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RESEARCH ARTICLE

The alcohol breath test in practice: effects of exhaled volume

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Anderson JC, Hlastala MP. The alcohol breath test in practice: effects of exhaled volume. *J Appl Physiol* 126: 1630–1635, 2019. First published April 11, 2019; doi:10.1152/japplphysiol.00726.2018.—Alcohol breath test (ABT) measurements are sensitive to the volume of the exhaled breath. Although a minimum breath volume is required for a legally acceptable sample, any additional increase in the volume of exhaled air increases the measurement of breath alcohol concentration (BrAC). Using a sample of 115 ABTs collected by police agencies for evidentiary purposes, we studied the influence of exhaled air volume on the measurement of BrAC. The 115 ABTs were performed on 30 different Alcotest 9510s. Each of the tests included paired, time series measurements of exhaled breath flow rates and breath alcohol content. The exhalation flow rates and exhalation times were used to create exhalation volume-BrAC plots. On average, exhaled air volumes were ~50% of the subjects' age-, height-, race-, and sex-predicted vital capacities (VC). More than 80% of the samples had exhaled air volumes ranging between 30 and 70% of the subject's predicted VC. Breath volumes for duplicate breath samples were similar. For all breath samples, BrAC increased with exhalation volume, an expected behavior for any very high blood solubility compound such as alcohol. Beyond the legally accepted minimum expiratory volume, BrAC increased, on average, at a rate of 9.2 ± 2.8%/liter air exhaled. As a result, a person who exhales just beyond the minimum volume will have a lower BrAC compared with a person who exhales a full VC. Exhaled volume materially impacts the measurement of an ABT.

NEW & NOTEWORTHY Subjects who provide breath samples for evidentiary alcohol breath tests exhale, on average, about half of their predicted vital capacity. Because breath alcohol concentration increases with greater exhaled air volume, subjects who exhale more than average volume will have a greater breath alcohol concentration, whereas subjects who exhale less than average volume will have a lesser breath alcohol concentration. A quantification of air volume impact on breath alcohol concentration is provided.

airway gas exchange; bias; forensic science; single exhalation; vital capacity

INTRODUCTION

The alcohol[1] breath test (ABT) was developed primarily in the 1950s and early 1960s by Harger et al. (13) and Borkenstein and Smith (6) after initial introduction by Antsie (5) in the 1870s. At that time, no data were available on the mechanism of ethyl alcohol exchange in the lungs. Thus, ethanol was assumed to exchange in the alveolus, like the well-studied respiratory gases oxygen and carbon dioxide. As a direct consequence, two assumptions critical to the administration and interpretation of the alcohol breath test were made. End-expired breath alcohol concentration (BrAC) was assumed to be identical to alveolar alcohol concentration. Additionally, alveolar alcohol concentration was assumed to be related to blood alcohol concentration (BAC) through a fixed relationship defined by the high air to blood partition coefficient for ethanol. Thus, sampling end-expired air provided a measure of alcohol in alveolar air, which could be related back to BAC through the ethanol blood-air partition coefficient. By this reasoning, end-expired breath could be used as an indirect estimate of BAC.

Whereas the vast majority of respiratory gas exchange occurs between the alveolar air and blood in the pulmonary circulation, the vast majority of ethanol exchange occurs in the airways between respired air and bronchial blood supplied by the systemic circulation (3, 15). Like ethanol, many gases with high blood-to-air solubility ratios, such as diethyl ether, acetone, and isopropanol, exchange partially or completely in the airways (2, 4, 8). The magnitude and location (airway versus alveolus) of gas exchange depends on the solubility of the gas in blood (4, 11, 21–23). Ethanol, with a high blood-to-air partition coefficient (1,810 at 37°C; see Ref. 18), exchanges almost completely in the airways (3, 7, 12, 24). In fact, so much ethanol exchange occurs before inspired air reaches the alveoli that very little, if any, ethanol exchanges in the alveolus (3, 7).

Because of airway gas exchange, end-expired breath does not contain an alcohol concentration equal to that in alveolar air. In fact, the BrAC varies with a variety of pulmonary factors, including pretest breathing pattern, breath temperature, and exhaled air volume (14). However, alcohol breath testing continues to require that subjects exhale a minimum volume (i.e., 1.1–1.5 liters) to obtain an alveolar sample at the mouth. It is now known that BrAC increases with the volume of air exhaled (19).

To maximize the BrAC, the subject is often encouraged to exhale a full and complete exhalation. If the subject complies by providing a complete exhalation, the BrAC will be greater than it is with a minimal exhalation (16, 19, 27). To have enough air to exhale a full vital capacity (VC), a subject must make a full inhalation to total lung volume, followed by a full VC exhalation to residual volume. A full inspiration followed by a full exhalation takes considerable effort, usually requiring coaching by a trained technician with real-time monitoring. Subjects tested in the field are unlikely to provide a satisfactory VC measurement.

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[1] In this paper, alcohol refers specifically to ethyl alcohol.

This study determined how much air volume is exhaled under normal breath test situations in which a trained police officer instructs the subject on provision of a satisfactory breath sample. In addition, the effect of the observed range of exhaled air volumes on the BrAC measurements acquired was evaluated.

BACKGROUND

For a breath sample to be accepted within the state of Washington, four criteria must be met: *1*) flow >8.0 l/min to start the test and then maintain an airflow >4.0 l/min, *2*) minimum volume expired of 1.5 liters, *3*) a minimum exhalation time of 5.0 s, and *4*) a change in BrAC over time (i.e., BrAC slope) that is is less than a specified value (10). Per the Alcotest 9510 manual for the state of Washington (10), these "...criteria have to be met in order for the Alcotest 9510 instrument to accept a breath sample and ensure that the breath sample analyzed represents an alveolar (deep lung) air sample."

A single exhalation can never produce a breath sample with an alcohol concentration equal to that from the alveolar air. Studies using a variety of models have demonstrated that alcohol exchanges in the airways of the lung (3, 7, 12). During inhalation, alcohol is added to the airstream from the airway mucus and tissue. Once inspired air reaches the alveolus, alcohol completely equilibrates between the alveolar air and the pulmonary capillary blood. During exhalation, alcohol deposits onto the airway wall (mucus and tissue). On its journey from the alveolus to the mouth, the exhaled air loses some alcohol to the airway wall as it passes through each airway generation. As exhalation continues, the amount of alcohol deposited on the airway wall decreases due to the increasing alcohol concentration within the airway wall and decreasing the air-to-wall diffusion gradient. Thus, expired alcohol concentration increases as the exhalation continues. With a full inhalation followed by a full exhalation, it is not possible to reach more than ~80% of the alveolar alcohol concentration (14). The capacity for alcohol to dissolve in the airway wall is so large that it takes an expired volume of air at least 10 times the true VC for BrAC to achieve 99% of alveolar alcohol concentration (14).

METHODS

Breath test data. All ABT and demographic data were publically available (see below). We had no interaction with the subjects. We have been careful not to reveal any information that would allow identification of any of the subjects. Potential subjects were adults with acceptable ABTs published online in public records maintained by the Washington State Patrol (https://fortress.wa.gov/wsp/webdms/BreathTest). All ABTs for potential subjects were analyzed by an Alcotest 9510 (Draeger, Lübeck, Germany). Individual subjects were selected for study inclusion using a random number generator.

The Alcotest 9510 is a tabletop breath-testing instrument that uses both infrared absorption and fuel cell technology for alcohol analysis. Breath alcohol concentration (BrAC; g/210 liters) via infrared absorption and exhalation flow rate (l/min) are sampled at 4 Hz throughout the exhalation (i.e., time series data). At the completion of the breath test, an attached printer generates a breath test ticket that contains the end-expired BrAC and total exhaled volume for each breath sample. The time series data are stored and maintained electronically by the Washington State Patrol.

For each subject, police reports from the jurisdiction charging the alcohol-related offense and the time series data from the Washington State Patrol were obtained through public records requests. The police report provided demographic information (i.e., age, height, race, and sex) and the breath test ticket. The time series data containing BrAC and exhaled flow rate at quarter-second intervals were transformed to generate plots of BrAC versus exhaled volume (i.e., BrAC profiles). To do this, flow rate was numerically integrated to exhaled volume at each quarter-second time point. Exhaled volume was paired to BrAC at the corresponding time point to create BrAC profiles. Relative changes in BrAC as a function of exhaled volume were calculated using the BrAC profile.

Predicted vital capacity. For each individual, vital capacity (VC) was predicted using individual demographic data and correlations recommended by American Thoracic Society guidelines (1). Predicted volumes have a ±20% uncertainty due to variations in human anatomy. We used data of Crapo et al. (9) for white males, Crapo et al. (9) for white females, Rossiter and Weil (20) for black males, and Johannsen and Erasmus (17) for black females.

Statistics. Results are expressed as means ± SD unless otherwise stated. Correlations between changes in BrAC and total exhaled volume were evaluated using linear regression and the corresponding Pearson's correlation coefficient. A one-tailed z-test was performed to determine whether the average difference in exhaled volumes was different from zero. Statistical significance was set at $P < 0.05$.

RESULTS

All ABTs were performed on 30 different Alcotest 9510s for law enforcement between February 2015 and April 2018 in 20 jurisdictions (4 municipalities and 16 counties) across the state of Washington. One-hundred fifteen alcohol breath tests consisting of two acceptable breath samples (n = 230) were evaluated. All breath samples were considered to be valid for legal purposes. Subjects were largely male (n = 88, 76%) and white (n = 108, 93%). The population had an average age of 38 ± 14.4 yr (range: 18–73 yr), an average height of 1.75 ± 0.08 m [69 ± 3.3 in; range: 1.50–1.93 m (59–76 in.)], and an average predicted vital capacity of 4.85 ± 0.83 liters [range: 2.7–6.4 liters].

For each breath sample, the exhaled volume as reported on the breath test ticket was normalized by the predicted VC for the subject. For the 230 breath samples (115 ABTs), the distribution of relative volumes exhaled for each valid breath sample was plotted in Fig. 1. The average normalized exhaled volume was 53 ± 16% of predicted VC, with a range of

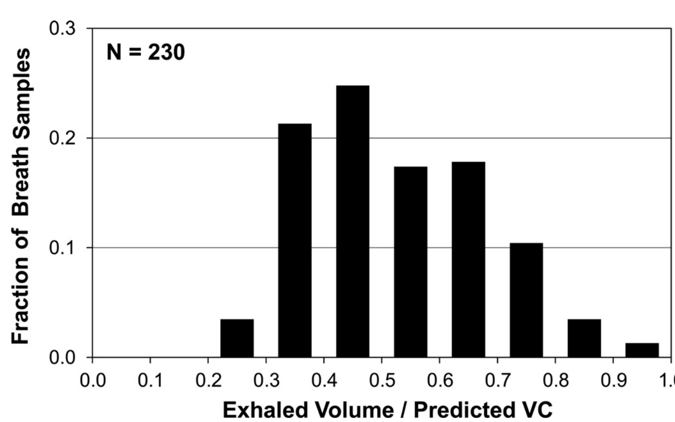

Fig. 1. Distribution of exhaled breath volume normalized by predicted vital capacity (VC). Data taken from 115 subjects providing duplicate breath samples for an alcohol breath test.

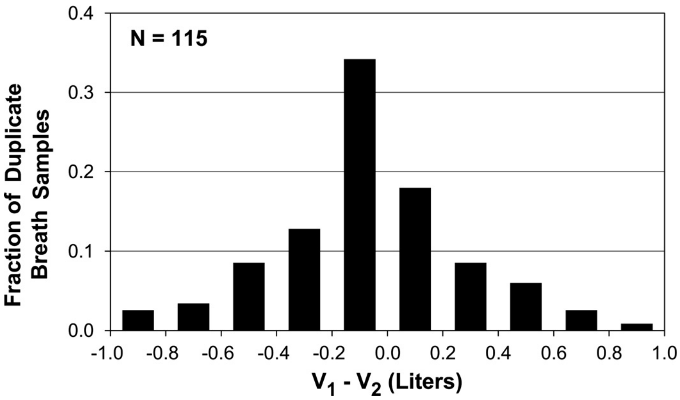

Fig. 2. Distribution in exhaled volume changes between sequential breath tests. Data are taken from 115 subjects providing duplicate breath samples for an alcohol breath test.

25–97%. One hundred eighty-seven (81% of total no. of breath samples) of the expired volumes fell within the range of 30–70% of predicted VC. Eight percent of the subjects provided at least one sample where the exhaled volume was within 20% of the subject's predicted VC (i.e., normalized exhaled volume ≥80%). Thus, 8%[2] of the subject expired volumes may not have been different from true VC.

The difference in volume between *breath sample 1* and *breath sample 2* was calculated. The fraction of subjects with a given difference in volume is shown in Fig. 2. On average, *breath sample 1* was smaller in volume than *breath sample 2* by 0.04 ± 0.37 liters, with a range of −1.3 to 0.9 liters. The average change in breath sample volume was not different from zero ($P = 0.894$).

The percent difference in exhaled volume (on an absolute scale) between paired breath tests was plotted against average normalized volume (Fig. 3). Eighty-one percent of the paired tests had expired volumes within 10% of each other. The difference in breath volumes was not dependent on the amount of volume exhaled.

Per the ABT requirements, the minimum exhaled breath volume to achieve an acceptable sample is 1.5 liters. Therefore, the breath sample can be obtained anywhere between an expired volume of 1.5 liters and an exhaled volume equal to VC. The VC for healthy adults ranges from ~2 to 7 liters (1). Figure 1 suggests that most subjects exhale much less than the predicted VC, and the Alcotest 9510 will accept the breath sample whenever the subject stops exhaling beyond the minimum volume.

Continued exhalation after 1.5 liters causes BrAC to increase because of ongoing ethanol exchange in the lung airways. BrAC profiles were analyzed to further understand the relationship between BrAC and exhaled air volume. The percent change in BrAC at the end of exhalation relative to BrAC at 1.5 liters of exhalation was calculated for 220 BrAC profiles. For 10 breath samples, either BrAC profile data were unavailable ($n = 5$) or exhaled volume was equal to 1.5 liters ($n = 5$). A sample calculation for a single breath sample is shown in Fig. 4. The percent increase in BrAC between the minimum volume and end of exhalation (%ΔBrAC) increased with end-expired volume (Fig. 5). A best-fit line with a prescribed volume intercept of 1.5 liters showed a strong linear relationship ($r^2 = 0.79$).

The slope of the BrAC profile between the end-expired volume and V = 1.5 liters was calculated as a percent change in BrAC per liter of air (Fig. 4). For these 220 breath samples, the average percent change in BrAC per liter of exhaled air was 9.2 ± 2.8%/liter (range: 0.0–19.0). A similar analysis was performed using 1.1 liters as the minimum volume requirement, the minimum volume requirement for other breath testing devices. For 225 breath samples using a minimum volume of 1.1 liters, the average percent change in BrAC per liter of exhaled air was 10.3 ± 3.1%/liter (range: 2.7–25.2).

The BrAC printed on the breath test ticket ($BrAC_T$) is the value used for legal purposes. The maximum breath alcohol concentration from the BrAC profile ($BrAC_P$) was the final value, end-expired BrAC. The two values should be equal. The difference between $BrAC_T$ and $BrAC_P$ was calculated ($\Delta BrAC_{T\text{-}P}$) for each breath sample ($n = 223$) and plotted against $BrAC_T$ (Fig. 6). For 92% of these BrAC pairs, breath ticket BrAC was larger than the final BrAC of the BrAC profile (i.e., $\Delta BrAC_{T\text{-}P} > 0$). This difference increased with $BrAC_T$.

DISCUSSION

All data used within this study were publically available and could be used by the state of Washington to prosecute individuals for alcohol-related offenses. Within this evidentiary data were ABTs consisting of exhaled breath volumes and BrACs. For each subject's ABT, we examined the fraction of available lung air used to provide a breath sample and the change in exhaled air volume between breath samples. Additionally, sensitivity of BrAC to exhaled air volume was quantified.

These data indicate that a full and complete exhalation was not typical. Subjects exhaled ~50% of their available lung air (i.e., predicted VC), with 81% of the subjects exhaling between 30 and 70% of their predicted VC (Fig. 1). If lung disease was present, predicted VC might have been overestimated. Subjects unable to quickly reach the minimum flow rate will have a reported exhaled volume that is smaller than the true exhaled volume. For these cases, the true fraction of VC exhaled will be greater than that reported here. For a given subject, the amount

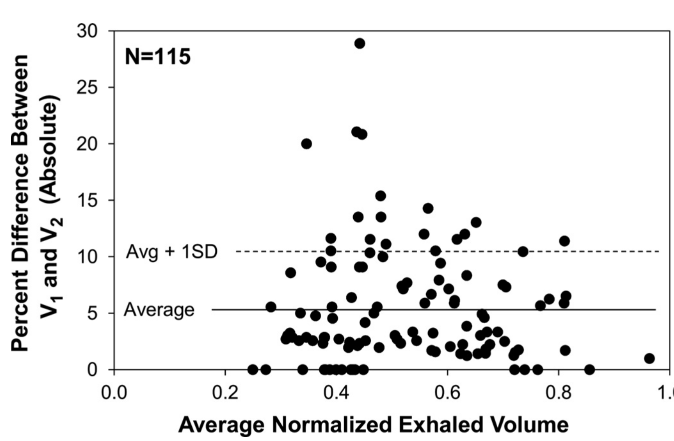

Fig. 3. %Difference in exhaled volume for paired breath tests plotted as absolute values and against the average normalized volume for the breath test pairs.

[2] The percentage calculated does not account for the uncertainty of predicting VC.

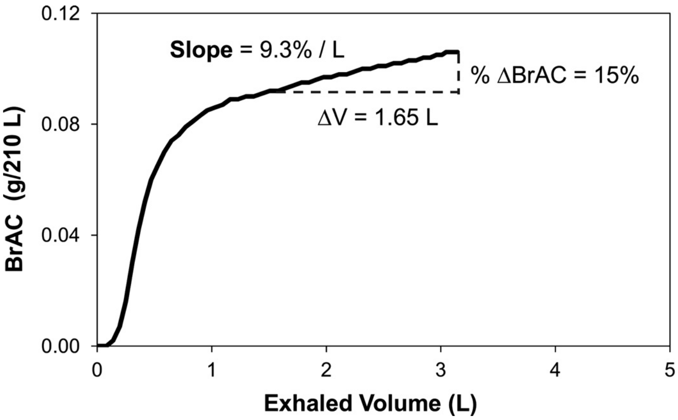

Fig. 4. Breath alcohol concentration (BrAC) plotted against expired volume for a single exhalation into an Alcotest 9510. Exhaled volume is determined by numerical integration of the flow signal. The dashed lines illustrate the calculation of relative slope between 1.5 liters of exhalation and end of exhalation.

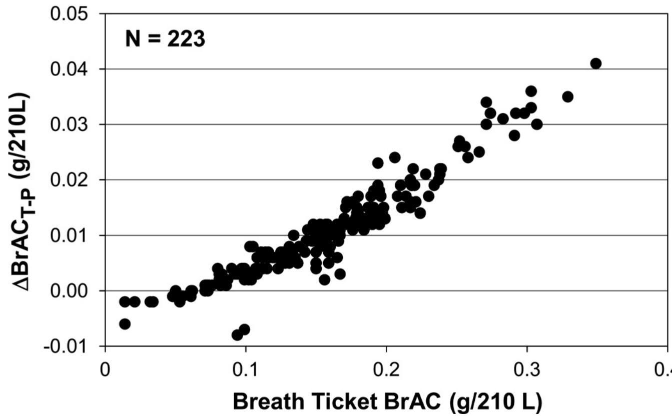

Fig. 6. Difference ($\Delta BrAC_{T\text{-}P}$) between breath alcohol concentration (BrAC) as printed on the breath test ticket and BrAC at the end of the BrAC profile (i.e., end-expired BrAC). $\Delta BrAC_{T\text{-}P} > 0$ for 92% of the BrAC pairs and increased with the reported $BrAC_T$ (breath test ticket).

of exhaled air volume depends on VC primarily and effort secondarily. The amount of air available in the lungs for exhalation depends on the amount of air inspired. If a small amount of air is inspired, then less air is available for expiration. A full, complete exhalation requires a maximal inhalation. Normally, these maximal efforts are not performed due to the extreme effort required and lack of adequate coaching for both maximum inhalation and maximum exhalation. A larger inspired air volume requires more work by the inspiratory muscles. Similarly, expiration to below functional residual capacity requires work by different respiratory muscles. More expired air volume requires more work by the expiratory muscles. The relative amount of respiratory effort used by any subject varies, depending on a number of factors, including instructions provided by the administering person, perceptions of the subject, potential physical limitations of the subject, the presence of lung disease in the subject, level of intoxication, and other environmental factors.

Figure 3 shows the absolute difference between two breath volumes versus the normalized expired volume. The average exhaled volumes varied between 28% VC and 96% predicted VC (Fig. 3). Eighty-one percent of the subjects exhaled breath volumes that were within 10% of each other whether they were large or small exhaled volumes. Therefore, subjects make similar efforts for each of the two tests, which increases the probability of having two BrACs that are within ±10% of the mean BrAC, a requirement for breath test acceptability in the state of Washington. In addition, exhaled air volumes for the second exhalation may be influenced by the breath test operator. Officers are encouraged to achieve similar exhaled air volumes between subject breath samples (25). To assist with this goal, the screen on the Alcotest 9510 provides a blue bar graph indicating the cumulative exhaled volume, with a line indicating the minimum breath volume criteria (10). During delivery of the second breath sample, the total exhaled volume of the first sample is displayed in gray under the blue exhaled volume bar graph. This feedback allows the officer to encourage subjects to exhale so that the second volume matches the first. Thus, the two breath test measurements are not completely independent measurements of BrAC.

BrAC never leveled off during exhalation for any of the ABTs evaluated. For all 220 BrAC profiles, BrAC increased with exhaled air volume (Figs. 4 and 5). This finding is consistent with the understanding that ethanol, a highly blood-soluble gas, exchanges almost completely within the conducting airways of the lung (3, 7, 12). However, many forensic scientists believe that alcohol exchanges predominately in the alveoli because they rely on plots of BrAC against time. They interpret a leveling off of BrAC near the end of exhalation as an indication that alveolar air is present at the mouth. The leveling off will always occur and is simply an indication that exhalation has stopped. When both BrAC and expired flow are plotted against time, the leveling off of BrAC will always coincide with the end of expiration (after correcting for any time lags in the analysis).

Because BrAC increases with exhaled air volume, the measured BrAC can vary up to ~40%, depending on the subject's VC[3] (16, 19). This variation is bounded on the lower end by the minimum volume required to obtain a breath sample = 1.5

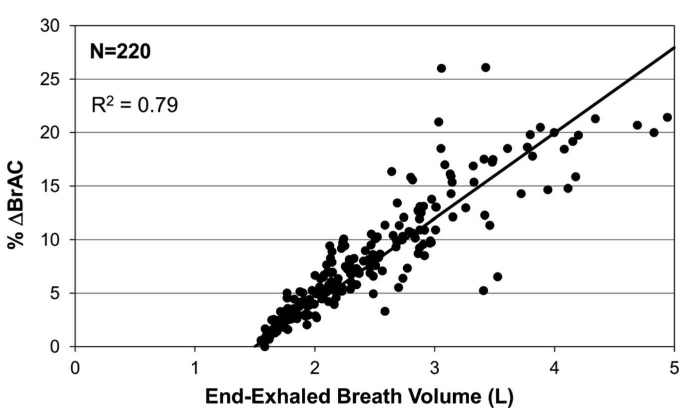

Fig. 5. %Change in breath alcohol concentration (BrAC) between the minimum (V = 1.5 liters) volume and end-expired volume increased with end-expired breath volume. A best-fit line shows a strong relationship between factors ($r^2 = 0.79$).

[3] A subject with a smaller lung volume, say 2.5 liters, must expire a larger percentage of lung volume to satisfy the minimum expired volume requirement. So, there is less relative change in BrAC in the remaining expired volume.

liters and on the upper end by the subject's VC. The percent increase in BrAC as a function of exhaled volume was found to be 9.2 ± 2.6% of BrAC per liter of exhaled air. This rate of increase is similar to that found from experimental and mathematical modeling (3, 12). The variation in the calculated slope was affected by breath samples with smaller exhaled air volumes. In subjects who exhaled <110% of the minimum volume (= 1.65 liters), the BrAC slope had twice the variation (SD = 5.1%/liter) as that found across the population. Of note, the two breath samples with a slope of 0.0 had exhaled air volumes of 1.58 liters. The BrAC slope was not a function of predicted VC. The lack of dependence of BrAC slope on VC is separate and does not contradict the biasing effect of lung volume on BrAC, as noted previously (16, 19).

The lack of control of expiratory volume leads to a moderate degree of uncertainty in the BrAC. A subject who exhales 1.6 liters will have a lower BrAC than a subject who exhales a full VC volume of breath. Thus, there is a bias against a cooperative subject who responds to the administering officer's encouragement to "keep blowing, keep blowing... ." The magnitude of the uncertainty is greater for subjects with larger lung volumes compared with subjects with a smaller lung volume (16). But there is a bias against a subject with a smaller lung volume because they must expire further into their available VC to provide a minimal sample volume (16).

Considering the fact that BrAC increases with increasing expired volume and our observation of considerable variation in expired volume among individual subjects, it is essential that breath test manufacturers develop a method to correct for expired volume variation to decrease uncertainty resulting from variation in expired volume. Exhaled breath changes temperature as it loses heat to the airway tissue, increases temperature as it passes through the heated external breath tube, passes through the tubing within the heated breath test instrument, and enters the sample analysis chamber, which is held between 39 and 50°C. Correction of volume to reflect the thermodynamic conditions within the chest [body temperature, pressure, and saturated water vapor (BTPS)] requires knowledge of breath temperature at the location of the flow sensors due to Charles' Law[4]. The differential pressure sensor used to measure exhaled flow rate, which is integrated into exhaled volume, is not calibrated by the state of Washington (26). This lack of calibration and lack of conversion to BTPS adds uncertainty to the measurement of exhaled air volume reported here.

The BrAC presented on the evidentiary ticket ($BrAC_T$) was compared with BrAC based on the BrAC profile ($BrAC_P$) . $BrAC_T$ was greater than $BrAC_P$ for 205 of the 223 breath test pairs (92%). Additionally, the difference increases nonlinearly with $BrAC_T$. Thus, the relative change (i.e., difference as a percent of $BrAC_T$) increases with $BrAC_T$ and appears to asymptote around 10% for $BrAC_T$ >0.3 g/210 liters. It is puzzling why one value should be greater than the other and why the difference should increase with $BrAC_T$. A single Alcotest 9510 measuring a single breath sample created each of the BrAC pairs. It is our understanding that no adjustments are made to correct for any physiological factor such as breath temperature, breathing pattern, or breath volume.

This work also has implications for experiments using single exhalation maneuvers to assess toxic high-solubility gas exposure. The role of airway exchange must be considered, and full vital capacity exhalations are needed for better estimates of true alveolar and blood gas concentrations.

In summary, the volume of air exhaled for an alcohol breath test is important. Subjects typically exhaled ~50% of their predicted VC, with 81% of breath samples ranging between 20 to 70% of predicted VC. On average, duplicate breath samples had similar volumes. However, these volumes are likely not completely independent, because the Alcotest machine provides feedback about exhaled volume, which assists operators and subjects to provide equivalent sample volumes. For all breath samples evaluated, BrAC continually increased as the exhalation progressed and never reached a plateau, an indication of alveolar alcohol concentration. Therefore, BrAC depends on the volume of breath exhaled, a relationship that is consistent with the exchange of alcohol in the airways of the lung. Beyond a minimum expiratory volume, BrAC increased on average at a rate of 9.2 ± 2.8%/liter air exhaled. A person who exhales just beyond the minimum volume required by the breath test will have a markedly lower BrAC compared with a person who exhales a full VC, assuming that both subjects have the same BAC. Because exhaled volume materially impacts the accuracy of an ABT, calibration of the device to measure volume and conversion of the measurement to a fraction of predicted VC is critical. Additional investigation is needed to understand why BrAC on the evidentiary ticket was greater than BrAC from the BrAC profile and why this difference increased with BrAC on the evidentiary ticket for 92% of breath alcohol measurements.

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DISCLOSURES

J. C. Anderson serves as an expert witness regarding alcohol breath testing. The other author has no conflicts of interest, financial or otherwise, to disclose.

AUTHOR CONTRIBUTIONS

M.P.H. conceived and designed research; J.C.A. performed experiments; J.C.A. and M.P.H. analyzed data; J.C.A. and M.P.H. interpreted results of experiments; J.C.A. prepared figures; J.C.A. and M.P.H. drafted manuscript; J.C.A. and M.P.H. edited and revised manuscript; J.C.A. and M.P.H. approved final version of manuscript.

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