analyzing these data according to a two-tailed Fisher's Exact Test, games with multiple skin abrasions were significantly more likely to occur on artificial turf than on natural turf ($p<0.0001$). This supports the finding presented in Table 1 where all abrasions were considered.

Table 1. Skin abrasion rate ratios for intercollegiate soccer played on the new generation of artificial turf and on natural turf (2008 season).

Groups	Number of teams reporting games on indicated surface	Total games reported	Total skin abrasions reported	Total player hours monitored	Abrasions per 1000 player hours (abrasion rate)	Abrasion rate ratio: artificial/natural (95% CI)[1]
Women artificial turf	22	99	64	1634	39	3.0 (2.0-4.4)
Women natural turf	24	194	42	3,201	13	
Men artificial turf	18	59	26	974	27	2.3 (1.4-3.7)
Men natural turf	20	172	35	2,838	12	
Women + men artificial turf	40	158	90	2,607	35	2.7 (2.0-3.7)
Women + men natural turf	44	366	77	6,039	13	
Women + men both surfaces	53	524	167	8,646	19	Not applicable

[1] Abrasions per 1,000 player hours on artificial turf /abrasions per 1,000 player hours on natural turf. Confidence intervals (CIs) for abrasion rate ratios were calculated according to Rothman (2002).

Table 2. Fraction of games played on artificial or natural turf that resulted in multiple (≥2) skin abrasions requiring treatment.

Surface type	Games	Games with ≥ 2 skin abrasions	% games with ≥ 2 treated skin abrasions
Artificial	158	20	12.7*
Natural	366	5	1.4*

*The 12.7 percent value is significantly greater than the 1.4 percent value by the two-tailed Fisher's Exact Test ($p < 0.0001$)

The data covering abrasion seriousness are presented in Table 3. Athletic trainers were asked to categorize each abrasion. Category 1 was an abrasion with a red color, but without bleeding. A category 2 abrasion had some light bleeding, characterized as pinpoints of bleeding. Category 3 was characterized by extensive bleeding, where individual pinpoints of blood were no longer distinguishable.

Based on the Chi Square Test, the distributions of abrasions among seriousness categories were not significantly different for the two surfaces ($p=0.28$). However, the small numbers of category 3 abrasions suggest that more data should be collected before concluding that there is no surface effect for this category. This caveat notwithstanding, the data suggest that although abrasions happen two- to three-fold more often per player hour on artificial turf compared to natural turf (Table 1), the abrasions are most often of the category 2 type, followed by category 1, and finally category 3, regardless of surface type (Table 3).

Table 3. Seriousness of skin abrasions caused by artificial or natural turf.

Surface Type	Abrasion Category 1 (red only)	Abrasion Category 2 (pinpoints of bleeding)	Abrasion Category 3 (extensive bleeding)
Artificial turf	31%[1] (28)[2]	58% (52)	10% (9)
Natural turf	36% (28)	60% (46)	4% (3)

[1] Percent of abrasions suffered on artificial or natural turf in indicated seriousness category
[2] Number of abrasions in each category

Our survey also asked the athletics trainers to record whether or not each treated abrasion occurred at a site on the body which was covered by clothing or protective equipment at the time of injury. We reasoned that if one surface were significantly more abrasive than the other, it is possible that we would see significantly more abrasions at covered body sites for that surface. Table 4 shows the distributions of abrasions between covered and uncovered sites for the two surfaces. As expected, most abrasions occurred at uncovered sites. Furthermore, the distributions of covered and uncovered sites were not significantly different for the two surfaces according to a two-tailed Fisher's Exact Test ($p=0.5$). These results compliment the data on abrasion seriousness in Table 3 in that both data sets indicate similar abrasion seriousness for the two surfaces.

Table 4. Likelihood abrasion sites were covered at the time of injury on artificial or natural turf.

	Covered	Uncovered
Abrasions on artificial turf	30%[1] (25)[2]	70% (57)
Abrasions on natural turf	36% (26)	64% (46)

[1] Percent of abrasions in the indicated category (covered or uncovered) for that surface
[2] Number of abrasions in the indicated category (covered or uncovered) for that surface

Data also were collected indicating the site on the player's body where the abrasion occurred. As expected, the great majority of abrasions occurred on the leg or thigh, regardless of surface type (Table 5). The arm or hand was the next most frequent site for artificial turf, compared to the hip or buttocks for natural turf. Abrasions to the face were the least frequent for both surfaces. The distribution of abrasion sites for artificial turf was significantly different from the distribution for natural turf according to a Chi Square Test ($p=0.04$). The reasons for these differences are unknown. However, the small numbers of abrasions at sites other than leg/thigh suggest more data should be collected before concluding that abrasion frequencies at these sites were influenced by surface type.

Table 5. Location of abrasions occurring during intercollegiate soccer games played on artificial or natural turf.

	Arm/hand	Leg/thigh	Hip/buttocks	Face
Artificial turf	14%[1] (12)[2]	82% (72)	3% (3)	1% (1)
Natural turf	10% (8)	71% (55)	16% (12)	3% (2)

[1] Percent of abrasions at the indicated body location for that surface
[2] Number of abrasions at the indicated body location for that surface

Discussion

The primary finding of this prospective study, covering intercollegiate soccer played in California and Nevada during the summer and fall of 2008, is that artificial turf containing crumb rubber infill was associated with two- to three-fold more skin abrasions per player hour than natural turf. This was true for both female and male teams. These results were for abrasions sustained during varsity matches between opposing schools. The abrasions were caused by contact with the playing surface, and were serious enough to require treatment by the team's athletic trainer.

A number of prospective studies (described below) have addressed the question of whether the new generation of artificial turf is associated with a higher injury rate than natural turf. Most have concentrated on injuries serious enough to have caused the athlete to miss playing time, either during practices or formal games. Examples are muscle tears, ankle sprains, and ligament tears. Since the majority of skin abrasions cause little if any loss of playing time, most would not have been counted in these prior studies. Nonetheless, counting only time-loss injuries, Fuller et al. (2007a) detected a 2.5-fold higher rate of "laceration/skin lesion" during male intercollegiate soccer games played on the new generation of artificial turf relative to natural turf. This difference was not detected in a similar study that counted only injuries sustained during training (Fuller et al., 2007b). One can only speculate as to whether this difference between games played

on artificial and natural turf would have been quantitatively similar had zero time-loss laceration/skin lesions been included in the analysis.

A study of the new generation of artificial turf by Meyers and Barnhill (2004) did include time-loss and zero time-loss injuries sustained by high school football players. This included a category of "surface/epidermal injuries" that covered abrasions, lacerations, and puncture wounds, but not bruises. These surface/epidermal injuries occurred at a nine-fold higher rate on artificial turf compared to natural turf. However, these injuries resulted from both player-to-player contact and player-to-playing surface contact. Our study focused specifically on abrasions caused by contact of the player with the playing surface. Therefore, the two data sets are not directly comparable.

"Surface/epidermal injuries" also have been reported for college football played on new generation artificial turf and natural turf (Meyers, 2010). Unlike the high school study discussed above, the rate for this class of injury in college games was similar on the two surfaces. The reasons for this difference between high school (Meyers and Barnhill, 2004) and college football (Meyers, 2010) are not known.

There are several potential sources of bias that could have influenced the abrasion rates we measured. Since only a minority of the athletic trainers we contacted agreed to participate in this study, it is possible that trainers disliking artificial turf were more willing to participate. If these trainers had a tendency to over-report abrasions from artificial turf and under-report abrasions from natural turf, this might explain our finding. In addition, the players may have been more likely to seek treatment for abrasions received on artificial turf, due to their unfamiliarity with this surface. A third area of uncertainty relates to the condition of the natural turf fields comprising this study. Since these were college and university fields, they might have been better maintained than typical high school or town fields. Poorly maintained high school or town fields with bare patches, ruts and holes might be expected to cause more abrasions. Thus, the abrasion frequencies for natural turf might be higher if our study covered youth or high school soccer, resulting in less or no difference between artificial and natural turf.

Assuming that the higher skin abrasion rates we detected on artificial turf compared to natural turf were accurate, there are at least three possible reasons for this. Soccer players may contact the surface (falls and sliding tackles) more often when the game is played on artificial turf. Alternatively, the contacts with an artificial surface may be more violent and forceful than those with a natural surface. Lastly, the artificial surface itself may be more abrasive than the natural surface, yielding a higher probability of skin abrasion for each contact.

As to whether soccer players fall or perform sliding tackles more or less frequently on the new generation of artificial turf, this has been addressed in a number of studies. Sliding tackles have been tabulated as an indication of how willing the players were to contact the playing surface with their bodies. Two studies performed by the Federation Internationale de Football Association (FIFA undated[a]; FIFA undated[b]) and another from the published literature (Andersson et al., 2008) reported that from 25 to 100 percent more sliding tackles were performed by amateur and professional soccer players during matches on natural turf than during matches on the new generation of artificial turf. In our own preliminary study, we attended four intercollegiate male soccer games and tabulated the number of times the players contacted the playing surface during both accidental falls and purposeful sliding tackles. In three games played on grass there were 41, 47, 50, 51, 54, and 61 such events per team per game. In one game played on artificial turf there were 54 and 60 such events. We consider these rates similar, although this

is only based on a few games and more data are needed to verify that the rates are truly similar. Considering the studies described above, along with our preliminary data, the data suggest that soccer player contacts with the playing surface occur at a similar or possibly lower rate on artificial turf compared to natural turf. Therefore, the higher skin abrasion rates we measured for artificial turf (Table 1) most likely were not due to more player contacts with that surface.

With regard to the possibility that falls to the playing surface are more violent (i.e., forceful) on artificial turf than on natural turf, the violence of a fall is difficult to quantify. However, the number of fouls called by a referee during a game gives some indication of the level of violent play, including forceful contacts with the surface that are both associated with fouls and independent of fouls. Violent play is specifically prohibited by the rules of soccer. It is punishable by issuance of a yellow (warning) or red (expulsion) card to the offending player. Therefore, the number of fouls and yellow/red cards per game may be used to estimate the level of violent play. Several FIFA studies (FIFA, undated [a-d]), covering professional and amateur matches played on new generation artificial turf and on natural turf, reported that fouls and yellow cards per game were generally similar on the two surfaces. This suggests that soccer played on the new generation of artificial turf is no more violent than soccer played on natural turf, and that the higher rates of skin abrasion we detected on artificial turf were not due to more violent play (including more violent falls) on the artificial surface.

This leaves the possibility that the higher skin abrasion rates on artificial turf were due to that surface's greater abrasiveness relative to natural turf. To help test this hypothesis, an independent measure of surface abrasiveness should be used. Such a method is available: ASTM F1015-03(2009) Standard Test Method for Relative Abrasiveness of Synthetic Turf Playing Surfaces (ASTM, 2009). Published data collected according to this standard show that the abrasiveness of artificial turf playing surfaces varies with manufacturer, and that artificial turf containing infill is consistently less abrasive than old-style Astroturf® (McNitt, 2005). However, we have been unable to locate any data comparing the abrasiveness of new generation artificial turf to natural turf. The reason for this data gap may be the difficulty in obtaining consistent data from within individual natural turf playing fields, due to the variability in turf quality (including patches of bare dirt) across many such fields. Therefore, although there is the likelihood that the higher rate of skin abrasion we measured was due to artificial turf's greater abrasiveness compared to natural turf, this remains a hypothesis. We acknowledge that an independent measure of abrasiveness should be used to confirm or refute this hypothesis. In this regard, it would be useful to determine the source of each surface's abrasiveness. While the green blades of artificial grass constitute the most visible part of the artificial surface, we suspect that the infill contributes more to the abrasive interaction that takes place each time an athlete falls forcefully to the surface. If so, it would also be useful to determine whether the abrasiveness of rubber ground at ambient temperatures differs from that ground at cryogenic temperatures.

Our concern with skin abrasions stems from the findings that skin wounds in general (Bartlett et al., 1982; Sosin et al., 1989; Nguyen et al., 2005; Turbeville et al., 2006; Kirkland and Adams, 2008; Garza et al., 2009; Hall et al., 2009), and turf burns in particular (Begier et al., 2004; Kazakova et al., 2005; Cohen, 2008), are risk factors for infection of athletes by MRSA and other pathogenic bacteria. The important public health question is whether artificial turf is associated with more bacterial skin infections than natural turf. We considered asking the athletic trainers to report this information. However, such infections can appear days or weeks after the initial skin abrasion. Therefore, more effort is needed to perform the kind of extensive follow-up that is required to address this issue. In the absence of such data, we can only make predictions about the relationship between abrasion rate and infection rate for each surface.

If the source of the infecting bacteria is the turf itself, the infection rate would depend on, among other things, the number of abrasions and the number of viable bacteria associated with the turf. Artificial turf caused about 2- to 3-fold more abrasions than natural turf (this study). However, natural turf harbored more bacteria; artificial turf harbored from 0 to 53,000 bacteria per gram of turf component compared to 637,000 to 305,000,000 bacteria per gram of natural turf component (including several species of *Staphylococci;* see bacterial chapter of this report). The higher abrasion rate on artificial turf would increase infections on artificial turf relative to natural turf, while the lower bacterial content of artificial turf would decrease infections on artificial turf relative to natural turf. Therefore, based on this specific infection scenario, it is not possible to predict whether artificial turf poses a greater or lesser infection risk than natural turf.

However, the source of infecting bacteria may not be the turf. Rather, abrasions may be efficient portals of entry for bacteria, leaving the athlete at greater risk for infection during subsequent player-to-player contacts. Information on healing rates for abrasions caused by each surface would be useful in this regard. If this is the correct sequence, then artificial turf and its increased rate of skin abrasions would put athletes at greater risk for skin infection than natural turf. Performing a study similar to ours, in which bacterial skin infection rates were measured following athlete exposures on each surface, is the most direct way to determine if artificial turf puts athletes at greater risk for serious skin infections.

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Chapter 5

Literature review and data gap identification

Chemicals and particulates in the air above the new generation of artificial turf playing fields, and artificial turf as a risk factor for infection by methicillin-resistant Staphylococcus aureus (MRSA)

Executive Summary

The Office of Environmental Health Hazard Assessment (OEHHA) is evaluating the safety of the new generation of artificial turf playing fields. This new generation of turf contains artificial soil termed "infill." Infill helps to soften the surface and prevent injuries. Infill also improves drainage.

Rubber crumb made from finely ground, recycled tires is commonly used as infill in the new generation of artificial turf. Tire rubber is a complex material, containing many naturally-occurring and man-made chemicals. Therefore, as part of its stewardship of tire recycling in California, the California Integrated Waste Management Board (now the Department of Resources Recycling and Recovery, or CalRecycle) has asked OEHHA to evaluate the following aspects of artificial turf playing fields:

1. Whether these fields emit levels of chemicals or particulates into the air that cause illness when inhaled.
2. Whether these fields infect athletes with the dangerous bacterium called methicillin-resistant *Staphylococcus aureus* (MRSA).

The following is our review of the published literature covering these two topics. In addition, we have attempted to identify data gaps that, when filled, will allow performance of a more accurate safety assessment.

Chemicals and Particulates Measured in the Air Above Artificial Turf Fields

Published studies were located that measured chemicals and particulates in the air above artificial turf playing fields. In all cases these fields contained crumb rubber infill. Prior to 2009, the most complete dataset was published by Dye et al. (2006). They identified almost 100 different chemicals and particulates. Another 200 chemicals were detected but not identified. This study covered fields in ***indoor*** stadiums.

Many of the chemicals identified by Dye et al. (2006) were also emitted into air by rubber flooring made of recycled tires. Similarly, laboratory studies of chemicals emitted into the air by crumb rubber made from recycled tires identified many of the same chemicals. A list of the chemicals and particulates emitted into the air during rubber manufacturing also overlapped with those identified by Dye et al. (2006). Therefore, the published literature suggests the data from Dye et al. (2006) are reliable.

In spring 2009 two studies were released that measured chemicals and particulates in the air above ***outdoor*** artificial turf fields containing recycled rubber crumb (New York State, 2009; TRC, 2009). Both studies targeted the same two fields in New York City. Totals of 65 and 85 chemicals were identified at relatively low concentrations in the air above the two fields. Many of

these occurred at similar concentrations in the air sampled upwind of the fields. Concentrations of particulates above the fields were similar to the levels upwind of the fields. Both reports concluded that these fields did not constitute a serious public health concern, since cancer or non-cancer health effects were unlikely to result from these low-level exposures.

A comparison of the chemicals detected in the air above the same two artificial turf fields that comprised the studies by New York State (2009) and TRC (2009) shows that chemical concentrations were consistently higher in the New York State (2009) study, ranging from 1.7-fold to 85-fold higher. The reasons for these differences are unknown. These variable results highlight the difficulties faced in obtaining consistent results from potential point sources of outdoor air pollution. Despite this variability, both studies found that the chemical concentrations they measured were unlikely to produce adverse health effects in persons using these fields.

Is the Air Above Artificial Turf Fields Hazardous to Human Health?

OEHHA constructed a test scenario for an athlete playing soccer from ages 5 to 55 years on the new generation of artificial turf fields containing crumb rubber infill. The data from Dye et al. (2006) were used for chemical concentrations in the air above the fields, since this was the most comprehensive data set available at the time. Breathing rates were based on published data. Time spent on the fields for soccer games and practices was estimated.

From among the chemicals identified by Dye et al. (2006), eight appear on the California Proposition 65 list of chemicals known to the state to cause cancer. Exposure to five of these via inhalation (benzene, formaldehyde, naphthalene, nitromethane, styrene) gave increased lifetime cancer risks that exceeded one in one million (10^{-6}), generally considered the negligible risk level. In other words, more than one cancer case could be expected to occur in a hypothetical population of 1 million people regularly playing soccer on these artificial turf fields between the ages of 5 and 55. The highest risk was from nitromethane, which could cause about nine cancer cases in a hypothetical population of 1 million soccer players. While these estimated risks are low compared to many common human activities, they are higher than the negligible risk level of one cancer in a population of 1 million people. Data gaps exist that could lead to overestimates or underestimates of these risks.

Two of the chemicals identified by Dye et al. (2006) appear on the California Proposition 65 list as developmental/reproductive poisons (toluene and benzene). Using the same exposure scenario described above for soccer players, concentrations of both chemicals in the air above artificial turf soccer fields were below the Proposition 65 screening levels, suggesting a negligible risk of developmental or reproductive toxicity via the inhalation route of exposure.

From among the 20 chemicals detected at the highest levels by Dye et al. (2006), seven were also detected in the New York State (2009) study. Concentrations of these seven chemicals were from 5- to 53-fold higher in the air above indoor fields (Dye et al., 2006) compared to the air above outdoor fields (New York State, 2009). Concentrations of particulates were also higher in the indoor study. Therefore, using indoor data to calculate health risks from outdoor play overestimates the outdoor risks.

Does Artificial Turf Promote Infection of Athletes by the Bacterium Methicillin-Resistant Staphylococcus aureus (MRSA)?

MRSA Outbreaks in Sports

Staphylococcus aureus is a bacterium that can cause serious infections in humans. A strain has developed that is resistant to the antibiotic methicillin, termed methicillin-resistant *Staphylococcus aureus* (MRSA). This strain has caused a number of outbreaks in team sports including football, wrestling, rugby, and soccer. Participation in contact sports increases the risk of infection by MRSA. Skin abrasions and other types of skin trauma also increase the risk of infection by MRSA. Person-to-person contact is the primary way MRSA is spread. Whether transmission occurs via inanimate objects (including playing surfaces) is less certain.

Artificial Turf and MRSA

It is not known if the new generation of artificial turf causes more MRSA infections than natural turf. However, one study of high school football demonstrated more "surface/epidermal injuries" for games played on the new generation of artificial turf compared to natural turf. Since skin trauma increases the risk of infection by MRSA, careful monitoring and treatment of such wounds may help prevent MRSA outbreaks.

It seems unlikely that the new generation of artificial turf is itself a source of MRSA, since MRSA has not been detected in any artificial turf field.

Data Gaps

- Using indoor data to estimate the health risks from outdoor fields probably overestimates those risks.
- Only two outdoor artificial turf fields were evaluated in the New York State (2009) study. The same two fields comprised the TRC (2009) study. Testing additional outdoor fields for the release of chemicals and particulate matter is warranted.
- Dye et al. (2006) did not determine what amount of each chemical was released by the artificial turf field and what amount was present in the ambient air. Therefore, future studies of artificial turf fields should include measurements from both above the fields and off of the fields.
- No study has measured the metals content of the particulates released by artificial turf fields. In addition, it is not known if field use increases particulate release.
- The variables of field age and field temperature should be monitored to determine whether they influence the release of chemicals and particulates into the air above these fields.
- Data are needed for the amount of time athletes spend on artificial turf playing fields. Data are needed for a variety of sports, age groups, and for both men and women. Other subgroups with potentially heavy exposure to fields include coaches, referees, and maintenance workers.
- Only a single study was located that compared the rate of skin abrasions on the new generation of artificial turf to natural turf. This was for high school football. Similar studies are needed for other sports, age groups, and for both male and female athletes.

- No data were located on the seriousness of the skin abrasions suffered by athletes on the new generation of artificial turf compared to natural turf.
- The bacterium MRSA has not been detected in artificial turf fields. However, fields in California have not been tested. Therefore, fields from different regions of the state should be tested to verify that the new generation of artificial turf does not harbor MRSA or other bacteria pathogenic to humans.

Work in Progress

OEHHA is currently working to fill the above data gaps. OEHHA will sample air from above the new generation of artificial turf fields in outdoor settings and measure concentrations of potentially hazardous chemicals and particulates. Coaches will be surveyed to determine how much time athletes spend on these fields. Rates of skin abrasion will be measured on artificial and natural turf. Various components of the artificial turf, as well as soil and grass from natural turf, will be analyzed for bacteria. Using these new data, OEHHA will determine whether the new generation of artificial turf playing fields releases chemicals or particulates into the air that pose an inhalation risk to persons using the fields. OEHHA will also determine whether artificial turf fields increase the risk of infection by dangerous bacteria such as MRSA.

Introduction

The California Tire Recycling Act (Public Resources Code 42870 et seq.) requires the California Integrated Waste Management Board (now the Department of Resources Recycling and Recovery, or CalRecycle) to develop new markets for recycled tires. The use of recycled tires in the new generation of artificial turf playing fields is one such new application. In the new generation of artificial turf playing fields, rubber crumb made from recycled tires serves as an artificial soil, filling in between the artificial blades of grass. This rubber infill softens the surface, helping to prevent injuries and facilitating rapid drainage. The infill is often recycled crumb rubber alone, or a combination of rubber and sand. Two other types of infill materials are new plastic granules and mulched coconut husks. The inclusion of an infill layer is one of the principal reasons the new generation of artificial turf outperforms previous generations.

The new generation of outdoor artificial turf playing fields has important advantages over natural turf. The fields can be used around the clock with little or no down time for repair, are weather-resistant, and require no watering, fertilizer, or pesticides. However, a number of unanswered questions remain concerning their safety for human health. Therefore, as part of their stewardship of tire recycling in California, CIWMB contracted with the Office of Environmental Health Hazard Assessment (OEHHA) to evaluate the following two aspects:

1. Whether these fields emit chemicals or particulates into the outdoor air at levels that constitute a potential human health hazard via the inhalation route of exposure, and
2. Whether these fields increase the risk of infection by methicillin-resistant *Staphylococcus aureus* (MRSA).

This report summarizes what is available in the published literature about these two aspects, with emphasis on the crumb rubber component of the artificial turf fields. Most of the studies discussed in the report presented original data covering the volatile chemicals and particulates detected in the air above artificial turf fields, the volatile chemicals emitted by recycled rubber, and the association between skin damage and artificial turf to MRSA outbreaks in athletic teams. MRSA is of particular concern due to its identification as the causative agent in a number of

infectious outbreaks in high school, college, professional and club sports (see Part II). A bibliography is also included at the end of the report listing relevant studies that were not cited in the text.

It should be noted that although one study discussed in this report did analyze the particulates in the air over these fields (Dye et al., 2006), the particulates were not analyzed for heavy metals, including lead. Therefore, there are no data with which to estimate the health risks from inhalation exposures to heavy metals emitted by these fields via airborne particulates.

After discussing the published literature, each section in this report lists conclusions and identifies data gaps. At the end of Part I, the available but limited data on chemicals and particulates in the air above artificial turf are used to estimate the risk of cancer or developmental toxicity to soccer players using these fields. This screen only addresses the inhalation route of exposure. As mentioned above, since Dye et al. (2006) did not measure the metals content of inhalable particulates, this screen does not address the hazards posed by the inhalation of heavy metals such as lead.

OEHHA is currently performing a study to fill the data gaps identified in this report. OEHHA will sample air from above the new generation of artificial turf fields in outdoor settings and measure concentrations of potentially hazardous chemicals and particulates. Coaches will be surveyed to determine how much time athletes spend on these fields. Rates of skin abrasion will be measured on artificial and natural turf. Various components of the artificial turf, as well as soil and grass from natural turf, will be analyzed for bacteria. Using these new data, OEHHA will determine whether the new generation of artificial turf playing fields releases chemicals or particulates into the air that pose an inhalation risk to persons using the fields. OEHHA will also determine whether artificial turf fields increase the risk of infection by dangerous bacteria such as MRSA.

Part I: Chemicals and Particulates in the Air above Artificial Turf

Studies that measured chemicals and particulates in the air above the new generation of artificial turf playing field

Table 1 shows five studies that measured chemicals and particulates in the air above the new generation of artificial turf playing field. For the studies by Dye et al. (2006), the Instituto De Biomecanica De Valencia (IBV, 2006), van Bruggen et al. (2007) and Milone & MacBroom (2008), the fields contained rubber crumb manufactured from recycled tires. The rubber crumb in the fields measured by Broderick (2007) was also likely recycled material, although this was not specifically stated in the reports. All fields were outdoors except those in Dye et al. (2006), which were soccer pitches in three indoor stadiums in Norway. Therefore, it is likely that the concentrations of chemicals and particulates measured by Dye et al. (2006) were higher than what would have been measured had the fields been outdoors.

Study quality and characteristics

The studies by Dye et al. (2006) and van Bruggen et al. (2007) were performed by governmental institutes located in Norway and The Netherlands, respectively. The study by IBV was performed by a university-affiliated research institute in Spain. Broderick (2007) refers to J.C. Broderick &

Associates, Inc., an environmental consulting and testing firm located in New York State. Milone & MacBroom refers to an environmental consulting firm located in Connecticut.

The study by Dye et al. (2006) is the most detailed of the five, presented in a formal institute report. Multiple air samples were collected from above three indoor soccer pitches, two of which contained infill of ground rubber; however, samples from outside the stadiums were not collected, so that no conclusions can be drawn concerning the concentrations of chemicals and particulates in the vicinities of these stadiums. Thus, it is difficult to assess which chemicals were released by the artificial turf and which were already present in the ambient air. The study included data on the environmental conditions during sampling such as temperature, relative humidity, and barometric pressure. Indoor ventilation rates were not measured. The chemical and particulate sampling height(s) above the pitches were not indicated. This study measured volatile organic chemicals (VOCs), polycyclic aromatic hydrocarbons (PAHs) in the gas phase and associated with particulate matter (PM_{10}), phthalates in the gas phase, and particulate matter ($PM_{2.5}$ and PM_{10}). Thirty-eight PAHs were analyzed. Comparing the two fields containing infill made of ground rubber, there is generally good agreement between the chemicals and particulates detected over the two fields. For example, Table 6a in the report lists the concentrations of benzothiazole, toluene, 4-methyl-2-pentanone and total volatile organic compounds (TVOCs) measured over the two fields; the concentrations measured over the first field were within 0.7-, 5.6-, 1.0- and 2.5-fold, respectively, of the concentrations measured over the second field. For the three PAHs occurring at the highest concentrations over both fields (naphthalene, 2-methylnaphthalene, acenaphthylene), the values from the first field were within 2.7-fold of the values from the second field. With regard to particulate matter, the concentration of PM_{10} collected from the two fields was 40.1 and 31.7 micrograms per cubic meter ($\mu g/m^3$), while $PM_{2.5}$ was 17.3 and 18.8 $\mu g/m^3$, again demonstrating good agreement between the two fields.

Dye et al. (2006) also measured the air above a field containing infill made of "thermoplastic elastomer." Comparing this field to the other two fields containing recycled rubber infill, the air above the field containing thermoplastic elastomer contained lower levels of VOCs, PAHs (both in the gas phase and associated with particulates), total $PM_{2.5}$ and the $PM_{2.5}$ fraction consisting of rubber dust.

van Bruggen et al. (2007), also presented in a formal institute report, collected multiple samples from above four outdoor soccer fields made of artificial turf, as well as samples upwind of the fields to measure the ambient environmental levels. Weather data included wind speeds, and the heights above the fields where sampling was performed were also reported. This study only measured nitrosamines. Eight were analyzed.

The short report from Broderick (2007) shows that while duplicate samples were collected from above two outdoor artificial turf fields, as well as off of the fields, no weather data (including wind speed) were presented. In addition, the reports do not indicate the height above the fields at which sampling was performed. This study only measured PAHs (in the gas phase and in particulates collected on a 2.0 µm filter). Sixteen PAHs were analyzed.

The IBV (2006) study was in the form of a meeting presentation, available online at the website for the 2006 Dresden Conference titled, "Impact of Sports Surfaces on Environment and Health." Six samples were collected over a single outdoor artificial soccer pitch. No background air samples were collected from off the pitch. Thus, it is difficult to assess which chemicals were released by the artificial turf and which were already present in the ambient air. No weather data

were reported, and few other methodological details were provided. This study measured VOCs, PAHs (whether in gas or particulate phase was not indicated), and hydrogen sulfide.

The most recent study (Milone & MacBroom, 2008) collected a single air sample from above each of two artificial turf fields in Connecticut. Four additional samples were collected from off of each field. Temperature, humidity, and wind speed/direction data were included, and a sampling height of 4 feet above the surface was utilized. Analysis was for seven nitrosamines, 4-(tert-octyl)phenol and benzothiazole. These last two chemicals had been detected volatilizing from recycled rubber crumb analyzed under laboratory conditions (see study by Environment & Human Health, Inc. [EHHI, 2007] in Table 4).

Comparing studies

Dye et al. (2006) identified 94 chemicals in the air above artificial turf fields located in indoor stadiums. More than 200 additional VOCs were detected in this study (13 to 16 percent by weight), but not identified. By comparison, the IBV (2006) study detected 13 chemicals and Milone & MacBroom (2008) detected one. The two remaining studies utilized detection levels that were too high; as a consequence, no chemicals were detected.

The failure to detect PAHs in the study by Broderick (2007) is consistent with the data in Dye et al. (2006). The individual PAH levels in Dye et al. (2006) were all $\leq$ 2.7 µg/m^3, while the individual PAH detection levels in Broderick (2007) were 6.0 µg/m^3. Utilizing nitrosamine detection levels of 8-16 ng/m^3, van Bruggen et al. (2007) did not detect nitrosamines above three outdoor fields containing recycled rubber. Some nitrosamines volatilize readily from soil and water surfaces, while others are considered nonvolatile. Their study was initiated after a single air measurement above an artificial turf field containing recycled rubber detected N-nitrosodimethylamine (NDEA) at 93 ng/m^3. Similarly, Milone & MacBroom (2008) did not detect nitrosamines above two fields (reporting limits 1.0 to 1.4 µg/m^3). Dye et al. (2006) also did not report any nitrosamines above two indoor fields containing recycled rubber, although the nitrosamine detection levels were not indicated in the report.

Table 1. Air measurements above artificial turf fields

Reference	Scenario	Chemicals/particulates measured
Dye et al., 2006	Three indoor soccer stadiums 10-18°C 42-53 percent humidity One field 2 months old (other 2 ages not indicated) Two fields contained recycled rubber crumb (yielding values shown on right)	VOCs : 69 detected at ≥ 0.8 μg/m^3 PAHs: 22 detected at ≥ 1.0 ng/m^3 (mostly in the gas phase, some in the particulate fraction) Phthalates: 3 detected at ≥ 0.06 μg/m^3 (in the gas phase) $PM_{2.5}$: total = 18.8 μg/m^3, rubber = 8.8 μg/m^3 PM_{10}: total = 40.1 μg/m^3, rubber = 9.3 μg/m^3 Twenty highest VOCs were (in μg/m^3): toluene (85), butenylbenzene (82.5), benzoic acid (81), diethenylbenzene (41), benzothiazole (31.7), p- and m-xylene (25.5), ethylbenzaldehyde (19.7), acetonitrile (16.8), acetone (15.3), o-xylene (13.1), 4-methyl-2-pentanone (12.7), alpha pinene (10.5), 3-phenyl-2-propenal (10.2), cyclohexanone (9.8), pentenyl benzene (7.3), pentanedioic acid dimethylester (6.8), ethylbenzene (6.7), formaldehyde (6.5), hexenylbenzene (6.1), styrene (6.1) Ten highest PAHs (total in gas phase plus PM_{10}-associated) were (in ng/m^3): naphthalene (2700 or 56 for two different methods), acenaphthylene (78.1), 2-methylnaphthalene (57.8), 1-methylnaphthalene (42.6), biphenyl (32.8), phenanthrene (25), fluorene (19.2), dibenzofurane (17), acenaphthene (14.2), pyrene (4.4) Three phthalates were (in μg/m^3): dibutylphthalate (DBP, 0.38), diisobutylphthalate (DiBP, 0.13), diethylphthalate (DEP, 0.06)

Reference	Scenario	Chemicals/particulates measured
IBV 2006	One outdoor soccer field containing recycled rubber crumb	VOCs: 5 detected (highest value in µg/m^3): p- and m-xylene (4.4), toluene (3.1), o-xylene (2.5), ethylbenzene (2.2), benzene (0.4) PAHs: 8 detected (highest value in ng/m^3): phenanthrene (6.9), pyrene (4.2), fluoranthene (1.1), fluorene (0.92), anthracene (0.46), acenaphthene (0.32), naphthalene (0.3), acenaphthylene (0.21)
Broderick 2007	Two outdoor high school athletic fields containing rubber crumb	All 16 PAHs analyzed were below the minimum detection level of 6.0 µg/m^3
van Bruggen et al., 2007	Three outdoor fields containing recycled rubber crumb and one containing new rubber For fields with recycled rubber, one recently installed and two older than one year Sampling performed between 11-20°C on sunny days at 30-100 cm above pitch	All eight nitrosamines analyzed were below the minimum detection limit of 8-16 ng/m^3
Milone & MacBroom 2008	Two outdoor fields containing recycled rubber crumb Sampling performed on summer days between 75 and 85°F with light winds Samples taken at 4 feet above surface	Seven nitrosamines were analyzed: samples from both fields were below the minimum reporting limit of 1.0 to 1.4 µg/m^3 4-(tert-octyl)phenol: samples from both fields were below the minimum reporting limit of 0.19 to 0.21 µg/m^3 Benzothiazole: one field's sample was below the minimum reporting limit of 0.19 to 0.21 µg/m^3; the other field's sample was 1.0 µg/m^3 (includes correction for 39% sample spike recovery)

Table 2 shows a comparison of the concentrations of the eight PAHs and five VOCs detected by IBV (2006) to the highest values reported by Dye et al. (2006). Despite uncontrolled variables such as field age and temperature during sampling, all 13 chemicals detected by IBV (2006) were detected by Dye et al. (2006). For 12 of the 13, the concentrations were lower in IBV (2006). This might be expected, since the field in the IBV (2006) study was outdoors, while the fields in the Dye et al. (2006) study were indoors. For the eight PAHs, concentrations measured in IBV (2006) ranged from similar (pyrene) to 9,000-fold (naphthalene) lower than the corresponding concentration measured in Dye et al. (2006). For the five VOCs the differences were less, ranging from three-fold (ethylbenzene) to 27-fold (toluene) lower in the IBV (2006) study. The VOC benzothiazole was also detected over an outdoor field by Milone & MacBroom (2008); its concentration was 32-fold lower over this outdoor field compared to the concentration reported over indoor fields by Dye et al. (2006). Therefore, the data in IBV (2006) and in Milone & MacBroom (2008) support those of Dye et al. (2006) in that all 13 chemicals detected over outdoor fields were detected at higher levels over indoor fields. This suggests that persons using the new generation of artificial turf in outdoor settings are exposed to many of the same chemicals as persons exposed indoors, albeit at lower concentrations. Thus, exposure calculations for outdoor play based on the data from Dye et al. (2006) would probably overestimate exposure to most chemicals. Since neither the IBV (2006) study nor the Dye et al. (2006) study measured the background level of chemicals, it remains possible that the 13 chemicals discussed above were not emitted from the artificial turf, but were already present in the ambient air. However, due to the presence of a number of VOCs that Dye et al. (2006) considered to be typical rubber components (such as benzothiazole, 4-methyl-2-pentanone, and styrene), the authors believed that the rubber infill was the source of many of the VOCs they detected.

Unfortunately, since the report of Dye et al. (2006) contained the only published values for $PM_{2.5}$ and PM_{10} from above artificial turf fields, there are no other studies for comparison. As discussed above, the good agreement between the PM values from the two fields measured in the study by Dye et al. (2006) provide some assurance that the data are reliable. However, it is difficult to use these indoor data from Dye et al. (2006) to predict the concentrations of PM over outdoor artificial turf fields.

Table 2. Comparison of chemical concentrations measured in the studies of Dye et al. (2006) and IBV (2006)

Chemical	Concentration in IBV (2006) (µg/m^3)	Concentration in Dye et al. (2006) (µg/m^3)[1]	[Dye]/[IBV]
PAHs			
Acenaphthene	0.00032	0.014	44
Acenaphthylene	0.00021	0.078	371
Anthracene	0.00046	0.002	4.3
Fluoranthene	0.0011	0.004	3.6
Fluorene	0.00092	0.019	21
Naphthalene	0.0003	2.7 or 0.056	9000 or 187
Phenanthrene	0.0069	0.025	3.6
Pyrene	0.0042	0.004	1
VOCs			
Benzene	0.4	2.4	6
Ethylbenzene	2.2	6.7	3
Toluene	3.1	85	27
o-Xylene	2.5	13.1	5.2
p and m-Xylene	4.4	25.5	5.8

[1] Highest value reported

Conclusions

- Only five studies were located which quantified the chemicals and particles in the air above the new generation of artificial turf playing fields.
- The study by Dye et al. (2006) of indoor soccer stadiums provides the largest dataset: 69 VOCs at $\geq$ 0.8 µg/m^3, 22 PAHs at $\geq$ 1.0 ng/m^3 (mostly in the gas phase), 3 phthalates at $\geq$ 0.06 µg/m^3 (in the gas phase), $PM_{2.5}$ at 18.8 µg/m^3 and PM_{10} at 40.1 µg/m^3 were detected.
- The chemicals identified by Dye et al. (2006), as well as their concentrations, are consistent with the other four studies.

Data Gaps

- A study similar to that of Dye et al. (2006), that analyzes a large range of VOCs and particulates over multiple fields, is needed for outdoor artificial turf fields, since use of the Dye et al. (2006) data for estimating the health risks from outdoor fields probably overestimates those risks.

- Dye et al. (2006) did not sample air from outside the stadiums for comparison to the indoor samples. Therefore, it is not possible to know what amount of each chemical was contributed by the artificial turf field and what amount was present in the ambient air.
- Approximately 200 of the 300 VOCs (13 to 16 percent by weight) detected by Dye et al. (2006) were not identified, but were only reported as peaks on a graph. Therefore, potential health risks posed by these chemicals cannot be estimated.
- Many of the chemicals identified in the study of Dye et al. (2006) have no associated health-based screening levels, so that their health risks cannot be estimated. Thus, any attempt to classify these chemicals as carcinogens or developmental/reproductive toxicants will be an underestimate.
- The Dye et al. (2006) study provides the only data on particulate levels from above artificial turf playing fields. Data from above outdoor fields are needed, where the values are likely to be lower.
- Dye et al. (2006) did not measure the metals content of the airborne particulate matter ($PM_{2.5}$ and PM_{10}). Thus, the health risks posed by inhaled particulates and the metals they contain, such as lead, cannot be determined.
- The effect of temperature on chemical and particulate levels has not been measured.
- The contribution of field age to chemical and particulate levels has not been measured.
- The effect of field use on the levels of either VOCs or particulates has not been measured. Thus, it is possible that air sampling before or during games would give different results.

Studies that measured chemicals emitted by rubber flooring made from recycled tires

CIWMB sponsored two studies (2003 and 2006) that measured chemical emissions from tire-derived rubber flooring. This type of flooring is used in indoor applications such as auditoriums and classrooms. The flooring contained at least 80 percent tire-derived rubber, making it chemically very similar to the crumb rubber infill used in many new generation artificial turf fields, including those in the study of Dye et al. (2006) and the other studies in Table 1. Emissions of individual chemicals were measured in environmental chambers and normalized to the surface area of flooring in each chamber, yielding chemical-specific emission factors. The data cannot be directly compared to the air concentrations from Dye et al. (2006). However, the emission factors were used to model the chemical concentrations expected to occur in a variety of indoor settings.

Table 3 shows those concentrations for the largest rooms modeled: an auditorium and a classroom. The results for the largest rooms are presented since these are closest to the dimensions of the indoor stadiums in the Dye et al. (2006) study.

Table 3. Indoor emissions from tire-derived rubber flooring

Reference	Indoor area modeled	Modeled room chemical concentrations (μg/m^3) based on measured emission factors
CIWMB, 2003	State auditorium, 70x70x15 ft, 73,500 ft^3 3.5 air changes per hour Flooring samples tested contained at least 80 percent recycled styrene butadiene rubber and ethylene propylene diene monomer Chemical emission rates were determined at 14 days, modeled concentrations in right column are based on the highest measured emission rate for each chemical	VOCs 21 identified: α, α-dimethylbenzenemethanol (420), acetophenone (160), diethyl propanedioate (80), propylene glycol (47), 1-ethyl-3-methylbenzene (43), 1,2,4-trimethylbenzene (40), α-methyl-styrene (38), benzothiazole (37), 1-ethyl-4-methylbenzene (22), 1,2,3-trimethylbenzene (18), triethylphosphate (18), 1-ethyl-2-methylbenzene (13), 2-ethylhexyl acetate (11), cumene (5.5), 2-ethyl hexanoic acid (3.9), 1-methyl-2-pyrrolidinone (1.8), dodecane (1.4), naphthalene (0.99), nonanal (0.74), decanal (0.5), ethyl benzene (0.5)
CIWMB, 2006	State classroom, 960 ft^2 x8.5 ft high, 8160 ft^3 0.9 air changes per hour Most flooring samples contained $\geq$ 81 percent tire-derived rubber Chemical emission rates were determined at 14 days, modeled concentrations in right column are based on the highest measured emission rate for each chemical	VOCs 31 identified: benzothiazole (1677), methyl isobutyl ketone (154), m-/p- xylene (142), carbon disulfide (116), acetophenone (86), cyclohexanone (77), toluene (60), acetone (43), ethyl benzene (32), benzene (24), chlorobenzene (23), nonanal (22), n-undecane (21), octanal (18), styrene (17), acetaldehyde (16), butyraldehyde (14), α-methylstyrene (12), phenol (10), decanal (9), isopropyl alcohol (9), 1,2,4-trimethylbenzene (9), formaldehyde (7), n-decane (6), 1-ethyl-4-methylbenzene (6), 1,3,5-trimethylbenzene (6), naphthalene (4), hexanal (3), 4-phenylcyclohexene (3), 1,2,3-trimethylbenzene, o-xylene (2)

Eight of 21 chemicals emitted by the tire-derived flooring in the 2003 CIWMB study also were detected above artificial turf fields in indoor stadiums (Dye et al., 2006). Half of these (4/8) were modeled as occurring at higher concentrations in the auditorium compared to the stadiums. Eighteen of 31 chemicals emitted by the flooring in the 2006 CIWMB study also were detected above artificial turf fields in indoor stadiums (Dye et al., 2006), with 16 of the18 occurring at higher concentrations in the modeled state classroom compared to the indoor stadiums. For those chemicals detected in CIWMB (2003) or (2006) but not in Dye et al. (2006), it is not known if they were even analyzed in the latter study. There were six chemicals detected in both CIWMB studies and by Dye et al. (2006): 1,2,4-trimethylbenzene, 1-ethyl-4-methylbenzene, benzothiazole, ethylbenzene, naphthalene, and nonanal. Three of these were emitted by 100 percent rubber crumb heated under laboratory conditions: 1,2,4-trimethylbenzene, benzothiazole and ethylbenzene (see Table 4). This suggests that these three chemicals in the air are reliable markers for the crumb rubber from recycled tires used as infill in artificial turf. Ethylbenzene and naphthalene also were detected by IBV (2006) and benzothiazole was detected by Milone & MacBroom (2008) in outdoor air above artificial turf fields (Table 1), while all except 1-ethyl-4-methylbenzene were emitted by sections of artificial turf maintained in environmental chambers (see next section, Moretto, 2007).

It should be mentioned that recycled tire rubber used as indoor flooring (CIWMB 2003) emitted hundreds of low-level VOCs that were not identified. Hundreds of low-level VOCs were also detected in the air over artificial turf in indoor stadiums (Dye et al., 2006). When all VOCs were totaled (TVOCs), they reached up to 716 $\mu g/m^3$ in the Dye et al. study (2006) and exceeded one milligram (mg)/m^3 in the CIWMB study (2003). The health effects from breathing low levels of many volatile organic chemicals have not been adequately studied. This lack of information should be noted when calculating the health risks from individual chemicals that were identified in these studies.

Conclusions

- Twenty of the VOCs released by tire-derived indoor rubber flooring (CIWMB 2003 and 2006) also were detected in the air above indoor soccer pitches made of the new generation of artificial turf containing rubber infill.
- For the more recent flooring study (CIWMB, 2006), 18 of 31 chemicals emitted by the flooring also were detected in the air above the turf (Dye et al., 2006). This demonstrates good agreement between the studies and supports using the data from Dye et al. (2006) for making health risk estimates via inhalation.
- Three VOCs were consistent markers for tire-derived rubber: 1,2,4-trimethylbenzene, benzothiazole, and ethylbenzene.

Data Gaps

- Tire-derived flooring emitted hundreds of low-level VOCs that were not identified, while other identified chemicals had no associated health-based screening levels. Therefore, the health risks posed by these chemicals cannot be estimated.
- Total VOCs (TVOCs) emitted by tire-derived flooring exceeded one mg/m^3. Similar measurements of TVOCs should be made above artificial turf fields, since breathing low levels of a mixture of many VOCs may pose a health risk.

Laboratory studies of the emission of volatile chemicals from tire-derived crumb rubber infill

Three studies were located which analyzed the gaseous emissions from tire-derived crumb rubber infill in laboratory settings (Table 4). The studies by Plesser and Lund (2004) and EHHI (2007) analyzed samples of 100 percent rubber infill heated to 60-70°C, while Moretto (2007) used whole sections of artificial turf (containing recycled crumb rubber infill) maintained at 23°C in environmental chambers.

Moretto (2007) identified 112 VOCs emitted from the artificial turf. This is more than reported in any other study. Twenty-seven of these were also detected by Dye et al. (2006) over artificial turf fields in indoor soccer stadiums. Moretto (2007) did not provide quantitative data on the amounts of chemicals that were released by the sections of artificial turf. Of the 12 VOCs identified by Plesser and Lund (2004), five were also detected by Dye et al. (2006). From among the four VOCs identified in EHHI (2007), only benzothiazole was also identified by Dye et al. (2006).

Conclusions

- The study by Moretto (2007) of artificial turf in environmental chambers confirmed 27 of the chemicals detected in indoor soccer stadium air by Dye et al. (2006). This supports the use of the data from Dye et al. (2006) for estimating the health risks posed by artificial turf playing fields.
- Benzothiazole was detected in two of three emissions studies in Table 4 (EHHI, 2007; Moretto, 2007), in both indoor flooring studies in Table 3 (CIWMB 2003 and 2008), and in air above artificial turf fields (Table 1; Dye et al., 2006; Milone & MacBroom, 2008). It appears to be a consistent and relatively high-level off-gassing product of rubber crumb made from recycled tires.

Data Gaps

- Many of the chemicals identified in the chamber emission study of Moretto (2007) were not detected in stadium air by Dye et al. (2006). This may be due to the conditions used by Moretto (2007): a sealed environmental chamber, maintained at 23°C, in which chemicals emitted at low levels have a chance to accumulate. Since chemical concentrations in the chambers were not provided in the report, this cannot be determined.

Table 4. Gaseous emissions per gram of tire-derived rubber in laboratory studies

Reference	Conditions	VOCs detected (in ng/g of rubber)
Plesser and Lund, 2004	Samples heated at 70°C for 30 minutes	Twelve VOCs detected: 1,2,4-trimethylbenzene (102), toluene (80), m/p-xylene (37), o-xylene (35), cis-1,2-dichloroethene (32), n-butylbenzene (31), p-isopropyltoluene (23), 1,3,5-trimethylbenzene (23), ethylbenzene (18), propylbenzene (15), iso-propylbenzene (12), trichloromethane (8)
EHHI, 2007	Samples heated at 60°C for 42 minutes	Four VOCs detected: benzothiazole (867), butylated hydroxyanisole or BHT alteration product (53), 4-(tert-octyl)-phenol (22), hexadecane (1.58)
Moretto, 2007	Samples off-gassed for 28 days in chambers at 23°C	112 VOCs detected, but emissions per gram of rubber not indicated

Chemicals and particulates emitted during rubber manufacturing

Due to the large numbers of chemicals and materials used to manufacture rubber, many occupational health studies have examined the safety of various steps in the manufacturing process. The studies listed in Table 5 measured the concentrations of volatile chemicals and particulates to which rubber workers have been exposed. While it is to be expected that the levels of these chemicals would be higher in factory air during the rubber manufacturing process compared to a setting where the rubber end product is used, such as in artificial turf infill, some of the more prevalent chemicals should be detected in both situations. Such a comparison can be a useful test of the validity of the studies presented in Table 1 that attempted to identify the chemicals and particulates above artificial turf fields containing recycled tire rubber as infill.

With respect to VOCs, Rappaport and Fraser (1977) measured six VOCs in a vulcanization area of a tire manufacturing plant. Three of these—toluene, ethylbenzene, and styrene— also were detected by Dye et al. (2006) in indoor stadium air above new generation artificial turf containing recycled crumb rubber infill; the stadium concentrations were 51-fold, 73-fold, and 78-fold lower, respectively, than the factory concentrations. Cocheo et al. (1983) measured VOCs in the vulcanization and extrusion areas of a tire retreading factory. From among the 60 VOCs identified, 15 were also detected by Dye et al. (2006) in the indoor stadium study; concentrations of the 15 VOCs were from four-fold to 625-fold lower in the artificial turf application. Van Ert et al. (1980) investigated eight organic solvents used in a tire and tube manufacturing plant. Measurements were performed in the tire building and final inspection areas. Five of the eight solvents were also detected by Dye et al. (2006): heptane, toluene, octane, benzene, and xylene. The concentrations ranged from 34-fold to 10,750-fold lower in the indoor stadium air compared to the factory air. Armstrong et al. (2001) identified five VOCs in rubber tire manufacturing plants. Of these, three (formaldehyde, benzene and toluene) were also identified by Dye et al. (2006), but at 34-fold to 238-fold lower concentrations. Lastly, two of four VOCs identified by Correa et al. (2004) in the outdoor air circulation area of a tire recapping unit were also identified by Dye et al. (2006); toluene and styrene were 131-fold and seven-fold lower in the air above indoor artificial turf fields compared to the tire recapping area. Thus, five separate studies of rubber manufacturing have detected VOCs that were also in the air over the new generation of artificial turf fields; in each case the chemical was at a lower concentration above the fields compared to the manufacturing setting. These findings support the use of the data from Dye et al. (2006) for estimating chemical exposures to persons using the new generation of artificial turf fields, at least until similar measurements can be performed in outdoor settings.

Nitrosamines have been detected by sampling air in rubber manufacturing plants (Table 5). Oury et al. (1997) measured total nitrosamines in tire factory air. The highest concentration detected was 2.3 $\mu g/m^3$. Monarca et al. (2001) detected two nitrosamines (N-nitrosodimethylamine [NDMA] and N-nitrosomorpholine [NMOR]) in the range of 1-2 $\mu g/m^3$ inside a styrene-butadiene rubber factory. Iavicoli and Carelli (2006) sampled air in a rubber manufacturing plant. While the great majority of air samples had no detectable nitrosamines (detection limit = 0.06 $\mu g/m^3$), some had detectable levels, the highest being 0.35 $\mu g/m^3$ for N-nitrosodimethylamine. All the above nitrosamine concentrations are above the minimum detection level of 8-16 ng/m^3 used by van Bruggen et al. (2007) to analyze air samples from above outdoor artificial turf fields containing recycled rubber crumb (Table 1). There are at least two possible reasons for the failure of van Bruggen et al. (2007) to detect the volatile nitrosamines, given that they were present at detectable levels during manufacturing. First, most of the more volatile nitrosamines may have been emitted by the rubber crumb prior to field installation. Second, volatilization may be so rapid that the chemicals rapidly dissipate into the atmosphere.

Table 5. Chemicals and particulates released into the air during rubber manufacturing

Reference	Work area sampled	Chemicals and particulates measured
Nutt, 1976	Tire factory areas including mixing, extrusion, curing, pressing, trimming	Benzo[a]pyrene was Soxhlet-extracted from particulates: mean concentration of 49 factory air samples (12.3 ng/m^3) was not significantly different from outside air B[a]P concentration
Rappaport and Fraser, 1976	Rubber vulcanization performed in the lab	Fourteen VOCs were identified, with the highest relative concentrations being methylbenzene, 4-vinylcyclohexene, styrene, tert-butylisothiocyanate, and 1,5,9-cyclododecatriene
Rappaport and Fraser, 1977	Tire vulcanization area in a factory	Six VOCs measured (mean values in µg/m^3): toluene (4,371), ethylbenzene (486), styrene (473), 4-vinylcyclohexene (408), 1,5,9-cyclododecatriene (105), 1,5-cyclooctadiene (28.5)
Van Ert et al., 1980	Tire building and final inspection areas in two tire and tube manufacturing plants	Eight organic solvents measured (highest mean values in mg/m^3): hexane (64), heptane (8.6), isopropanol (7.9), toluene (3.2), pentane (2.2), octane (1.9), benzene (1.3), xylene (1.3)
Cocheo et al., 1983	Vulcanization and extrusion areas in a tire retreading factory	Sixty VOCs measured, the following being the 10 highest in concentration (mg/m^3): diisobutyl phthalate (2.5), cyclohexene-1-methyl-4-(1-methylvinyl) (1.7), benzene (1.2), toluene (0.8), methylcyclohexane (0.8), dibutyl phthalate (0.5), heptane (0.5), 1-isopropyl-4-methylbenzene (0.45), 2,6-di-ter-butyl-4-ethylphenol (0.42), cyclododecatriene (0.4)
Heitbrink and McKinnery, 1986	Tire manufacturing plants: mixing and milling areas	Mean total aerosol ranges (in mg/m^3): for mixing (0.08 to 1.54), for milling (0.2 to 1.22); mean respirable aerosol ranges (in mg/m^3): for mixing (0.06 to 0.34), for milling (0.08 to 0.4)
Oury et al., 1997	Tire factory including steps of mixing, pressing, quality control and storage	Total nitrosamines (NDMA, NDEA, NDBA, NPIP, NMOR) were between 0.01 and 2.3 µg/m^3 (range of 45 measurements)
Meijer et al., 1998	Rubber manufacturing areas in belt factory (compounding and mixing, calendaring, extruding, repair, curing)	"Inhalable dust" mean values ranged from 0.9 to 9.4 mg/m^3

Reference	Work area sampled	Chemicals and particulates measured
Fracasso et al., 1999	Rubber manufacturing areas included weighing, mixing, calendaring, compounding, extruding	PAH concentration ranges (in μg/m^3): phenanthrene (not detected), pyrene (0.006 to 0.213), benzo(a)anthracene (not detected to 0.005), chrysene (0.01 to 0.05), benzo(a)pyrene (not detected to 0.012), dibenzo(a,h)anthracene (0.003 to 0.106)
Armstrong et al., 2001	Five rubber tire manufacturing plants	Aerosol particle concentrations (means in μg/m^3): PM_1 [<1 μm] (120); PM_1 to PM_5 [1 to 5 μm] (123); PM_5 to PM_{10} [5 to 10 μm] (109); VOCs (means in mg/m^3) formaldehyde (0.22), benzene (0.57), furfural (< 0.91), isopropyl alcohol (5.66), toluene (12.38)
Monarca et al., 2001	Styrene-butadiene rubber factory	Total mean PM_{10}=0.23 mg/m^3; mean nitrosamines (in μg/m^3): NDMA (0.98), NMOR (2.28); 17 PAHs were Soxhlet-extracted from PM_{10}, with the 10 highest (in ng/m^3): dimethylnaphthalene (1200), naphthalene (400), pyrene (29), benzo(ghi)perylene (20), indeno(1,2,3-cd)pyrene (18), phenanthrene (12), benzo(b)fluoranthene (7.3), fluoranthene (7.0), benzo(a)pyrene (5.7), benzo(a)anthracene (2.3)
Ward et al., 2001	Rubber manufacturing plant: high exposure areas (reactor, recovery, tank farm, lab); low exposure areas (blending, baling, packaging, coagulation, water plant)	1,3-butadiene concentrations, mean 12-hour time weighted averages (in mg/m^3) for: high exposure areas = 3.8, for low exposure areas = 0.15
Chien et al., 2003	Two tire shredding plants-chopping, shredding, granulating and storage areas	PM_{10}, means ranged from 0.23 to 1.25 mg/m^3
Correa et al., 2004	Outdoor circulation area of a tire-recapping unit	In μg/m^3 : toluene (11,100), styrene (44.3), 4-chlorotoluene (7.6), 4-chlorostyrene (9.0), benzo(a)anthracene (16.7 extracted from particulates), chrysene (17.5 extracted from particulates)
de Vocht et al., 2006	Tire factory: milling and mixing/curing departments	“Inhalable particulate matter” mean value was 0.3 mg/m^3

Reference	Work area sampled	Chemicals and particulates measured
Iavicoli and Carelli, 2006	Rubber manufacturing (e.g., belts, no tires)	Great majority of nitrosamine samples were below the limit of detection (0.06 $\mu g/m^3$); however, some values were higher (in $\mu g/m^3$): N-nitrosodimethylamine (0.35 for one sample), N-nitrosomorpholine (0.16, mean of 4 samples), N-nitrosodiethylamine (0.15, mean of 5 samples), N-nitrosodi-n-butylamine (0.06 for one sample)
de Vocht et al., 2008a	Polish rubber tire plant; departments sampled included crude materials, milling and mixing, pre-treating, assembly, curing, finishing, storage	Geometric mean concentrations for the different departments ranged from: 1.7 to 5.8 mg/m^3 for inhalable aerosols, <1.0 to 578 $\mu g/m^3$ for aromatic amines
de Vocht et al., 2008b	Rubber manufacturing in five European countries	Inhalable dust measured with personal samplers on workers, means ranged from 0.72 to 1.97 mg/m^3

PAHs have also been detected in the air of factories producing rubber (Table 5). Surveying the levels in factory air, all were well below the detection level of 6.0 μg/m^3 used by Broderick (2007) when sampling the air above outdoor artificial turf fields containing recycled rubber crumb (Table 1). Thus, it is not surprising that Broderick (2007) failed to detect PAHs. Using lower detection levels, Dye et al. (2006) reported 22 PAHs at $\geq$ 1.0 ng/m^3 in the air above artificial turf fields in indoor stadiums (Table 1). Comparing the PAHs detected by Dye et al. (2006) to those reported in the occupational studies in Table 5 yields the following: two of six PAHs detected by Fracasso et al. (1999), 10 of 16 detected by Monarca et al. (2001), and none of two detected by Coorea et al. (2004) were also identified by Dye et al. (2006). The agreement between Monarca et al. (2001) and Dye et al. (2006) seems close; however, while six of the PAHs were at higher levels in factory air compared to the indoor stadium air, four were at higher levels in the stadium air. A possible explanation is that Dye et al. (2006) analyzed PAHs occurring in both the gas and particulate phases, while Monarca et al. (2001) only analyzed the particulate phase. Thus, the more volatile PAHs might be expected at higher levels in the former case. The four PAHs detected at higher levels by Dye et al. (2006) were in fact the relatively volatile PAHs acenaphthylene, fluorene, phenanthrene, and anthracene.

Values for respirable particulate (PM_{10}; particles capable of penetrating deeply into the lungs, into the region where gas exchange occurs) concentrations in factory air were distributed over a fairly narrow range: up to 400 μg/m^3 in a tire manufacturing plant (Heitbrink and McKinnery, 1986), up to 352 μg/m^3 in five tire manufacturing plants (Armstrong et al., 2001), and up to 1250 μg/m^3 in two tire shredding plants (Chien et al., 2003). The PM_{10} concentrations were roughly 10-fold lower in the indoor stadium air measured by Dye et al. (2006), ranging up to 40.1 μg/m^3, of which 9.3 μg/m^3 was identified as rubber particulate. Inhalable particulate (relatively large particles, capable of being inhaled but not penetrating deeply into the lungs) concentrations in factory air were generally higher than respirable concentrations, ranging as high as 5800 and 9400 μg/m^3 in the studies by de Vocht et al. (2008) and Meijer et al. (1998). These results for respirable particulates are similar to those for VOCs, in that concentrations above indoor artificial turf fields were much lower than those in the factories, including the tire shredding plant (Chien et al., 2003).

Conclusions

- A number of VOCs detected above third-generation artificial turf fields by Dye et al. (2006) were also detected in the air of rubber manufacturing plants. In all cases, the concentrations were lower in the air over the artificial turf fields compared to the factory settings.
- For the nitrosamines, their levels in air above artificial turf fields and in rubber factory air suggest that either these chemicals volatilize from the rubber crumb prior to installation in a field, or their levels over a field are too low to detect.
- Air sampling data from rubber factories confirm most of the PAHs detected by Dye et al. (2006) in the air over artificial turf fields.
- Air sampling in rubber factories and tire shredding plants detected levels of respirable particulates (PM_{10}) that were approximately 10-fold higher than the levels measured above third generation artificial turf fields containing rubber crumb infill (Dye et al., 2006).

Data Gaps

- Measure the time dependence (as the fields age) of respirable particulate ($PM_{2.5}$ and PM_{10}) release from artificial turf fields containing rubber crumb.
- Determine if levels of respirable particulates ($PM_{2.5}$ and PM_{10}) vary with field use; i.e., are the levels in the air higher during games compared to periods when the fields are idle?

Estimating the risk of cancer and developmental/reproductive toxicity via inhaled air in soccer players on the new generation of artificial turf.

The purpose of this section is to estimate the increased lifetime cancer risk and increased risk of developmental/reproductive toxicity due to the inhalation of volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs) by soccer players using the new generation of artificial turf playing fields. To perform this screen, the chemicals detected above artificial turf fields were compared to the California Proposition 65 list of chemicals known to the state to cause cancer or developmental/reproductive toxicity.

As described earlier in this report, Dye et al. (2006) published a study analyzing the air above three artificial turf playing fields located indoors in Norwegian soccer stadiums. This section uses these values, along with published values for age-specific breathing rates, and estimated lifetime play scenarios for soccer players on artificial turf, to calculate the following for those chemicals that also appear on the California Proposition 65 list:

1. Daily chemical intake rates averaged over a lifetime to estimate the increased lifetime cancer risk, and
2. Daily chemical intake rates not averaged over a lifetime, for comparison to maximum allowable dose levels (MADLs) to estimate the increased risk of developmental/reproductive toxicity.

Estimating the daily intake of air above artificial turf playing fields

Table 6 estimates the daily intake of air by soccer players from above artificial turf playing fields. The breathing rates are recommended for persons in the indicated age group engaged in “heavy” activities over “short-term” intervals. The 1.5- and 2.0-hour intervals seem to us to be reasonable estimates for the time a soccer player spends playing a timed game or practicing.

Table 6. Intake of field air on days of artificial turf field use.

Age interval	Breathing rate[1]	Time of field use per day (soccer game or practice session)[2]	Total intake of field air per day of field use[3]
5-15 years	1.9 m^3/hr	1.5 hr/day	2.85 m^3/day
16-18 years	1.9 m^3/hr	2 hr/day	3.8 m^3/day
19-55 years	3.2 m^3/hr	2 hr/day	6.4 m^3/day

[1] For 5-18 years: recommended mean value for short-term exposures to a child ≤ 18 years and performing heavy activities (U.S. EPA Child-Specific Exposure Factors Handbook, September 2002, Table 7-14); for 19-55 years: recommended mean value for short-term exposures to adults performing heavy activities (OEHHA Technical Support Document for Exposure Assessment and Stochastic Analysis, September 2000, Table 3.9).
[2] Estimates based on length of timed game or practice session for ages < 16 years (1.5 hours) or ≥ 16 years (2 hours).
[3] Calculated by multiplying the value in column two by the value in column three.

Estimating the daily intake of air from above artificial turf playing fields averaged over a 70-year lifetime

The play scenarios shown in Table 7 are our best estimates for a lifetime of soccer play by a soccer enthusiast. The scenarios are not based on data. The daily intakes of air from above artificial turf fields were averaged over a 70-year lifetime, including 51 years of organized soccer play (from age 5 to 55). The daily intakes were also averaged over an entire year, since it was estimated that at most, 102 days per year (for the age 19 to 22 group) would include use of artificial turf (Table 7). We consider this lifetime exposure rate of 0.464 m^3/day (Table 7) a heaviest use scenario for soccer players, since this assumes all organized soccer games and practices over a lifetime would be on artificial turf.

Table 7. Intake of field air for 51 years of artificial turf field use (soccer) averaged over a 70-year lifetime.

[1]Age inter-val	[2]Soccer play scenario on artificial turf fields	[3]Field air intake per day of field use (practice or game) for this play scenario	[4]Days of use per year for this play scenario	[5]Years of use per 70 year lifetime for this play scenario	[6]Daily field air intake for this play scenario averaged over a 70 year lifetime	[7]Daily field air intake normalized to body weight in m^3/kg-d
5-15	Two 15-game club seasons/year with 30 associated practice days	2.85 m^3/day	60 day/365 days	11 years/70 years	0.074 m^3/day	0.0021
16-18	One 15-game club season/year with 15 associated practice days; one 10-week high school season (6 days/week)	3.8 m^3/day	90 days/365 days	3 years/70 years	0.040 m^3/day	0.0006
19-22	One 15-game club season/year with 15 associated practice days; one 12-week college season (6 days/week)	6.4 m^3/day	102 days/365 days	4 years/70 years	0.102 m^3/day	0.0015
23-55	One 15-game club season/year with 15 associated practice days	6.4 m^3/day	30 days/365 days	33 years/70 years	0.248 m^3/day	0.0034
Total					0.464 m^3/day	

[1] Estimated age intervals for each soccer play scenario.
[2] Estimated play scenarios, with game or practice times as shown in Table 6.
[3] From fourth column of Table 6.
[4] Estimated games and practices per year for the corresponding play scenario.
[5] Estimated years of play for the corresponding play scenario.
[6] Calculated by multiplying columns three, four and five.
[7] Body weight means for combined males and females over each interval were: 35.6 kg for the 5-15 interval, 67.5 kg for the 16-18 interval (U.S. EPA, 2002); 67.2 kg for the 19-22 interval, 74.0 kg for the 23-55 interval (U.S. EPA, 1997).

Estimating the increased cancer risk from inhaling air above artificial turf fields

Eight of the chemicals identified in the air above indoor artificial turf fields (Dye et al., 2006) also appear on the California Proposition 65 list of chemicals known to the state to cause cancer (PAHs below 0.001 µg/m^3 were not included). Table 8 shows the increased lifetime cancer risks from breathing each of these during soccer play on artificial turf fields. The risk for each chemical was calculated using the highest air concentration from among eight independent measurements over three different artificial turf fields (Dye et al., 2006). This may overestimate the true chemical concentration in the air. Risks for two age intervals per chemical were calculated, so that a safety factor of three could be added for the 5-15 year interval (U.S. EPA, 2005). Five of the eight chemicals were associated with increased lifetime cancer risks that exceeded the broadly accepted negligible risk level of 10^{-6}: benzene, formaldehyde, naphthalene, nitromethane, and styrene. Their increased cancer risks ranged from 1.6 x 10^{-6} for formaldehyde to 8.7 x 10^{-6} for nitromethane. Since these risks exceeded the 10^{-6} benchmark, it is important for future studies to measure the concentrations of these chemicals above outdoor artificial turf fields. In addition, their concentrations should be measured in the ambient air in the vicinities of the fields. Comparing the concentrations in the air over and off of the fields will establish which carcinogenic chemicals are emitted by artificial turf, and whether mitigation measures are required.

Table 8. Inhalation of chemicals from above artificial turf fields in indoor stadiums in Norway that also appear on the California Proposition 65 list of chemicals known to the state to cause cancer: increased lifetime cancer risks from soccer play.

Chemical	Age inter-val in years	[1]Daily field air intake in m^3/kg-d	[2]Indoor field air concentra-tion of chemicals in mg/m^3	[3]Daily chemical intake in mg/kg-d	[4]Safety Factor	[5]Cancer Slope Factor in $(mg/kg\text{-}d)^{-1}$	[6]Increased lifetime cancer risk
Acetaldehyde	5-15	0.0021	0.0043	9.03 x 10^{-6}	3	0.01	5.0 x 10^{-7}
Acetaldehyde	16-55	0.0055	0.0043	2.37 x 10^{-5}	1	0.01	
Benzene	5-15	0.0021	0.0024	5.04 x 10^{-6}	3	0.1	2.8 x 10^{-6}
Benzene	16-55	0.0055	0.0024	1.32 x 10^{-5}	1	0.1	
Benzo[a]pyrene	5-15	0.0021	1.2 x 10^{-6}	2.52 x 10^{-9}	3	3.9	5.5 x 10^{-8}
Benzo[a]pyrene	16-55	0.0055	1.2 x 10^{-6}	6.6 x 10^{-9}	1	3.9	
Ethylbenzene	5-15	0.0021	0.0067	1.41 x 10^{-5}	3	0.0087	6.8 x 10^{-7}
Ethylbenzene	16-55	0.0055	0.0067	3.69 x 10^{-5}	1	0.0087	

Chemical	Age inter-val in years	[1]Daily field air intake in m^3/kg-d	[2]Indoor field air concentra-tion of chemicals in mg/m^3	[3]Daily chemical intake in mg/kg-d	[4]Safety Factor	[5]Cancer Slope Factor in $(mg/kg\text{-}d)^{-1}$	[6]Increased lifetime cancer risk
Formaldehyde	5-15	0.0021	0.0065	1.37×10^{-5}	3	0.021	1.6×10^{-6}
Formaldehyde	16-55	0.0055	0.0065	3.58×10^{-5}	1	0.021	
Naphthalene	5-15	0.0021	0.0027	5.67×10^{-6}	3	0.12	3.8×10^{-6}
Naphthalene	16-55	0.0055	0.0027	1.49×10^{-5}	1	0.12	
Nitromethane	5-15	0.0021	0.0041	8.61×10^{-6}	3	0.18	8.7×10^{-6}
Nitromethane	16-55	0.0055	0.0041	2.26×10^{-5}	1	0.18	
Styrene	5-15	0.0021	0.0061	1.28×10^{-5}	3	0.026	1.9×10^{-6}
Styrene	16-55	0.0055	0.0061	3.36×10^{-5}	1	0.026	

[1] From last column in Table 7. For the 16-55 interval, the value of 0.0055 is the sum of the values for the 16-18, 19-22 and 23-55 age intervals in Table 7.
[2] Dye et al., 2006; highest value from among eight independent measurements over three different artificial turf fields in indoor stadiums.
[3] Calculated by multiplying column three by column four.
[4] Safety factor for the increased sensitivity of 2-15 year old children to carcinogens (U.S. EPA, 2005).
[5] All cancer slope factors were taken from the OEHHA Toxicity Criteria Database available at www.oehha.ca.gov except for nitromethane and styrene; nitromethane cancer slope factor is available at www.oehha.ca.gov/prop65/law/pdf_zip/NitromethaneNSRL120707.pdf ; styrene cancer slope factor from OEHHA, 2009, Public Health Goal for Styrene, under review.
[6] Increased lifetime cancer risks due to each chemical were calculated by multiplying columns five, six and seven and adding together the resulting risks for the two age intervals.

Estimating the risk of developmental/reproductive toxicity from inhaling air above artificial turf fields

Benzene and toluene were the two chemicals identified in Dye et al. (2006) that also appear on the California Proposition 65 list of chemicals known to the state to cause developmental/reproductive toxicity. Toluene is listed as a developmental toxicant, while benzene is listed as a developmental and male reproductive toxicant. For developmental toxicants, the subpopulation most at risk is pregnant females. Were a pregnant female to use these fields for a two-hour interval, her exposure to benzene and toluene via inhaled air would be below the corresponding maximum allowable dose level (MADL, Table 9).

Table 9. Daily intake rates of chemicals inhaled via air from above artificial turf fields in indoor stadiums in Norway that also appear on the California Proposition 65 list of chemicals known to the state to cause developmental/reproductive toxicity: comparison to maximum allowable dose levels (MADLs).

Chemical	Indoor field air concentration detected in Norwegian study (ug/m^3)[1]	Chemical intake via field air (not averaged over lifetime) (ug/day)[2]	MADL (ug/day)[3]
Benzene	2.4	15.4	49
Toluene	85	544	13,000

[1] Dye et al., 2006; highest value from among eight independent measurements over three different artificial turf fields in indoor stadiums.
[2] Calculated by multiplying the daily intake of field air for 19 to 55 year-olds (6.4 m^3/day, Table 6) by the field air concentration shown in column two of this table.
[3] MADL = maximum allowable dose level, accessed June 2008 at http://www.oehha.ca.gov/prop65/pdf/2008MayStatusReport.pdf .

This section estimates the risk of cancer or developmental/reproductive toxicity in soccer players using the new generation of artificial turf playing field. A single study (Dye et al., 2006) was used as the source of VOC and PAH concentrations from above this type of field. Since Dye et al. (2006) was performed in indoor soccer stadiums, we believe it likely that the chemical concentrations over outdoor fields would be significantly lower, due to the dispersion of the chemicals into the atmosphere. Comparing Dye et al. (2006) to IBV (2006), as shown in Table 2 of this report, suggests that this is indeed the case. Support also comes from comparing the benzothiazole concentration measured indoors by Dye et al. (2006) to that measured by Milone & MacBroom (2008) outdoors: 31.7 compared to 1.0 µg/m^3. Thus, the daily chemical intakes calculated in Tables 8 and 9 probably overestimate the intakes that would result from breathing air over outdoor artificial turf fields. More accurate estimates of the cancer and developmental/reproductive hazards will be possible when air from above additional outdoor synthetic turf fields is analyzed, along with background levels from off of the fields.

The lifetime soccer play scenarios are not based on data but on personal experience and informal discussions. Relevant data may exist that will help reduce the uncertainty in this component of the exposure assessment. Until those data are located, we consider this cumulative play scenario from ages 5 through 55 exclusively on artificial turf to represent a heaviest use scenario for soccer players. However, soccer is only one of many sports played on today's artificial turf fields. Football, lacrosse, baseball, softball, and rugby are some others, along with the unorganized, informal play that predominates for young children under the age of 5. All these modes of play have characteristic ages for participants, years of expected play, and time spent on the field per game. This will result in chemical exposures via inhalation that are different from those calculated above for soccer. In addition, the people who coach, supervise, or referee these sports will each have different exposures, as will the people who maintain artificial turf fields. Therefore, the risks calculated for soccer players in Tables 8 and 9 should not be interpreted as covering the risks for other sports, age groups, or occupations.

Lastly, it should be noted that most of the VOCs detected above artificial turf fields in the Dye et al. (2006) study were never identified. For example, for the field yielding the highest level of total volatile organic compounds (TVOCs, 716 ug/m^3), 85 percent of the individual chemicals (representing about 20 percent of the mass of TVOCs) were not identified. This remains a significant source of uncertainty in assessing the health risks posed by these fields.

Conclusions

- The Dye et al. (2006) study provided the most complete dataset from which to calculate inhalation exposures to chemicals in the air above artificial turf playing fields.
- Lacking published data, the time that soccer players spend on artificial turf over a lifetime was estimated.
- Dye et al. (2006) quantified eight chemicals that appear on the California Proposition 65 list of chemicals known to the state to cause cancer.
- Estimated inhalation exposures of soccer players to five of these (benzene, formaldehyde, naphthalene, nitromethane, and styrene) gave theoretical increased lifetime cancer risks that exceeded the insignificant risk level of 10^{-6} (OEHHA, 2006).
- Data from indoor fields were used to estimate outdoor exposures and calculate these cancer risks. In addition, it was assumed that all organized soccer play over a lifetime occurred on artificial turf fields. Together, these assumptions tend to overestimate the cancer risks for soccer players using artificial turf fields.
- Benzene and toluene were the two chemicals quantified by Dye et al. (2006) that also appear on the California Proposition 65 list of chemicals known to the state to cause developmental/reproductive toxicity. Their concentrations in the air over indoor artificial turf fields were below the associated screening levels for developmental/reproductive toxicity. This suggests there is a low risk for such health effects due to inhalation exposures in soccer players.

Data Gaps

- To calculate the inhalation health risks from outdoor artificial turf fields, an air sampling study similar to Dye et al. (2006) is needed, but it should be performed over outdoor fields, including ambient air samples from off of the fields.
- For more accurate exposure estimates, better data are needed for the hours per day, days per year, and years per lifetime that athletes spend using artificial turf playing fields. Data are needed for a variety of sports, ages and for both female and male athletes. Use of these fields for informal play by children under the age of 5 should also be considered.
- Exposures to professionals such as coaches, referees, and maintenance workers should also be estimated.
- Approximately 300 of 400 VOCs detected by Dye et al. (2006) were not identified, so that their health risks cannot be determined.
- Since the airborne particulates measured by Dye et al. (2006) were not analyzed for metals, including lead, the health risks they pose via inhalation cannot be determined.
- While most of the VOCs identified by Dye et al. (2006) do not have MADLs developed under Proposition 65, data exist indicating that some cause developmental/reproductive

effects in test animals. Thus, additional screening is required to more fully evaluate these risks.

- Health risks due to high levels of total volatile organic compounds (TVOCs) have not been adequately assessed.
- The variable of field age should be investigated since chemical release may decrease with time, leading to lower health risks. Conversely, particulate release may increase with time.
- One possible mitigation measure that should be investigated for indoor fields is to increase the ventilation rate.

Part II: Artificial Turf as a Possible Risk Factor for Infection by Methicillin-resistant Staphylococcus aureus (MRSA)

Is artificial turf a risk factor for infection by MRSA?

Staphylococcus is a genus of gram positive bacteria commonly found on the surface of human skin. These bacteria can infect the skin, causing diseases such as impetigo and boils. *Staphylococcus aureus* (*S. aureus*) is a species that is particularly pathogenic to humans. Besides infecting skin, it can also cause food poisoning. If *S. aureus* from a skin infection moves internally, it can spread throughout the body, causing serious organ damage. Normally, only a small percentage of *S. aureus* skin infections progress to the point where hospitalization is required.

Methicillin is a broad spectrum antibiotic often used to treat *S. aureus* infections. However, methicillin-resistant *S. aureus* (MRSA) has developed. A number of outbreaks of MRSA have occurred in athletic teams, including high school, college, professional, and club teams. Thus, it is important to identify modes of transmission of MRSA and other risk factors for infection.

MRSA outbreaks in human populations are considered to be one of two kinds. Outbreaks in hospitals often occur in persons with weakened immune systems. This is considered health care-associated MRSA. Outbreaks in the general community, in otherwise healthy individuals, are considered community-associated MRSA. Risk factors for community-associated MRSA include young age and playing a contact sport (Boucher and Corey, 2008). In the case of athletes, this may be due in part to the frequent physical contact that occurs during play, as well as the propensity of these athletes to have skin cuts and abrasions.

A number of community-associated outbreaks of *S. aureus* and MRSA have been described in sports settings (Table 10; Lindenmayer et al., 1998; MMWR, 2003; Huijsdens et al., 2006; Turbeville et al., 2006; Kirkland and Adams, 2008). The outbreaks included boils (furunculosis), other types of skin abscesses such as impetigo, and cellulitis. In a review of the sports medicine literature (59 infectious disease outbreaks between 1922 and 2005) by Turbeville et al. (2006), the most common causes of outbreaks were *S. aureus* (often MRSA, 22 percent of outbreaks) and herpes simplex virus (22 percent of outbreaks). The sports with the most outbreaks were football (34 percent of outbreaks), wrestling (32 percent of outbreaks), rugby (17 percent of outbreaks), and soccer (3 percent of outbreaks). These are all considered contact sports, with player-to-player contact that ranges from incidental to violent. However, these sports also result in forceful impacts between the players and the playing surface. In the cases of football, rugby, and soccer, the surface would usually be an outdoor field of natural or artificial turf. For wrestling, the surface would most often be a vinyl-covered wrestling mat.

The outbreaks mentioned above suggest two possibilities for the high incidence of *S. aureus* skin infections in contact sports: the bacteria are transferred by player-to-player contact or by player contact with a contaminated playing surface. The data from health care-associated MRSA outbreaks, as well as those from sports-associated MRSA outbreaks (Turbeville et al., 2006; Benjamin et al., 2007; Boucher and Corey, 2008; Cohen, 2008; Kirkland and Adams, 2008), suggest that person-to-person contact is a major mode of MRSA transmission. Whether contact with outdoor playing surfaces, such as occurs during falls to the surface, promotes transmission of MRSA is less certain.

An association between MRSA infection and player-to-playing surface contact could have at least two different explanations. Such contacts could cause relatively long-lasting skin abrasions that serve as efficient portals of entry for MRSA, perhaps during subsequent player-to-player contacts. Alternatively, the playing surface itself might be a carrier of MRSA, such that player contact with the surface transfers MRSA to the previously uncontaminated skin.

An association between skin abrasions due to falls to the turf (termed turf burns) and skin infection by MRSA has been tested in two MRSA outbreaks among football teams. In a college football team, players with MRSA-induced boils were 7.2-fold more likely to have had skin abrasions from artificial turf (new generation) than uninfected players (Begier et al., 2004). Comparative data for burns received from natural turf were not presented. In a professional football team, eight of eight MRSA-induced skin abscesses occurred at the site of a turf burn. Whether the turf burn was received on artificial (old generation Astroturf®) or natural turf was not reported. The results of these two studies demonstrated an association between skin trauma due to falls to the playing surface and skin infections by MRSA. This suggests that traumatized skin is more susceptible to MRSA entry and infection. An association between skin trauma and MRSA infection has been suggested in other outbreaks among competitive sports teams, where skin trauma was produced by other means, including irritation by protective equipment (MMWR, 2003), body shaving (Begier et al., 2004), and falls to wrestling mats (Lindenmayer et al., 1998). Other studies also support an association between skin trauma and MRSA infection during contact sports (Bartlett et al., 1982; Sosin et al., 1989; Cohen, 2008; Kirkland and Adams, 2008). In consideration of these data, it seems justified to consider skin trauma in general, and turf burns in particular, to be risk factors for MRSA infection during competitive contact sports. Whether the incidence or severity of turf burn is greater on the new generation of artificial turf compared to natural turf is discussed below.

As mentioned above, a second possible explanation for why player-to-playing surface contact might be a risk factor for MRSA infection in competitive sports is that the playing surface itself is a source of MRSA. An inanimate object capable of transmitting infectious bacteria to humans is called a fomite. While player-to-player contact is considered the most important mode of sports-associated MRSA transmission, possible instances of fomite transmission have been reported. A MRSA outbreak in fencers is noteworthy, since this sport does not involve person-to-person contact (MMWR, 2003). The fencers used sensor wires under their protective clothing, which were shared by multiple fencers without cleaning. The wires were possible fomites for MRSA transmission in this outbreak. Shared soap bars were identified as a risk factor in a MRSA outbreak in a collegiate football team (odds ratio, 15.0; 95 percent confidence interval 1.69-180) (Turbeville et al., 2006). A shared weight room was the only common point of contact between a high school football team and the dance team (Kirkland and Adams, 2008). While only two football players and one dance team member became infected with MRSA, this may represent an example of fomite transmission. In a MRSA outbreak among members of a high school wrestling team, no risk factors for infection could be identified (Lindenmayer et al., 1998). Nonetheless, the

study authors speculated that although most cases of transmission were probably due to wrestler-to-wrestler contact, the sharing of towels and locker room equipment, as well as shared wrestling mats, may have contributed. In emphasizing that fomite transmission of MRSA should be prevented, the National Collegiate Athletic Association (NCAA) medical guidelines recommend disinfecting wrestling mats before use.

Table 10. Sports-related skin abrasions and infections on artificial and natural turf.

Reference	Sport	Turf type	Endpoint	Findings
Keene et al., 1980	American football at U. of Wisconsin	Old-generation Tartan Turf®	"Scrapes"	Significantly more ($p<0.001$) scrapes on artificial turf than on natural grass
Bartlett et al., 1982	High school American football	Not indicated	Boils (furunculosis) caused by *S. aureus*	Frequent open wounds or bruises were risk factors ($p<0.05$) for boils; concluded wounds and bruises are portals of entry for *S. aureus* into the body
Ekstrand and Nigg, 1989	Soccer played at different levels	Old-generation artificial and natural turf	"Abrasion injuries"	In three different studies, there were more abrasion injuries on artificial turf than on natural turf (severity not indicated)
Sosin et al., 1989	High school American football and basketball	Natural turf (wood floors for basketball)	Boils (furunculosis) caused by *S. aureus*	Players with >2 skin abrasions/week had 2.7-fold higher risk of infection ($p<0.01$); fomite contact not a risk factor
Begier et al., 2004	American football, one college team	New (third) generation artificial turf	MRSA-induced cellulitis and skin abscesses	Infected players were 7.2-fold more likely to have "turf burns" from artificial turf than uninfected players
Meyers and Barnhill, 2004	High school American football	New (third) generation artificial turf and natural turf	Injuries, including 0-day time loss (i.e., mild) and 1-22+ days time loss injuries	"Surface/epidermal injuries"(abrasions, lacerations and puncture wounds) were nine-fold more common on artificial turf compared to natural turf
Kazakova et al., 2005	Professional American football, one team	Old-generation Astroturf® and natural turf	MRSA-induced skin abscesses	8/8 infections occurred at site of turf burn; players reported more and more serious turf burns for games on artificial turf (2-3 per week); field swabs of artificial turf were negative for MRSA
Ekstrand et al., 2006	Elite soccer in Europe (male only)	New (third) generation artificial turf and natural turf	Time loss injuries	No difference in overall injury rate on artificial and grass; did not report skin abrasions, most of which are probably 0-day time loss
Benjamin et al., 2007	Various sports	Not indicated	MRSA infection	There is little evidence that MRSA infection occurs via fomite transmission; infection probably due to skin-to-skin contact

Reference	Sport	Turf type	Endpoint	Findings
Fuller et al., 2007a	Collegiate soccer, male and female, matches only	New (third) generation artificial turf and natural turf	Time loss injuries occurring during matches	Overall injury incidence and severity similar on artificial and natural turf; only lacerations/skin lesions in men were higher (2.95-fold, $p<0.01$) on artificial turf (relatively serious since they were time loss)
Fuller et al., 2007b	Collegiate soccer, male and female, training only	New (third) generation artificial turf and natural turf	Time loss injuries occurring during training	All injuries similar incidence and severity on artificial and natural turf
Steffen et al., 2007	Female soccer, under-17 league	Second and third generation artificial turf and natural turf	Acute, time loss injuries	Overall injury rate was the same on the artificial and natural turf; did not report skin abrasions, most of which are probably 0-day time loss
Andersson et al., 2008	Male elite soccer	New (third) generation artificial turf and natural turf	Number of standing and sliding tackles per player per game	Fewer sliding tackles on artificial turf compared to natural turf ($p<0.05$), possibly related to the risk of turf burn
Cohen, 2008	Various sports	Not indicated	MRSA infection	Risk factors identified: 1)skin-to-skin contact, 2)skin damage (such as mat burns in high school wrestling), 3)sharing equipment (e.g., towels)
McNitt et al., 2008	Not discussed	New (third) generation artificial turf and natural turf in Pennsylvania	Bacterial colony forming units (CFUs) cultured from turf samples	Rubber crumb from artificial turf yielded fewer CFUs on a per gram basis than soil from natural turf; no colonies were positive for *Staphylococcus aureus*
FIFA, undated	Male soccer, under-17 world championship games	New (third) generation artificial turf and natural turf	Time loss and total injuries during games	Overall injury incidence similar on the two surfaces

One way to determine whether artificial turf is a reservoir for infectious MRSA is to inoculate bacterial cultures with various turf components or wipe test the components to measure bacterial growth. Very few such data have been collected from potential fomites associated with outbreaks of sports-associated MRSA, including artificial and natural turf. Following an outbreak of MRSA on a high school wrestling team, environmental sampling of the wrestling facilities failed to detect any MRSA (Lindenmayer et al., 1998). During a MRSA outbreak on a professional football team, environmental sampling included the stadium's artificial turf field, weight-training equipment, towels, saunas, steam rooms, and whirlpool water (Kazakova et al., 2005). For the field sampling, one-foot square areas of Astroturf® located in the parts of the field with the highest numbers of tackles were wipe-sampled. No MRSA was detected; however, methicillin-sensitive *S. aureus* (MSSA) was detected in two samples of whirlpool water and on a gel-applicator stick used for taping ankles. The most recent test of whether artificial turf harbors MRSA is a study in which 20 new generation artificial turf fields were sampled at two locations per field (McNitt et al., 2008). The artificial blades of grass and infill material (crumb rubber or crumb rubber/sand mix) were sampled separately for bacterial culture. All field samples were negative for *S. aureus*. Quantitative data were only presented for the infill samples. Those samples contained unidentified bacteria at levels ranging from 0 to 80,000 colony forming units (CFUs) per gram of infill. In comparison, two samples of natural soil yielded 260,000 and 310,000 CFUs per gram of soil. *S. aureus* was detected on a number of surfaces including football blocking pads, weight equipment, a stretching table, and used towels, demonstrating that the detection method for *S. aureus* was functional. Thus, considering the three studies described above, there is no evidence that artificial turf fields harbor *S. aureus* in general, or MRSA in particular. While these conclusions are based on a small number of samples, an absence of *S. aureus* from artificial turf playing fields is not unexpected, given the dry and often hot conditions of that environment.

As discussed above, skin trauma is a likely risk factor for MRSA infection in contact sports (Begier et al., 2004; Kazakova et al., 2005). Therefore, it would be informative to determine if falls to the new generation of artificial turf put players at greater risk for turf burns than falls to natural turf. It is also important to determine if the turf burns caused by artificial turf are more long-lasting or more prone to infection by *S. aureus* compared to burns received from natural turf.

Unfortunately, most injury studies comparing artificial and natural turf have concentrated on so-called "time-loss" injuries (Table 10). These are relatively serious injuries that cause at least some loss of practice or game time. The great majority of turf burns are not time-loss injuries, and would not have been monitored in those studies. However, some data on skin abrasions are available. In a study of college football played on the old generation of Tartan Turf®, players were described as acquiring significantly ($p<0.01$) more "scrapes" on artificial turf compared to natural grass (Keene et al., 1980). This was the only injury type that was significantly increased on artificial turf compared to natural turf. In a five-year prospective study of injuries occurring on the new generation of artificial turf, both time-loss and 0-day time-loss (i.e., no playing time lost) injuries were recorded for eight high school football teams (Meyers and Barnhill, 2004). The latter category included "surface/epidermal injuries" that covered abrasions, lacerations and puncture wounds, but not contusions (i.e., bruises). This type of surface/epidermal injury had a nine-fold higher incidence on artificial turf (injury incidence rate = 0.9; 95 percent confidence interval = 0.5-1.4) compared to natural turf (injury incidence rate = 0.1; 95 percent confidence interval = 0.0-0.6). Players for a professional football team suffering a MRSA outbreak reported that skin abrasions happened more frequently and were more severe on first-generation Astroturf® (i.e., without infill) compared to natural turf, although no supporting data were presented

(Kazakova et al., 2005). In a study of collegiate male and female soccer players that recorded time-loss injuries during official matches, only the incidence of "lacerations/skin lesions" in males was significantly higher (2.95-fold, $p<0.01$) on new generation artificial turf (i.e., with infill) compared to natural turf (Fuller et al., 2007a). However, this finding was not replicated in an identical study that covered injuries sustained during training (Fuller et al., 2007b). Lastly, male soccer players at the 2005 Federation Internationale de Football Association U-17 Championship in Peru played 86 matches on natural grass and 42 on new generation artificial turf (FIFA, undated). While skin abrasion incidences were not presented, the incidences of total injuries (0-day time-loss and time-loss) per player-hour were similar on the two surfaces.

Considering the small database presented above, two studies (one soccer and one football) found increased incidences of skin abrasions on the new generation of artificial turf compared to natural turf (Meyers and Barnhill, 2004; Fuller et al., 2007a), while two studies (both soccer) measured similar rates on both surfaces (Fuller et al., 2007b; FIFA, undated). No data were located on the relative severity of skin abrasions caused by the artificial and natural surfaces. Given that both studies by Fuller et al. (2007a and 2007b) only monitored time-loss injuries, these studies almost certainly missed the majority of skin abrasions, which do not cause loss of playing time. Furthermore, the FIFA (undated) study did not provide data on the incidence of skin abrasions, only on total injury incidence. This leaves only the football study by Meyers and Barnhill (2004) as evidence that new generation artificial turf puts football players at increased risk for skin abrasions relative to natural turf. Whether this conclusion is specific for male football players competing at the high school level is unknown, until studies can be performed for other sports and age groups.

Conclusions

- Participation in contact sports is a risk factor for infection by MRSA. Football and wrestling have recorded the most outbreaks.
- Person-to-person transmission of MRSA is the major mode of infection. Transmission by inanimate objects (termed fomites), such as the playing surface, is less well established.
- Skin abrasions and other types of skin trauma are risk factors for MRSA infection in contact sports.
- Whether the new generation of artificial turf causes more skin abrasions than natural turf has only been carefully addressed in a single study (Meyers and Barnhill, 2004) of male high school football players. In that study, artificial turf was associated with a nine-fold higher incidence of "surface/epidermal injury" compared to natural turf.
- Only one study has tested whether new generation artificial turf fields harbor MRSA (McNitt et al., 2008); none was detected in 20 fields in Pennsylvania.

Data Gaps

- Additional studies are needed to test the finding of Meyers and Barnhill (2004) that new generation artificial turf is associated with more skin injuries than natural turf. Studies should cover additional sports, age groups, and female participants.
- No study has reported on the severity of turf burn by the new generation of artificial turf compared to natural turf. Severity could include susceptibility to infection as well as the time required to heal.

- Additional new generation artificial turf fields should be sampled for MRSA and other bacteria pathogenic to humans, at different depths in the fields, and from different climatic regions in California.

Part III: Summary

Five studies were located that measured chemicals and particulates in the air above the new generation of artificial turf containing crumb rubber infill from recycled tires. The chemicals and particulates in the air over artificial turf were similar to those emitted by tire-derived rubber flooring, during rubber manufacturing, and in laboratory studies of rubber crumb heated in vessels. The most complete dataset, covering indoor artificial soccer fields in Norway (Dye et al., 2006), was used to estimate the risk of cancer or developmental toxicity. This screen only addressed the inhalation route of exposure in athletes using artificial turf fields for a lifetime of organized soccer play. Exposure estimates were used to calculate the increased lifetime cancer risk or risk of developmental toxicity for those chemicals appearing on the California Proposition 65 list. From among eight chemicals listed as carcinogens on the Proposition 65 list, exposure to five of these (benzene, formaldehyde, naphthalene, nitromethane, and styrene) during a lifetime of organized soccer play exceeded the 10^{-6} negligible risk level. Since these risks exceeded the 10^{-6} benchmark, it is important for future studies to measure the concentrations of these chemicals above outdoor artificial turf fields. In addition, their concentrations should be measured in the ambient air in the vicinities of the fields. Comparing the concentrations in the air over and off of the fields will establish which carcinogenic chemicals are emitted by artificial turf, and whether mitigation measures are required.

Dye et al. (2006) also identified two chemicals appearing on the California Proposition 65 list as developmental/reproductive toxicants: toluene and benzene. Their concentrations in the air over indoor artificial turf fields were below the associated screening levels for developmental/reproductive toxicity, suggesting a low risk for such effects due to these two chemicals. This screen contains two steps that tend to overestimate the risks for both cancer and developmental toxicity. First, the screen utilizes data from indoor artificial turf fields to estimate exposures from outdoor fields. Second, the screen assumes that all organized soccer play from the ages of 5 to 55 occurs on artificial turf fields.

The scientific literature was also searched for studies addressing the possibility that artificial turf playing fields promote infection of athletes by methicillin-resistant *Staphylococcus aureus* (MRSA). While the data suggest that skin trauma is a risk factor for MRSA outbreaks in contact sports, it is less certain whether the new generation of artificial turf causes more skin trauma than natural turf. Whether artificial turf fields harbor MRSA has been tested in only a few studies. No MRSA has been detected in any indoor or outdoor natural or artificial turf field.

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Addendum, July 2009

Review of two studies released in spring 2009 that measured chemicals and particulates in the air above the new generation of artificial turf playing fields

Study quality and characteristics

The study of artificial turf fields containing recycled crumb rubber infill performed by New York State (2009) is the most comprehensive to date. To measure the chemicals released into the air by these fields, air sampling was performed over two fields, along with a sample taken upwind of each field to measure the ambient background. One field was four years old and one was less than one year old. Samples were analyzed for VOCs and sVOCs. Off-gassing experiments performed in the laboratory with recycled rubber crumb identified five chemicals which were added to the target list of chemicals: aniline, 1,2,3-trimethylbenzene, 1-methylnaphthalene, benzothiazole, and tertbutylamine. Acceptable weather conditions for sampling were prescribed and followed (see Table 11). Particulate matter (PM_{10} and $PM_{2.5}$) in air was measured in real-time with monitors placed over or upwind of each field. In addition, particulate matter was collected by wipe and vacuum sampling of field surfaces and analyzed by microscopy.

A total of 65 chemicals were identified in the air over the four-year-old field and 85 over the one-year-old field (twenty highest concentrations shown in Table 11). For many chemicals the upwind air sample contained similar concentrations. Since eight samples were collected over each field compared to only a single upwind sample, it is likely that had more upwind samples been collected, more chemicals would have been detected in the upwind air. Most of the chemicals were tentatively identified compounds (TICs), i.e., identified by their gas chromatography/mass spectrometry (GC/MS) peaks. TICs with match qualities of less than 85 percent of the GC/MS peaks were considered “unknowns” and not included in the health evaluation (see below). Of the 19 TICs shown in Table 11, 17 fell into this category. Therefore, from among the chemicals occurring at the 20 highest concentrations, only benzothiazole, octane, and nonane were evaluated for health effects. The “unknowns” in Table 11 are indicated by asterisks.

Comparing the two fields shows good agreement for VOCs and sVOCs on the target list. Air samples from over the four-year-old field contained 17 chemicals on the target list. Air samples from above the one-year-old field contained the same 17 plus an additional three. For TICs the agreement was not as close. From among the 20 largest TIC peaks corresponding to air samples from either field (Table 11), only five were reported for both fields.

Chemicals of potential concern for adverse health effects were chosen for health evaluation based on three criteria: 1) low levels in laboratory and field blanks, 2) a concentration that was at least 35 percent higher in at least one field sample compared to the upwind sample, 3) match quality of the GC/MS peaks of at least 85 percent for TICs. These criteria yielded 15 and 16 chemicals of potential concern for calculation of inhalation health risks for the four-year-old and one-year-old fields, respectively.

Table 11. Air measurements above artificial turf fields: New York State (2009) and TRC (2009)

Reference	Scenario	Chemicals/particulates measured
New York State Department of Environmental Conservation and Department of Health, May 2009	Two outdoor playing fields made of new generation artificial turf containing recycled crumb rubber infill. One field was less than one year old, the second was four years old. No precipitation the day before sampling and during sampling, sampling on two consecutive days of light to moderate winds out of a constant direction, 77 to 84°F, sampling at multiple heights above the field (a few inches, three feet, six feet), a total of eight samples collected from each field. One sample collected upwind of each field (six foot height) to measure ambient background.	VOCs and sVOCs: 65 detected over one field, 85 detected over the second field. PAHs detected (in µg/m^3): 2-dibenzofuranamine* (12), 3-dibenzofuranamine* (11), 4-dibenzofuranamine* (9), benzo[b]thiophene, 6-methyl-* (8.7). Phthalates: none detected. $PM_{2.5}$ and PM_{10}: both classes of particulates detected by real-time monitoring at approximately 15 µg/m^3, similar concentrations over field and upwind of field; microscopy of wipe and vacuum field samples detected rubber particles in the millimeter range but not in the micron range. Twenty highest VOCs and sVOCs were (in µg/m^3): cyclohexanol* (27), 5-hexen-2-ol, (.+/-.)-* (24), cyclopropane, 1-chloro-2-ethenyl-1-methyl* (23), 2-hexen-1-ol, (z)-* (22), pentanamide, 4-methyl-* (15), 1H-benzotriazole-5-amine, 1-methyl-* (13), benzenemethanol, arethenyl-* (13), nonanamide* (13), 2-dibenzofuranamine* (12), 3H-indazol-3-one, 1,2-dihydro-2-methyl-* (12), 3-dibenzofuranamine* (11), 4-dibenzofuranamine* (11), cyclopentanone-2* (10), benzene, 1-methoxy-4-(1-propenyl)-* (9.9), methanimidamide, N,N-dimethyl-N'-phenyl-* (9.6), benzo[b]thiophene, 6-methyl-* (8.7), benzothiazole (6.5), octane (6.2), nonane (3.2), 2-butene, (z)* (2.7).

Table 11. (continued) Air measurements above artificial turf fields: New York State (2009) and TRC (2009)

Reference	Scenario	Chemicals/particulates measured
TRC, 2009	Two outdoor playing fields made of new generation artificial turf containing recycled crumb rubber infill; one grass field for comparison.	VOCs, sVOCs and metals: 8 VOCs and 1 metal were detected at the following highest concentrations (in $\mu g/m^3$): acetone (51), ethanol (22), methylene chloride (9), 2-butanone (MEK) (3), chloroform (2.9), toluene (2.7), n-hexane (2.1), chromium (1.4), chloromethane (1.1); seven tentatively identified compounds (TICs) included isobutane, pentane, 2-methyl-1,3-butadiene (a.k.a., isoprene), 2-methylbutane.
	One artificial turf field was less than three years old, the other was less than one year old.	PAHs: none detected.
		Phthalates: none detected.
	Air sampling was during the summer with temperatures from 79 to 94°F, sampling performed at three feet above the surface, 4-6 air samples collected from above each field.	$PM_{2.5}$ and PM_{10}: both classes of particulates detected by real-time monitoring at 3 to 50 $\mu g/m^3$, similar concentrations over fields and upwind of fields.
	Two air samples collected from upwind of each field to measure ambient background.	

*Indicates tentatively identified compound (TIC) with a GC/MS peak match quality of less than 85 percent.

Chemical concentrations in the air above the fields were compared to health-based screening levels, assuming continuous, lifetime exposures for athletes using the fields. These assumptions overestimate the risks, since athletes do not spend their entire lives on these fields. Non-cancer health effects were evaluated by calculating hazard quotients using the highest on-field concentrations. Most hazard quotients were very low, indicating a very low risk of non-cancer health effects. The highest ranged from 0.1 to 0.6 for the compounds 1,3-pentadiene, 1,4-pentadiene, (E)-1,3-pentadiene, and 2-methyl-1,3-butadiene. Hazard quotients of less than one suggest that non-cancer health effects are unlikely.

Eight potential chemicals of concern were evaluated for their cancer risks based on their highest on-field air concentrations. The highest excess lifetime cancer risk was 4×10^{-5} for 1,3-pentadiene (using the cancer potency of 1,3-butadiene as a surrogate). However, the concentration of 1,3-pentadiene in the air upwind of the field corresponded to a 2×10^{-5} cancer risk. Thus, it was judged that the cancer risks posed by this chemical due to its occurrence in field air and ambient air were similar. Other potential carcinogens were either below the air concentration associated with the 10^{-6} cancer risk level or occurred in only one of eight field samples (as TICs). The report concluded that these chemical exposures did not constitute a serious public health problem, and posed small risks of either cancer or non-cancer health effects.

For the particulate matter size classes of $PM_{2.5}$ and PM_{10}, real-time monitoring of one field showed no meaningful differences between the air concentrations over the field compared to upwind of the field. Technical problems were encountered in real-time monitoring of the second field. These data suggest these fields are not a source of $PM_{2.5}$ or PM_{10}. Samples collected by wipe sampling and vacuuming both fields were analyzed by microscopy. Rubber particles were in the millimeter range. Particles small enough to be inhaled, in the 5-7 micrometer range, were crustal minerals such as quartz and calcite. Rubber particles were not in the respirable range. Both the wipe data and the air monitoring data indicate that recycled crumb rubber infill in new generation artificial turf fields is not a significant source of $PM_{2.5}$ or PM_{10}.

TRC is an engineering and consulting firm which performed a study of artificial turf fields for the New York City Department of Health and Mental Hygiene (TRC, 2009). The study included air sampling from above and upwind of the same two artificial turf fields that were sampled for the New York State (2009) study. A single grass field was also sampled for comparison. Eight VOCs and one metal were detected in the air over the artificial turf fields. Three of the VOCs (2-butanone, chloroform, and n-hexane) were not detected in any of the upwind samples or over the grass field. In addition, seven TICs were detected, with four being specific to the artificial turf (isobutane, pentane, 2-methyl-1,3-butadiene, 2-methylbutane).

Monitoring of the air over and upwind of the artificial turf fields for $PM_{2.5}$ yielded the same concentration range. $PM_{2.5}$ concentrations ranged between 3 and 50 $\mu g/m^3$ for both.

Comparing the target list chemicals detected over the artificial turf fields to those detected in the upwind samples or over the grass field, three were specific to the on-field samples: 2-butanone, n-hexane, and chloroform. The concentrations of the first two chemicals were well below the corresponding New York State short-term and annual air guideline levels. Therefore, the chemicals were not considered for risk assessment. While the chloroform concentration was above the annual guideline level, the chemical was not considered for risk assessment because its presence over the single artificial turf field was thought to have resulted from drift from a nearby swimming pool commonly treated with chlorine. From among the four TICs that were specific to the artificial turf fields, three were well below their corresponding guideline values. The fourth, isoprene, does not have a guideline value. However, since it was detected in only one air sample

as a TIC, and it was not detected when a bulk sample of crumb rubber was analyzed in the laboratory, it was not considered for risk assessment. Thus, a formal risk assessment was not performed for any chemical detected by air sampling. The report concluded that health effects were unlikely to result from the types of inhalation exposures expected to occur at these artificial turf fields.

Comparing studies

Table 12. Comparison of the chemical concentrations measured in air above artificial turf fields in the studies by Dye et al. (2006) and New York State (2009)

Chemical	Concentration in Dye et al. (2006) (µg/m^3)[1]	Concentration in NY State report (2009) (µg/m^3)[1]	[Dye]/[NY State]
Toluene	85	1.6	53
Benzothiazole	31.7	6.5	5
p- and m-Xylene	25.5	0.8	32
Acetone	15.3	0.6	26
o-Xylene	13.1	0.3	44
4-Methyl-2-pentanone	12.7	1.2	11
Ethylbenzene	6.7	0.3	22

[1] Highest value reported

Table 12 compares the concentrations of seven VOCs detected in air samples from above indoor and outdoor artificial turf fields. From among the 20 chemicals detected at the highest levels by Dye et al. (2006) (see Table 1), these seven were also detected by New York State (2009) (see Table 11). The concentrations can be compared to determine if the indoor study measured consistently higher concentrations compared to the outdoor study. The last column in Table 12 shows that the concentrations of these seven VOCs were from 5- to 53-fold higher in the air over indoor fields compared to outdoor fields. Therefore, as discussed in this report, using the indoor values from Dye et al. (2006) to calculate health risks overestimates the risks athletes face from inhaling the air above outdoor artificial turf fields containing crumb rubber infill.

Similar to the chemical concentrations discussed above, the concentrations of particulate matter ($PM_{2.5}$ and PM_{10}) were somewhat higher for the indoor study by Dye et al. (2006). The indoor study detected $PM_{2.5}$ and PM_{10} concentrations as high as 18.8 and 40.1 µg/m^3, respectively. Ambient, background levels of particulates were not measured. Therefore, it was not possible to determine whether the particulates were released by the turf or were already present in the ambient, outdoor air. The outdoor studies by New York State (2009) and TRC (2009) did not detect these particulates above ambient, background levels (about 15 and 3-50 µg/m^3, respectively). The indoor study used a chemical marker for tire rubber (N-cyclohexyl-2-

benzothiazolamine) to quantify the rubber in the particulate matter. Rubber comprised from 23 to 50 percent of the $PM_{2.5}$ or PM_{10}. Using microscopy, the New York State (2009) study ruled out rubber as the source of the microscopic particles in the 5-7 micrometer range. Considering all three studies together, it appears that $PM_{2.5}$ and PM_{10} were at background levels in the air over outdoor artificial turf fields, but may have been present at above-background concentrations in the air above indoor fields.

Table 13 below shows a comparison of the chemicals detected in the air above the same two artificial turf fields that comprised the studies by New York State (2009) and TRC (2009). These are the eight chemicals that were specific to the air above artificial turf in the TRC (2009) study. Sampling for both of these studies was performed at the end of August and beginning of September 2008. The chemical concentrations were consistently higher in the New York State (2009) study, ranging from 1.7-fold to 85-fold higher. The reasons for these differences are unknown. These variable results highlight the difficulties faced in obtaining consistent results from potential point sources of outdoor air pollution. Despite this variability, both studies found that the chemical concentrations they measured were unlikely to produce adverse health effects in persons using these fields.

Table 13. Comparison of the chemical concentrations measured in air above the same two artificial turf fields in the studies by New York State (2009) and TRC (2009)

Chemical	Concentration in NY State report (2009) (µg/m^3)[1]	Concentration in TRC report (2009) (µg/m^3)[1]	[TRC]/[NY State]
2-Butanone (MEK)	-	3.0	-
Acetone	0.6	51.0	85
Chloroform	0.2	2.9	15
Chloromethane	0.1	1.1	11
Ethanol	-	22.0	-
n-Hexane	0.4	2.1	5
Methylene chloride	3.0	9.0	3
Toluene	1.6	2.7	1.7
Isobutane*	-	2.4	-
Pentane*	0.5	11.8	24
Isoprene (a.k.a., 2-methyl-1,3-butadiene)*	0.9	2.8	3
2-Methylbutane*	0.7	3.0	4

[1] Highest value reported, **-** not reported, * TIC

Conclusions

- The New York State (2009) report describes the most comprehensive study performed to date on the new generation of artificial turf containing recycled crumb rubber infill. Air sampling above two fields measured VOCs, sVOCs, PM_{10}, and $PM_{2.5}$.
- A total of 65 chemicals were identified in the air above a four-year-old field and 85 over a one-year-old field. Many of these were detected at similar concentrations in the air samples taken upwind of the fields.
- Most of the chemicals detected were tentatively identified compounds (TICs), as identified by their GC/MS peaks, with match qualities of less than 85 percent of the peaks. Therefore, these were considered "unknown" chemicals and not evaluated for health effects.
- $PM_{2.5}$ and PM_{10} levels were the same over one field and upwind of the field, suggesting the fields are not sources of PM release.
- Chemicals of potential concern were selected and evaluated for cancer and non-cancer health effects based on their measured air concentrations and assuming continuous, lifetime inhalation by athletes using the fields. These latter two assumptions tend to overestimate the health risks.
- Hazard quotients were all less than one, indicating a low risk of non-cancer health effects. Excess, lifetime cancer risks were either below the 10^{-6} risk level, were similar for the upwind and on-field samples, or the chemical was only detected in one of eight on-field samples. Therefore, the report concluded that these fields do not constitute a serious public health problem since the risks of health effects are low.
- The study by TRC (2009), monitoring the same two artificial turf fields as the New York State (2009) study, also concluded that health effects were unlikely to result from the types of chemical inhalation exposures expected to occur to athletes using these fields.
- The concentrations of chemicals in the air over indoor fields (Dye et al., 2006) were from 5- to 53-fold higher than their concentrations over outdoor fields (New York State, 2009). This demonstrates that using data from indoor fields to calculate the health risks from outdoor fields overestimates those risks.

Data Gaps (some of which are being addressed in the current OEHHA study of artificial turf)

- Only two artificial turf fields were evaluated in the New York State (2009) study. The same two fields comprised the TRC (2009) study. Testing additional fields for the release of chemicals and particulate matter is warranted.
- Testing fields of different ages and at different temperatures would help determine how those variables affect chemical and particulate release. In particular, fields near the end of their useful life should be evaluated.
- More air samples from upwind of the fields should be collected on the same days as field samples to determine if chemicals measured over the fields are also present at similar concentrations in the ambient air.
- The air above fields was not tested for airborne metals. The previously reported finding of lead in dust sampled from some artificial turf fields indicates a potential for lead and other metals to

become suspended in the air and possibly inhaled. Testing field air samples for metals is warranted.

- To estimate inhalation exposures it was assumed that athletes used the artificial turf fields continuously over their entire lifetimes. This overestimates the health risks. Data covering the time athletes spend on these fields would allow more accurate exposure and risk calculations and result in reduced risk estimates.
- In the study by New York State (2009), the relatively large number of TICs with peak match qualities below 85 percent indicates that these fields release many unidentified VOCs and sVOCs ("unknowns"). Some of these were at $\mu g/m^3$ levels (Table 11). It is likely that the health risks posed by these chemicals, if any, will not be known for the foreseeable future. The presence of a relatively large number of unidentified organic chemicals in the air over these fields is a potential health risk that cannot be evaluated at present.

References

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New York State (2009) An assessment of chemical leaching, releases to air and temperature at crumb-rubber infilled synthetic turf fields. New York State Department of Environmental Conservation and New York State Department of Health, May 2009.

TRC (2009) Air quality survey of synthetic turf fields containing crumb rubber infill. TRC, Windsor, Connecticut, prepared for New York City Department of Health and Mental Hygiene, March 2009.

Appendix to Artificial Turf Report

Table 1. Volatile organic compound (VOC) target list (in µg/m^3)

CAS#	Compound	MDL[1]	RL[2]
75-71-8	Dichlorodifluoromethane	1.78	4.46
74-87-3	Chloromethane (a.k.a., methyl chloride)	0.72	1.81
76-14-2	Freon 114	2.49	6.23
75-01-4	Vinyl chloride	0.91	2.28
106-99-0	1,3-Butadiene	0.81	2.03
74-83-9	Bromomethane	1.38	3.46
75-00-3	Chloroethane	0.94	2.35
64-17-5	Ethanol	2.22	5.56
75-69-4	Trichlorofluoromethane	2.00	5.01
67-64-1	Acetone	0.92	2.31
67-63-0	2-Propanol	1.10	2.76
75-65-0	t-Butanol	0.78	1.95
4227-95-6	Methyl iodide	0.60	1.50
75-35-4	1,1-Dichloroethene	1.37	3.44
107-13-1	Acrylonitrile	0.86	2.16
76-13-1	Freon 113	2.68	6.70
107-05-1	Allyl chloride	0.95	2.41
75-09-2	Dichloromethane	1.24	3.09
75-15-0	Carbon disulfide	4.56	9.12
156-60-5	trans-1,2-Dichloroethene	0.90	2.26
1634-04-4	Methyl tert butyl ether	0.84	2.10
107-12-0	Propionitrile	0.73	1.84
75-34-3	1,1-Dichloroethane	1.40	3.51
108-05-4	Vinyl acetate	1.95	9.77
78-93-3	2-Butanone	0.95	2.37
108-20-3	Diisopropyl ether	0.90	2.25
110-54-3	Hexane	0.82	2.05
126-98-7	Methacrylonitrile	0.89	2.24
141-78-6	Ethyl acetate	1.00	2.50
74-97-5	Bromochloromethane	0.89	2.23
109-99-9	Tetrahydrofuran	1.16	2.91

CAS#	Compound	MDL[1]	RL[2]
78-83-1	Isobutyl alcohol	1.58	7.90
156-59-2	cis-1,2-Dichloroethene	1.40	3.51
594-20-7	2,2-Dichloropropane	1.30	3.25
67-66-3	Chloroform (a.k.a., trichloromethane)	1.71	4.27
71-55-6	1,1,1-Trichloroethane	1.91	4.77
107-06-2	1,2-Dichloroethane	1.43	3.58
563-58-6	1,1-Dichloropropene	0.94	2.37
110-82-7	Cyclohexane	0.83	2.08
71-43-2	Benzene	1.13	2.83
56-23-5	Carbon tetrachloride	2.20	5.50
540-84-1	2,2,4-Trimethylpentane	0.80	2.00
142-82-5	n-Heptane	0.78	1.97
78-87-5	1,2-Dichloropropane	1.63	4.09
123-91-1	1,4 Dioxane	2.32	5.81
74-95-3	Dibromomethane	0.84	2.10
79-01-6	Trichloroethene	1.90	4.75
75-27-4	Bromodichloromethane	0.85	2.14
80-62-6	Methyl methacrylate	0.87	2.19
108-10-1	4-Methyl-2-pentanone (a.k.a., Methyl isobutyl ketone)	0.98	2.44
10061-01-5	cis-1,3-Dichloropropene	1.65	4.12
108-88-3	Toluene	1.33	3.33
10061-02-6	trans-1,3-Dichloropropene	1.62	4.05
79-00-5	1,1,2-Trichloroethane	1.91	4.77
97-63-2	Ethyl methacrylate	0.88	2.19
591-78-6	2-Hexanone	0.92	2.29
142-28-9	1,3-Dichloropropane	0.96	2.39
11-65-9	Octane	0.80	2.02
124-48-1	Dibromochloromethane	1.07	2.69
106-93-4	1,2-Dibromoethane	2.74	6.85
127-18-4	Tetrachloroethene	2.37	5.93
108-90-7	Chlorobenzene	1.61	4.03
630-20-6	1,1,1,2-Tetrachloroethane	0.90	2.23

CAS#	Compound	MDL[1]	RL[2]
100-41-4	Ethylbenzene	1.55	3.87
1330-20-7	m,p-Xylenes	3.07	7.67
111-84-2	Nonane	0.79	1.98
100-42-5	Styrene	1.50	3.77
75-25-2	Bromoform	0.88	2.20
95-47-6	o-Xylene	1.52	3.80
79-34-5	1,1,2,2-Tetrachloroethane	2.40	6.00
96-18-4	1,2,3-Trichloropropane	0.94	2.34
110-57-6	t-1,4-Dichloro-2-butene	1.09	2.72
95-49-8	2-Chlorotoluene	0.87	2.18
106-43-4	4-Chlorotoluene	0.85	2.13
103-65-1	n-Propylbenzene	1.16	2.92
98-82-8	Isopropylbenzene (a.k.a., cumene)	1.18	2.95
622-96-8	4-Ethyltoluene	0.96	2.39
108-67-8	1,3,5-Trimethylbenzene	1.79	4.47
124-18-5	Decane	0.93	2.33
98-06-6	tert-Butylbenzene	1.15	2.88
95-63-6	1,2,4-Trimethylbenzene	3.44	17.19
538-93-2	i-Butylbenzene	1.15	2.88
135-98-8	sec-Butylbenzene	1.22	3.07
541-73-1	1,3-Dichlorobenzene	4.20	21.02
99-87-6	Isopropyltoluene	1.20	3.01
100-44-7	Benzyl chloride	1.04	2.61
106-46-7	1,4-Dichlorobenzene	4.20	21.02
104-51-8	n-Butylbenzene	1.13	2.82
95-50-1	1.2-Dichlorobenzene	4.12	20.61
96-12-8	1,2-Dibromo-3-chloropropane	2.22	22.20
78-00-2	Tetraethyl lead	2.18	10.88
120-82-1	1,2,4-Trichlorobenzene	2.62	26.20
91-20-3	Naphthalene	3.95	15.82
87-68-3	Hexachlorobutadiene	7.53	37.66

[1] MDL = Representative method detection limits.
[2] RL = Representative reporting limits.

Abbreviations and Acronyms

ACGIH	American Conference of Governmental Industrial Hygienists
ASTM	American Society of Testing and Materials International
B[a]P	benzo[a]pyrene
Ca	calcium
CARB	California Air Resources Board
CFU	colony forming unit
CI	confidence interval
CIWMB	California Integrated Waste Management Board (now CalRecycle)
Cl	chlorine
CYSA	California Youth Soccer Association
FIFA	Federation Internationale de Football Association
FITR	Fourier Transform Infrared Spectroscopy
g	gram
GC/MS	gas chromatography/mass spectroscopy
IRIS	Integrated Risk Information System
K	potassium
kg	10^3 grams (kilogram)
LOAEL	lowest observed adverse effect level
LOD	limit of detection
m^3	cubic meters

MADL	maximum allowable dose level
MDL	method detection limit
MIBK	methyl-isobutyl-ketone
MRSA	methicillin-resistant *Staphylococcus aureus*
Na	sodium
NA	not applicable
NC	not calculated
NCAA	National Collegiate Athletic Association
ng	10^{-9} grams (nanogram)
NMOR	N-nitrosomorpholine
NOAEL	no observed adverse effect level
OEHHA	Office of Environmental Health Hazard Assessment
^{o}F	degrees Fahrenheit
PM_{10}	particulate matter with aerodynamic diameter less than 10 microns
$PM_{2.5}$	particulate matter with aerodynamic diameter less than 2.5 microns
PAH	polycyclic aromatic hydrocarbon
p-RfC	provisional reference concentration
RfC	reference concentration
S.	*Staphylococcus*
sVOC	semi-volatile organic compound
TIC	tentatively identified compound
TVOC	total volatile organic compounds

TWA	time-weighted average
µg	10^{-6} grams (microgram)
µm	10^{-6} meters (micrometer)
U.S. EPA	United States Environmental Protection Agency
VOC	volatile organic compound
XRF	x-ray fluorescence