Alveolar Breath Sampling and Analysis to Assess Trihalomethane Exposures during Competitive Swimming Training

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Alveolar breath sampling was used to assess trihalomethane (THM) exposures encountered by collegiate swimmers during a typical 2-hr training period in an indoor natatorium. The breath samples were collected at regular intervals before, during, and for 3 hr after a moderately intense training workout. Integrated and grab whole-air samples were collected during the training period to help determine inhalation exposures, and pool water samples were collected to help assess dermal exposures. Resulting breath samples collected during the workout demonstrated a rapid uptake of two THMs (chloroform and bromodichloromethane), with chloroform concentrations exceeding the natatorium air levels within 8 min after the exposure began. Chloroform levels continued to rise steeply until they were more than two times the indoor levels, providing evidence that the dermal route of exposure was relatively rapid and ultimately more important than the inhalation route in this training scenario. Chloroform elimination after the exposure period was fitted to a three compartment model that allowed estimation of compartmental half-lives, resulting minimum bloodborne dose, and an approximation of the duration of elevated body burdens. We estimated the dermal exposure route to account for 80% of the blood chloroform concentration and the transdermal diffusion efficiency from the water to the blood to in excess of 2%. Bromodichloromethane elimination was fitted to a two compartment model, which provided evidence of a small, but measurable, body burden of this THM resulting from vigorous swim training. These results suggest that trihalomethane exposures for competitive swimmers under prolonged, high-effort training are common and possibly higher than was previously thought and that the dermal exposure route is dominant. The exposures and potential risks associated with this common recreational activity should be more thoroughly investigated. *Key words*: alveolar breath sampling, bromodichloromethane, chloroform, exposure assessment, swimming, trihalomethanes (THMs). *Environ Health Perspect* 105:636–642 (1997)

Many people participate in regular physical fitness activities to maintain or improve physical well-being. Among these activities, the most serious athletes often engage in rigorous training schedules to remain competitive in their chosen sport. While any level of physical activity can cause injuries or other ailments, participation in athletics is generally considered to be a long-term physical benefit for most people. Illness and debilitation have been associated with long-term participation in certain sports (*1*) such as football, baseball, boxing, etc., but the risks of related infirmities are generally well known and accepted by the participants. It has become apparent, however, that certain sports and recreation-related risks are poorly understood or altogether unknown. Sports-related chemical exposures, for example, have received very little attention from either the participants or potential research groups, with the exception of ice hockey players' exposure to carbon monoxide from ice resurfacing machines (*2,3*). This study employs a recently developed alveolar breath sampling and analysis technique (*4,5*) to investigate the potential chloroform and bromodichloromethane exposures that occur during swimming, one of the most common recreational activities enjoyed around the world.

The chlorine-based disinfection compounds that are commonly used in water supply systems often combine with residual organic material to form measurable trihalomethane concentrations (THMs, i.e., chloroform, bromodichloromethane, chlorodibromomethane, and bromoform) in finished water supplies (*6,7*). This is a concern because chloroform is a known animal carcinogen (*8*), and recent studies have linked human bladder and rectal cancers to the routine use of chlorinated water supplies (*9*). While various studies have examined THM exposures resulting from routine ingestion of chlorinated water (*10*), more recent efforts have also examined dermal and inhalation exposures that occur in residential settings. Jo et al. (*11*), for example, used exhaled breath analysis to demonstrate that shower-related dermal and inhalation exposures are comparable and that, together, these shower-related exposures are roughly equivalent to typical ingestion exposures with the same water supply.

Because swimming pools are also commonly treated with chlorine-based disinfection compounds, a few recent studies have examined chloroform exposures resulting from recreational swimming. Aggazzotti et al. (*12*) collected blood samples from 127 swimmers in an effort to relate blood plasma chloroform concentrations with activities in the pool. They found geometric mean chloroform levels of 0.82 µg/l, with 13% of the blood samples higher than 1.91 µg/l. The mean blood levels in the agonistic swimmers were significantly higher than those in the nonagonistic swimmers and the nonswimming observers. Moreover, blood chloroform levels were significantly correlated with water and air concentrations, the number of swimmers in the pool, and the time an individual swimmer spent in the pool. The overall intensity of the physical activity was also correlated with blood chloroform levels. In a follow-up study, Aggazzotti et al. (*13*) collected alveolar breath samples from swimmers after a 90 min swim session. They found median alveolar breath chloroform at 83 µg/m³ (range 13.9–311 µg/m³), and they determined that postswim chloroform in breath was strongly influenced by environmental air chloroform levels, age, intensity of sporting activity, and the type of swimming.

Weisel and Shepard (*14*) also used exhaled breath measurements to examine chloroform exposures associated with recreational swimming. They found that after a routinized 30-min exposure period, breath elimination of chloroform was rapid, but it could not be fitted to the conventional multicompartment exponential decay models that have been previously used to describe

postexposure breath elimination of volatile organic compounds (VOCs). After an initial rapid decay, a secondary peak in alveolar breath levels was observed sometime between 60 and 90 min after the exposure period started. The authors suggested that this secondary postexposure peak was consistent with a relatively slow transdermal input term. Overall, they maintained that their data provided evidence that inhalation is more important than the dermal route and that the transdermal fraction of the exposure only becomes evident after careful examination of postexposure elimination breath profiles.

Lévesque et al. (*15*) investigated dermal and inhalation chloroform exposures during a routine 55-min swimming period using alveolar breath samples collected at 35 and 55 min exposure time. Neat chloroform was added directly to the pool water to provide a range of concentrations from 159 to 553 µg/l. To assess the relative magnitude of the dermal and inhalation routes of exposure, the participants used scuba gear in one of the trials to establish a "dermal only" exposure. They concluded that chloroform exposure was significantly associated with the aqueous chloroform concentrations, chloroform levels in the surrounding air, the intensity of the exercise, and the physiological characteristics of the subject. Like Weisel and Sheppard (*14*), they also concluded that inhalation was more important than dermal exposure, with approximately 24% of the resulting body burden being directly related to dermal absorption.

Wilson (*16*) used breath measurements to examine chloroform exposures that are related to recreational swimming. To isolate the dermal exposure route, his study subjects wore full face respirators during some of the trials to minimize potential inhalation exposures. Without activity in the pool, he found that breath concentrations came to virtual equilibrium in as little as 7 min. With activity, alveolar breath concentrations increased as the level of activity increased. The experiments with the respirators lead him to conclude that exposure via the dermal pathway was negligible during swimming. In further tests conducted in hot tubs, Wilson (*16*) found that the dermal route became important in this scenario, possibly due to the elevated water temperatures of the tub.

The present study uses the recently developed single breath canister (SBC) technique (*4,5*) and an innovative new microenvironmental whole air sampling method (*17*) to assess the chloroform and bromodichloromethane exposures that occurred during a 2-hr swimming work-out. This investigation presents breath concetration data for both the uptake and elimination of these compounds; subsequent modeling of the elimination of these compounds allows estimation of internalized dose and approximate half-lives in various body compartments. This study helps estimate the exposures experienced by competitive athletes in daily training and establishes an upper limit for exposures that may be encountered by more typical recreational swimmers who presumably spend less time in the water, swim less frequently, and swim at lower respiration and exercise rates.

Methods

Field study design. The exposures of two elite college athletes (one male and one female) were assessed during and after a typical 2-hr interval training session. The male subject was 23 years old, weighed 70 kg, and had been swimming competitively for 10 years. The female subject was 22 years old, weighed 65 kg, and had been swimming competitively for 15 years. At the time of the experiment, both athletes swam approximately three times per week for approximately 2 hr during each of these individual training sessions. The exposure portion of the experiment (and the preliminary training) took place in the 25-yard pool at the natatorium at the University of Montana.

Alveolar breath samples were collected in evacuated 1 liter stainless steel SUMMA canisters (SIS, Inc., Moscow, ID) according to a recently developed SBC protocol (*4*). This is a self-administered sample collection method; in essence, after a normal exhalation (eliminating the deadspace portion of a breath) the sample subject places one end of a short Teflon collection tube in his mouth and opens the canister valve to fill it with 1 liter of expiratory reserve (Fig. 1). Because the canister is initially evacuated, the sample is collected until the canister comes to atmospheric pressure. The primary breath sampling site, used to collect preexposure and postexposure breath samples, was established in the Health and Human Performance (HHP) Laboratory located in a separate building, approximately 100 m from the natatorium and thus free from a trihalomethane source.

Two preexposure breath samples were collected from both subjects in the HHP lab at 10 and 9 min before the exposure/ workout period began to establish baseline breath concentrations. Shortly after the second preexposure sample was collected, the subjects were escorted to the pool and the 2-hr training period began immediately. The workout was a typical interval type session consisting of five 100-yard intervals

Figure 1. Use of the self-administered single breath canister alveolar breath collection technique.

at a rate of 2 min/100 yds, followed by twenty-two 300 yard intervals at a rate of 5 min/300 yds. The sampling protocol called for the male subject to give breath samples at 2, 4, 6, 8, 10, 15, 20, 30, 45, 60, 90, and 120 min (nominal) during this period. To accommodate a limited number of sampling canisters, the female subject only provided samples at 65 and 120 min during the exposure period. These samples were collected while the subjects were in the pool during the period between the training intervals.

To help assess potential inhalation exposures, an integrated whole-air sample was collected at mid-pool approximately 30 cm above the surface of the water using a battery operated personal whole-air sampler (PWAS) (*17*). Confirmatory whole-air grab samples (*18*) were also collected with evacuated 1-liter canisters at mid-pool at 2, 60, and 120 min (nominal) exposure time. Two water samples were collected using standard procedures (*19*) to establish waterborne chloroform concentrations and provide comparability with similar investigations. With the completion of the final swim interval, both subjects were allowed to sit on the deck and the final exposure period samples were collected. Both subjects then quickly dried themselves, put on their warm-up suits, and proceeded back to the primary breath sampling site in the adjacent HHP laboratory.

The first postexposure breath samples were collected from both subjects at 1 and

2 min postexposure in the outdoor parking lot between the natatorium and the HHP lab. The remaining samples were collected at 4, 8, 10, 15, 30, 45, 60, 75, 90, 105, 120, 135, 150, and 180 min postexposure time (nominal) indoors at the primary breath sampling site. An integrated whole-air sample was collected with the PWAS during the 3-hr postexposure period to establish background contaminant concentrations. Whole-air grab samples were also collected at 1 min outdoors and at 90 and 180 min in the HHP lab to confirm background concentrations. A summary of the sampling design and sample collection times is presented in Table 1. The study protocol was reviewed and approved by the University of Montana's Human Studies Review Board, and informed consent was obtained from the participants.

Analysis. All samples were analyzed using an EPA Method TO-14 protocol (*20*) as implemented by Graseby Nutech for the Model 3550A Cryogenic Concentrator (Graseby Nutech, Smyrna, GA). The analytical system was an ITS40 (Magnum) GC-MS ion trap instrument (Finnigan MAT, San Jose, CA). Specifically, a 50-ml aliquot of air or breath sample was cryogenically focused at -165°C in a primary trap, heated and transferred in a helium stream to a secondary trap, and refocused at -190°C on a 2 m × 0.53 mm (deactivated) precolumn. The precolumn was then rapidly ramped to 150°C and the analytes injected in a sharp plug onto a XTI-5 30 m × 0.25 mm inside diameter (ID) 1-μm phase analytical column (Restek Corp., Bellefonte, PA). The oven temperature profile was programmed to hold at -50°C for 2 min, ramp to 220°C at 10°C/min, and then hold at 220°C for 8 min. The 3550A concentrator is also an autosampler for canisters and was used in this mode to perform up to 16 unattended analyses. Four-point external calibration standards used were prepared in a simulated breath matrix (5% CO_2, saturated water vapor) for chloroform, bromodichloromethane, chlorodibromomethane, and bromoform, by the EPA's Quality Assurance Division. Two field blanks were brought into the field, and replicate analyses were conducted on >13% of the samples.

Exposure assessment modeling. Postexposure breath elimination of chloroform was assessed using a modeling procedure found effective in other recent exposure assesssment studies (*21–24*). This model can be described as follows:

$$C_{alveolar} = \beta_1 e^{k_1 t} + \beta_2 e^{-k_2 t} + \beta_3 e^{k_3 t} + fC_{air} \quad (1)$$

where $C_{alveolar}$ is the alveolar breath concentration at any time during the elimination; the coefficients (β_i) represent the contribu-

tions from the theoretical body compartments; k_i is the exponential term associated with each body compartment; f is the fraction of the parent compound exhaled at equilibrium; and C_{air} is the ambient air concentration of the contaminant. The half-life of the compound in each compartment ($t_{1/2,i}$) is equal to (ln 2)/k_i. Note that the first compartment is generally associated with the blood, the second with highly perfused tissues, the third with lesser perfused tissues, etc. The breath elimination models were created using GraphPad Prism (GraphPad Software, Inc., San Diego, CA), a nonlinear modeling program. Initial model input parameters were estimated using standard curve stripping procedures. Optimal models were selected based on minimization of standard error and 95% confidence intervals.

Results and Discussion

Quality assurance. Excellent analytical precision was demonstrated in replicate analyses conducted on more than 13% of this study's samples: the mean relative difference between sample pairs was 5.3% for chloroform (range 1.1–15.7%) and 9.5% for bromodichloromethane (range 2.9–18.9%). A four-point chloroform calibration curve was established over the full range of exhaled breath values (0–400 μg/m³); excellent linearity was demonstrated for this curve with an R^2 >0.999. While a 4-point calibration curve was also prepared over the expected range of bromodichloromethane levels, all of the resulting breath samples were below the lowest point on this curve. A single-point calibration, based on the lowest laboratory standard, was therefore used to provide an estimate of resulting bromodichloromethane concentrations. The limit of quantitation (LOQ) for both compounds was established using a signal to noise ratio criterion of 5:1, leading to an approximate LOQ of 1.70 μg/m³ for chloroform and 0.39 μg/m³ for bromodichloromethane. Analysis of both field blanks showed chloroform and bromodichloromethane concentrations below their respective LOQs.

Microenvironmental data. The water samples collected in the pool during the exposure period had chloroform concentrations of 68 and 73 μg/l, well within the range of values previously reported in the literature (≈15–150 μg/l) (*13–16*). The chloroform concentrations in grab air samples collected at 60 and 118.8 min during the exposure period (both 145 μg/m³) were in excellent agreement with the integrated sample collected in the pool area during the 2-hr exposure (148 μg/m³). These levels are also consistent with other indoor pool air concentrations

Table 1. Sampling plan summary

Nominal time (min)	Male subject[a]	Female subject[a]	Grab samples
Preexposure			
-10	-10	-10	–
-9	-9	-9	–
Exposure period[b]			
2	1.3	–	1.2
4	3.4	–	–
6	5.4	–	–
8	7.4	–	–
10	9.5	–	–
15	13.3	–	–
20	18.3	–	–
30	28.3	–	–
45	43.4	–	–
60	58.4	65.1	60.0
90	88.3	–	–
120	119.2	119.2	118.8
Postexposure period[c]			
1	1.1	1.1	1.07[d]
2	2.0	2.0	–
4	4.0	4.0	–
8	8.0	8.0	–
10	10.0	10.0	–
15	15.1	15.1	–
30	30.0	30.0	–
45	45.1	45.1	–
60	60.0	60.0	–
75	75.0	75.0	–
90	90.1	90.1	90.0
105	105.0	105.0	–
120	120.0	120.0	–
135	135.0	135.0	–
150	150.0	150.0	–
180	180.1	180.1	180

[a]Actual collection time (min).
[b]Integrated whole air was collected by personal whole-air sampler for 118.6 min during the exposure period (collected mid-pool in breathing range).
[c]Integrated whole air was collected by personal whole-air sampler for for 174.8 min during the postexposure period (collected in the Health and Human Performance Laboratory).
[d]Collected in ambient air between the pool and the Health and Human Performance Laboratory.

previously reported in the literature in the range of 13–647 μg/m³ (*13–16*). While the grab sample collected 1.2 min into the period showed appreciably less chloroform (36.6 μg/m³) than any of the subsequent samples, the field technician collecting this sample noted in the log that it came to ambient pressure very quickly, suggesting the canister had a partial leak before the sample was collected. Another plausible explanation for this relatively low level grab sample could have been natural variability due to inhomogeneous mixing and variable air flow rates within the pool area. However, considering the consistency of the latter two grab samples and their close agreement with the 2-hr integrated sample, it seems most likely that the initial grab sample was indeed compromised.

The grab and 3-hr integrated samples collected in the HHP lab during the postex-

Table 2. Microenvironmental measurements

Sample location/time	Chloroform (µg/m³)	Bromodichloromethane (µg/m³)
Exposure period pool water	68, 73[a]	_[b]
Air grab, 1.2 min	36.6	0.78
Air grab, 60 min	145	2.76
Air grab, 118.8 min	145	3.02
2-Hr integrated air	147	2.68
Postexposure period		
Air grab, 1.1 min	2.86	<LOQ[c]
Air grab, 90.0 min	2.20	LOQ
Air grab, 180.0 min	1.79	<LOQ
3-Hr integrated air	3.96	<LOQ

[a]Units are µg/l for water samples.
[b]Analysis not conducted for water samples.
[c]Less than the limit of quantitation.

Figure 2. Chloroform in alveolar breath during the exposure period.

posure period show that chloroform concentrations were consistently less than 4.0 µg/m³ (mean grab = 2.28 µg/m³; integrated = 3.96 µg/m³), suggesting very limited potential impact on the breath elimination measurements that are presented below. All of the microenvironmental data gathered during this study are summarized in Table 2.

Alveolar breath samples. The preexposure breath samples collected in the HHP lab show very similar chloroform concentrations for both subjects, with values ranging between 3.07 and 3.46 µg/m³. These initial values are higher than levels reported in EPA's TEAM studies (*25–27*), a population-based exposure assessment study conducted in the 1980s that documented geometric mean chloroform-in-breath concentrations of less than 1.3 µg/m³ for nearly 800,000 people represented in the study. The high preexposure breath levels documented in the present study may reflect a slight, but measurable, long-term residual chloroform body burden associated with intensive swimming training. Bromodichloromethane concentrations in the preexposure samples were all below the LOQ.

At 2 min into the exposure period, the male's chloroform-in-breath level was 71.2 µg/m³; after 8 min, his level was 160 µg/m³, higher than the long-term pool air concentration of 148 µg/m³. This subject's breath chloroform levels continued to increase at a rapid rate until 90 min, when they reached a peak level of 371 µg/m³, the highest chloroform level recorded during this experiment. The concentration then fell in the final exposure period sample (t = 119.2 min) to 257 µg/m³, despite the fact that the exposure and exercise continued, presumably due to a slight reduction of effort during the late stages of the workout. While only two breath samples were collected from the female subject during the exposure period, these data suggest that her uptake was somewhat slower but eventually

of the same magnitude as the male subject. Breath data from both subjects are presented graphically in Figure 2.

These uptake observations help demonstrate the rate and relative importance of the dermal pathway in this exposure scenario. If this training activity only involved an inhalation exposure, the breath levels would have climbed asymptotically to some finite fraction of the breathing zone level (148 µg/m³) as the subject approached equilibrium with the environment. This fraction (i.e., breath concentration/environmental concentration at equilibrium) is defined as the *f* value for a given contaminant (*21*). As an anecdotal illustration of an inhalation-only exposure, one of the study coordinators who did not enter the pool gave a breath sample of 48.7 µg/m³ at 118 min exposure time, suggesting an *f* value of approximately 0.33. Conversely, only 8 min into the exposure period the male subject's breath levels were higher than the breathing zone air concentrations. This alone suggests that the dermal pathway was of major importance early on in the training period. The fact that breath concentrations launch past this long-term breathing zone level and keep climbing [to as high as 371 µg/m³ (male) and 339 µg/m³ (female), more than two times the maximum possible inhalation-only level] demonstrates that the dermal route is of major importance and that the transdermal transport rate continued to be very rapid. Moreover, the maximum alveolar breath concentrations ultimately rise to more than two times the indoor chloroform level, suggesting that the dermal pathway (in this scenario) has a higher capacity than the inhalation route alone.

The suggestion that dermal input is equal to or greater than the inhalation exposure is in basic agreement with the observations made by Jo et al. (*11*), who found that the dermal and inhalation pathways resulted
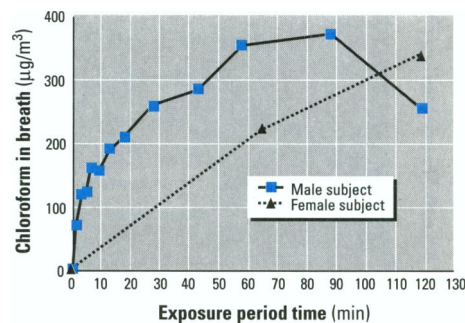
in approximately equivalent body burdens over the course of a 10-min shower, and by Weisel and Jo (*28*) when they studied the exposures from ingestion, inhalation, and transdermal transport that included a 30-min bath. The results of the present study, however, seem to contradict the other previous studies (*12–16*) which suggest that the dermal contribution to total body burden during swimming is at most 24% (*15*). But in contrast to these previous studies, the subjects in this experiment were totally immersed in the warm pool water (≈84°F) with near maximum sustainable heart rates for the entire 2-hr period. Because the rate of dermal absorption is known to increase when the skin is fully hydrated, when the temperature of the skin and solute are elevated, and when 100% of the body surface area is immersed (*29*), one would fully expect maximum dermal penetration during this training situation. Additionally, the agonistic exercise increases blood pressure and surface capillary perfusion, thus decreasing the transdermal path length for chloroform diffusion and increasing the volume of blood flow just under the skin.

The uptake of bromodichloromethane is similar to that of chloroform, with the overall trend being less distinct, possibly because the concentrations reported were only slightly higher than the LOQ. The data for the uptake of bromodichloromethane for both subjects are depicted in Figure 3.

The elimination of chloroform after the exposure terminated was consistent with the tri-exponential elimination profiles previously reported for other VOCs in the literature (*21,24*); these models are summarized in Table 3. To complete the model, C_{air} was set at 3.98 µg/m³, the long-term chloroform level in the HHP laboratory; the value of *f* for chloroform was set equal to 0.33, a value observed for one of the study coordinators (discussed above), which is very close to the *f* value observed for similar compounds cited in the literature (e.g., 1,1,1-trichloroethane and trichloroethylene, both equal to 0.3)
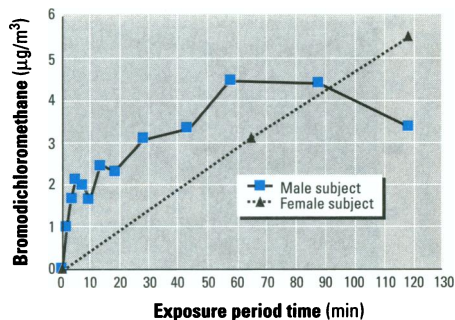
Figure 3. Bromodichloromethane in alveolar breath during the exposure period.

Table 3. Elimination curves modeling results

Compound (subject)	Equation parameters[a]						Descriptive parameters	
	β_1	k_1	β_2	k_2	β_3	k_3	R^2	$B_0{}^b$ (µg/l)
Chloroform	111	0.509	107	0.027	45.8	0.004	>0.99	1.86
(male)	(11.5)	(0.101)	(39.4)	(0.012)	(44.8)	(0.005)		
Chloroform	153	0.750	104	0.043	49.7	0.005	>0.99	2.10
(female)	(63.4)	(0.343)	(8.88)	(0.008)	(8.43)	(0.001)		
Bromodichloromethane[c]	1.70	0.114	1.60	0.009	–	–	>0.97	0.10[d]
(male)	(0.274)	(0.036)	(0.279)	(0.002)				
Bromodichloromethane[c]	2.31	0.130	1.46	0.009	–	–	>0.96	0.12[d]
(female)	(0.512)	(0.050)	(0.228)	(0.002)				

[a]Value shown in parentheses is standard error.
[b]Calculated blood concentration at t = 0 (immediately after the exposure period).
[c]Two compartment model only.
[d]Estimated blood/breath partition coefficient $p = 29.9$ (m³/1,000 l).

(21). Figure 4 presents the actual measured values and the models generated to fit these data. The models yield the following half-lives for the various body compartments (for the male and female, respectively): $T_{1/2,1}$ = 1.36 and 0.95 min, $T_{1/2,2}$ = 25.7 and 16.9 min, and $T_{1/2,3}$ = 173 and 138 min, which compare very well with the published literature, for instance Wallace, et al. (21). Note that the models are well fitted to the observations and that there is no evidence of delayed compartments or more complicated elimination kinetics (e.g., delayed dermal inputs). While these chloroform-in-breath results are higher than most of the samples from previous swimming-related studies (generally <83 µg/m³) (13,14,16), they were collected immediately after the exposure was terminated and they correspond to periods of comparatively heavy exercise.

In Figure 4, extrapolation back to the y-axis gives chloroform-in-breath concentrations at t = 0 of 264 and 303 µg/m³ for the male and female, respectively. Using a very conservative breathing rate of 7 l/min and integrating the area under the elimination curve, we can calculate that the male and female subjects exhaled 66.8 and 58.2 µg of chloroform, respectively, during the postexposure monitoring period. (Note that the last sample for the male subject was lost in shipment, making these elimination times 150 min for the male and 180 min for the female.) Given the fact that both subjects' final breath levels were still 8.6 (male) and 5.8 (female) times higher than their respective preexposure concentrations, a fourth elimination compartment might well have been established if sampling had proceeded longer (e.g., 4–12 hr postexposure).

If we apply a blood/breath partition coefficient to the breath measurements or modeled values at any point on the elimination curve, we can calculate the subject's bloodborne contaminant concentration at that time. Using the y-intercept established in Figure 4 and a blood/breath partition
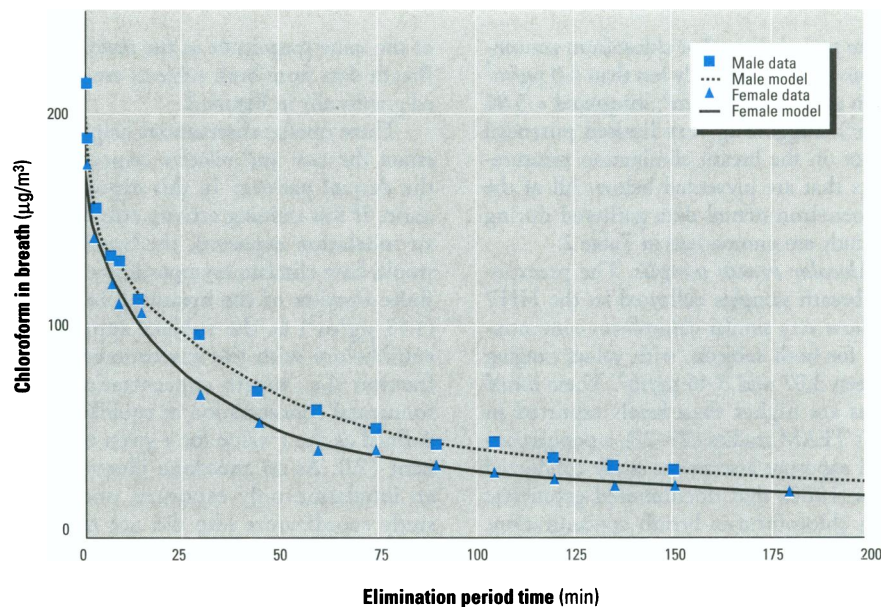

Figure 4. Observed and modeled chloroform elimination.

coefficient of 6.85 (30), the blood contaminant concentrations at the end of the 2-hr training period are estimated at 1.81 and 2.08 µg/l for the male and female, respectively. These calculated results are in excellent agreement with two previous studies, which made direct measurements of blood chloroform after swimming pool exposures: a study conducted by Copaken (31) measured an increase of 0.6 µg/l of blood after a 2-hr workout in a pool with 37 µg/l chloroform and Aggazzotti et al. (12) documented a geometric mean chloroform level of 0.82 µg/l, with 13% of the blood samples higher than 1.91 µg/l in a study of pools with between 17 and 47 µg/l of chloroform. While the calculated postexposure blood levels in the present study are generally two to three times higher than typical values found in either of these previous studies, chloroform concentrations in the pool water were also generally at least two times higher. It is also worth noting that the calculated

blood levels represent the moment the exposure period ended; the samples from the Aggazzotti et al. (12) study were collected anywhere from 1 to 40 min after the exposure ended, allowing more than enough time for substantial breath elimination and systemic metabolism. If the 15 min postexposure breath values (≈110 µg/m³) of the present study are used to estimate postexposure blood levels, we find concentrations that are very similar to those made in the two previous studies (e.g., ≈0.75 µg/l).

Given that the air chloroform concentration was measured at about 145 µg/m³ and the f value (steady state breath/environmental equilibrium ratio) estimated at 0.33, we calculate that the inhalation exposure route alone should contribute about 48 µg/m³ to the final breath concentration at the end of the exposure period. Assuming a linear contribution relationship, the dermal exposure route can then be estimated as providing the remaining
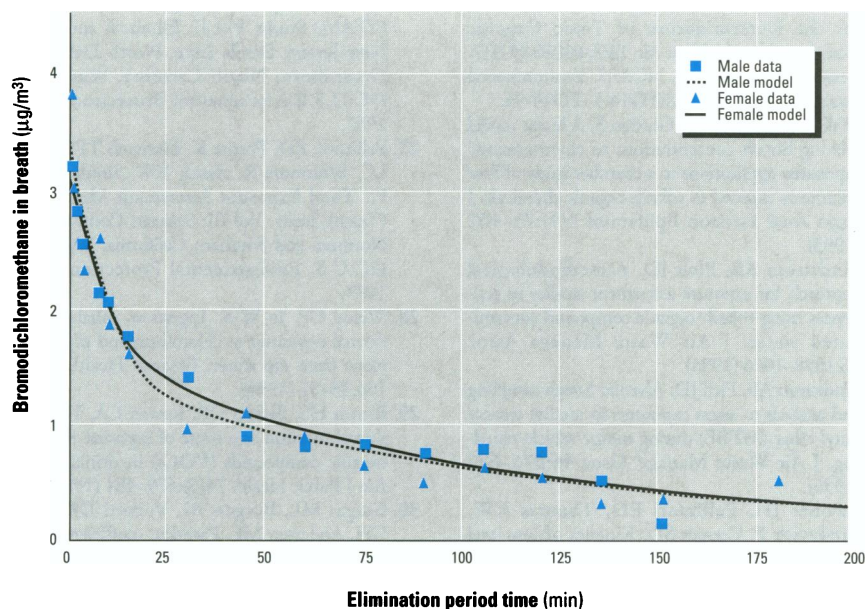
Figure 5. Observed and modeled bromodichloromethane elimination.

chloroform to the exhaled breath concentration for the male subject at 264 - 48 = 216 μg/m³ and for the female subject at 303 - 48 = 255 μg/m³. Thus, transdermal diffusion can be estimated to cause 1.48 and 1.75 μg/l chloroform concentration in the subjects' blood (male and female, respectively). This means that the dermal contribution to the blood chloroform concentration is greater than 80% and, given the measured mean water chloroform concentration of 70.5 μg/l, that the transdermal diffusion efficiency of chloroform from the water to the blood can be approximated at 2.1 and 2.5% for the two subjects, respectively.

Figure 5 represents the postexposure elimination of bromodichloromethane and the corresponding two compartment models fitted to these data (these models are also summarized in Table 3). Acceptable three compartment models (i.e., with relatively small standard errors) could not be established, probably because precision of data so close to the LOQ is relatively poor; we did not attempt to estimate the total eliminated compound, as this depends heavily on the third compartment parameters. Nevertheless, Figure 5 aptly demonstrates that both subjects received a verifiable bromodichloromethane dose during the exposure period and that the subsequent elimination was similar to that of chloroform. We estimated the blood/breath coefficient for bromodichloromethane from other trihalomethane data from Gargas et al. (*30*) at 29.9 to allow calculating the blood levels after training at 0.10 and 0.12 μg/l for the male and female subjects, respectively.

Conclusions

Elite swimmers' training exposures to chloroform and bromodichloromethane were investigated using the recently developed SBC and PWAS methods. Before the 2-hr training period, both subjects provided samples showing little (chloroform) to no (bromodichloromethane) body burden of these compounds. Uptake during the training period was rapid, with the breath levels from the male subject exceeding the long-term indoor levels within 8 min of the exposure's onset. The female subject's uptake was similar, but somewhat delayed with respect to the male's. Both subjects' peak chloroform-in-breath levels eventually reached higher than two times the long-term indoor levels, suggesting that the dermal uptake was very rapid and ultimately of greater importance than the inhalation dose alone; the dermal contribution was estimated at about 80%.

After the exposure, the elimination of chloroform from both subjects followed a conventional three compartment model, providing no evidence for more complicated elimination kinetics (e.g., a delayed transdermal pathway). The elimination of bromodichloromethane followed a similar pattern, but was only modeled using a two compartment model due to imprecision near the LOQ. The resulting models provide estimates of compartmental residence times and peak blood levels for both compounds and, additionally, total amount of chloroform eliminated from the body via exhalation. A measurable body burden of chloroform was observed during the 3-hr postexposure monitoring period, with

breath levels still more than five times higher than preexposure levels when the final sample was collected.

These methods have demonstrated a measurable body burden of chloroform and bromodichloromethane associated with competitive swimming training. Continued work using these sensitive methods should be considered to more thoroughly establish the relative importance of the various pathways, the magnitude of the resulting body burdens, and the duration of an observable internal dose. A careful analysis of the risks associated with these exposures should also be undertaken in the near future.

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