Physiological Errors Associated With Alcohol Breath Testing

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Summary

The design of current breath alcohol testers lead to several potential errors owing to normal physiological factors. Breath testing for blood alcohol concentration originated over thirty years ago. At that time understanding of the physiology of the lung was quite primitive. As a result testing procedures contain implicit errors. There are four major sources of error: (1) variability in the normal measured blood-breath alcohol partition ratio which may lead to a potential error of ±30% but individual cases can have even greater error; (2) variability in breathing pattern, because of the interaction of alcohol with the airway surface, can cause an error of as much as ±50%; (3) variation in normal body temperature can cause an error of ±6% and; (4) variation in normal blood hemotocrit can cause an error of ±14%. These errors alone add up to a very high random variability. Since the errors are caused by the normal physiology of the body and are external to the breath testing instrument, every breath tester currently used is subject to large potential error when used to estimate blood alcohol concentration.

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Introduction

Breath testing for blood alcohol concentration (BAC) has achieved an undeserved level of acceptance which has made it the standard for law enforcement around the United States. In most states, a breath alcohol reading of a certain value (usually the equivalent of a blood alcohol concentration of .10 gram per 100 ml of blood) is a presumption of intoxication and may be sufficient to convict on driving while intoxicated charges. In spite of the well-known inter-individual variation in physical performance at given BAC levels, states apply the same BAC criterion to all subjects.

Many studies have pointed to an inherent unreliability in breath testing (18). Over the years there have been unprecedented controversies in the courts because of major differences between the breath test value and the known facts in individual cases. It is now abundantly clear that very little attention has been paid to the physiological requirements of performing accurate alcohol breath tests. For example, by changing the breathing pattern when delivering an alcohol breath sample, it is possible to change the breath test by as much as ±50% from the true blood alcohol concentration.

Breath testers estimate the blood alcohol concentration indirectly. The subject blows (exhales) into a tube. When the subject stops blowing, the analysis instrument usually samples the last portion of the breath that was delivered to the instrument. However, it is now known that the breath alcohol concentration increases continuously during a single exhalation. In fact, a constant breath alcohol concentration is usually never achieved during exhalation. This results in a large uncertainty in the measured blood alcohol concentration. It should be pointed out that since the change in exhaled alcohol concentration is caused by the physiology of the lung, it will affect the accuracy of all breath alcohol testers currently on the market.

In spite of a great amount of care given to the operation and accuracy of the breath testing instrument, errors persist because of physiological factors which prevent any reasonable accuracy in using the breath to estimate BAC. In fact, by changing breathing technique within normally required guidelines, a subject can change the equivalent BAC as measured by the breath from as little as 50% to over 150% of the true BAC. The differences are caused by heating and cooling of the breath which causes changes in alcohol concentration during exhalation. Thus there is a large margin of error associated with breath testing which is unrelated to specific instrument problems. These errors are impossible to avoid in the breath testing instruments currently available. A large number of tests may be reasonably accurate (within 10%) but there are also a large number of individual cases in which errors of greater than 50% occur.

In some instances, sources of error have been identified but have been cast aside as being too small and therefore ignored. Other sources are just now being recognized but their relative magnitudes have not yet been appreciated. The major sources of error in a normal individual are: 1) Partition ratio uncertainty; 2) Breathing pattern, air temperature and humidity; 3)

Body temperature and 4) Hematocrit (blood red cell concentration).

Partition ratio uncertainty

The scientific relationship governing the solution of gases in liquids is Henry's Law which relates the equilibrium concentration of a dissolved gas in a liquid to its concentration in the air above the liquid. The proportionality constant between the liquid and air concentrations in Henry's Law is the partition ratio. Henry's Law (9) is a general scientific principle which relates to dilute solutions of all gases dissolved in liquids, not just to ethyl alcohol in blood. The partition ratio is different for various gases, various liquids, and is strongly temperature dependent.

The partition ratio describes the separation of molecules between air and a liquid. Imagine a closed glass container with an equal amount of some blood and air. If there is also some alcohol in the container, then the partition ratio will determine the distribution of molecules between the blood and the air. Assume for the moment that the partition ratio for the blood in the container is 2000. If there are 2001 alcohol molecules introduced into the container, then 1 molecule will be in the air and 2000 molecules will be in the blood. If the partition ratio were 1000, then of the 2001 molecules, 2 molecules would be in the air and 1999 molecules would be in the blood. The ratio of 1999/2 is approximately 1000. So halving the partition ratio would cause a doubling of the number of molecules in the air. If a measurement were made of the amount of alcohol in the air sample with a partition ratio of 1000, then using an assumed value of 2000 would result in a calculated BAC that is twice the correct value. The error in the breath testing instrument is directly related to the ratio of the assumed partition ratio of 2100 to the actual partition ratio.

It should be stated that the partition ratio term, as applied in breath testing, is a misnomer. The partition ratio defines the distribution at equilibrium of a material (such as alcohol) between two media (such as blood and air). It is a physiochemical property of the substances involved at the interface between the two media. If the alcohol concentration is altered in any way in either the air or the blood as they are being sampled or analyzed, then the partition ratio term should not be applied. In the lungs, the alcohol concentration changes during exhalation (11,16). Nevertheless, the partition ratio term has been applied before to the measurement of breath and blood and I will use it here to avoid confusion.

The uncertainty in the value of the partition ratio of alcohol in blood is due largely to the fact that physiological factors affecting the partition ratio are not controlled during breath testing. The methods for determining partition ratio have varied but most studies have used indirect means in that the breath testing instruments use exhaled air which is compared to blood analyzed with a different instrument. This indirect approach to making such determinations makes the important invalid assumption that alveolar alcohol concentration does not change as the air is being exhaled. Another problem is that two different instruments are used (one for breath and one for blood) which increases the error because of the potential for calibration error in each of the two instruments.

Values for the partition ratio have been published which vary from as low as 832 (2) to as high as 7289 (4). But the majority of values range between 1600 and 3200 (18). This range includes a large fraction of the reported values. An approximate average value has been determined to be 2100. This value has been shown to provide an average relationship between breath samples taken by various instruments and directly measured blood samples. It should be emphasized that these comparison studies are subject to all of the physiological variables listed below which account for the high degree of variability among and within the many different studies. The error seen for individual comparisons is often greater than 40%. If the actual blood partition ratio of a subject is 1600, then the breath test will give an apparent blood alcohol level which is 31% higher than the true BAC. On the other hand, an actual partition ratio of 3200 will result in an apparent BAC which is 34% lower than the true BAC.

The partition ratio for alcohol is difficult to measure directly using blood samples. Almost all of the previously reported studies have measured the partition ratio indirectly using breath samples. A very recent publication by Jones (13) presents an accurate value for the alcohol partition ratio obtained directly using blood samples and an equilibration chamber. The value for partition ratio for normal human blood at 37°C is 1756. The discrepancy between the true value and the indirect average value of 2100 can be explained by the interaction of alcohol with the airways of the lung during exhalation. It is likely that the alcohol concentration in alveolar gas is higher than expected because of the lower true partition ratio (1756). During exhalation, some of this alcohol interacts with the airways. The relative amount of interaction varies depending on the circumstances, which causes the apparent variation in indirectly determined partition ratio.

The error factor in breath testing owing to partition ratio uncertainty is partly because the various published values were obtained from a wide variety of subjects and experimental methods. On one hand, some of the error can be explained by the lack of control of the physiological variables herein discussed. On the other hand, some of the uncertainty can be explained by inter-individual variability. The measurements by Jones (13) show that the inter-individual variability in the partition ratio may be as low as $\pm 4\%$.

Breathing pattern

By far, the most overlooked error in breath testing for alcohol, is the pattern of breathing, both before and during the sample breath. Breath pattern can have a substantial effect on the alcohol concentration in the breath sample. This major error is accentuated by the difference in temperature between the outside air and the alveolar air and can cause the apparent breath test value to be different from the true blood alcohol concentration by more than $\pm 50\%$.

The lung is located within the chest. It is made up of over 300 million small air sacs called alveoli. Outside air comes to the alveoli from the mouth or nose via the airways. The major airway leading to the lungs from the throat is the trachea. The trachea divides into the left and right "mainstem bronchi" which divide further into the "lobar bronchi". This division

goes on 23 times until the alveoli are reached. Surrounding the alveoli are small blood vessels. The thinness (less than 0.001 millimeter) of the membrane separating blood from the air in the lungs allows oxygen and carbon dioxide to exchange between the blood and air. Because of the large number of very small alveoli, there is a very large surface area (70 square meters, about the size of a tennis court) for this gas exchange process. The alveolar region is where alcohol comes from the blood into the air in the lungs. The number of molecules that leave the blood and enter the alveolar air is dependent on the blood alcohol concentration and the partition ratio. In order to calculate the BAC from an alveolar air sample, the partition ratio must be known precisely and the alveolar alcohol concentration must be determined precisely.

It is impossible to sample air directly from the alveoli because of the small size of the airways. Therefore, all breath testers attempt to take a sample from the end of the breath for analysis under the assumption that the concentration of alcohol in the end-exhaled breath is the same as the concentration of alcohol in the air within the alveoli. In other words, it is assumed that nothing happens to the alveolar air sample as it is passing through the airways to the breath tester. However it is known that highly soluble gases (such as alcohol) in the breath interact with the airways during exhalation (11,16,19,23,24).

The theory behind breath testing correctly assumes that the first part of the breath must be discarded. This first part contains air coming from the airways and is called the "dead space" (air which does not participate in gas exchange). It contains very little alcohol. The theory further assumes the the remaining breath has a constant alcohol concentration which is related to the BAC by the partition ratio (Figure 1, dashed line). Moreover, the breath tester takes a sample of air from the end of the breath whenever the subject stops but the volume of breath exhaled is not controlled. Thus another important assumption is made, namely, that the alcohol concentration is the same at any point whenever the subject stops exhaling. In other words, it is assumed that the breath alcohol concentration will be the same irrespective of the exhaled volume as long as the minimum duration of exhalation is achieved. If the breath is analyzed continuously with a device such as a mass spectrometer or infrared absorption analyzer, a different pattern becomes apparent. The concentration of alcohol changes considerably during the breath (1,11,16,25). The portion of the exhaled breath curve shown in Figure 1 which comes from the alveolar portion of the lung is called the alveolar plateau (dashed line). The first part of the breath, after discarding the dead space, has an alcohol concentration much lower than the equivalent BAC. Whereas, the last part of the breath has an alcohol concentration that is much higher than the equivalent BAC (Figure 1, solid line). The last part of the breath can be over 50% above the blood alcohol level because the alveolar plateau has a positive slope. Thus, a breath tester reading of 0.14 g% taken from the last part of the breath may indicate that the blood level is only 0.09 g%. If the subject breathes out only a small volume (but beyond the minimum duration), then the calculated blood alcohol concentration can be substantially lower (<50%) than the true BAC. Thus, there is an error in breath testing of over ±50% because exhaled breath volume is not controlled by breath testing instruments.

This overestimate by taking the very last part of the breath for analysis is caused by the cooler temperature of the room air. As the subject breathes in, the process of warming and humidification of air cools the airways (20). Then while breathing out, some of the alcohol in the air coming from the warm lung condenses onto the airway surface (Figure 2). This is the same process that occurs when anyone breathes onto a cold window—it fogs up. So the first part of the lung air has a lower alcohol concentration because some is deposited on the airways. As the subject continues to breathe out, the airways warm up causing some of the alcohol in the airway surface to evaporate. This same process occurs as the window with the fog is warmed up—the condensed water evaporates. The later part of the breath receives additional alcohol while it is passing through the airways increasing the amount of alcohol above the amount present in the deep lung air. If dry air is inspired, the additional humidification required cools the airway further resulting in an even lower breath alcohol concentration. Because of this mechanism, breathing air of different temperature and humidity will alter the breath alcohol concentration by over 10% (14).

A further change can be caused by the breathing pattern immediately before the sample breath. Hyperventilation (deep breathing) for 20 seconds prior to delivering a sample breath to the breath tester causes a 11% reduction in breath alcohol concentration (15). By breath-holding for 30 seconds prior to exhalation, the breath alcohol concentration increases by 16% (15). These effects are caused by the cooling or warming of the airways.

Body temperature

There is a normal variation in body temperature from one individual to the next which influences the partition ratio for alcohol in blood and causes as much as ±6.5% error due to uncertainty in body temperature.

The partition ratio for a gas (such as alcohol) is determined by the physical properties of the gas, the nature of the liquid in which it is dissolved and the equilibrium temperature. As the temperature increases, there is an increased tendency for the gas molecules to leave the liquid. The result is a decreased partition ratio. As the partition ratio decreases, more of the gas molecules will be present in the exhaled air for a given BAC and the apparent breath test value will be higher than the actual BAC.

The average body temperature for humans is 98.6 degrees Fahrenheit (F), which is the same as 37 degrees Centigrade (C). Half of the normal population has a higher temperature and half are lower. The temperature of any individual may vary by as much as 1°C above or below the normal mean value of 37°C or 1.8°F from the mean value of 98.6°F. Moreover, the temperature of any person varies from time to time during the day by as much as 1°C. The temperature effect on blood alcohol partition ratio has been measured by a few investigators (8,13) who agree that the partition ratio decreases by 6.5% for each 1°C increase in temperature. So, given the normal variation in

body temperature, there is a normal error range of ±6.5% due to uncertainty in normal body temperature.

Certain factors can elevate body temperature above the normal range. Many diseases (such as influenza) can cause fever. In addition, physical trauma (such as a traffic accident) can elevate body temperature. An increase of body temperature by 3°C to 40°C or 104°F will result in breath test value which is erroneously high by 19.5%.

Hematocrit

Changes in hematocrit (blood cell concentration) have an effect of the alcohol partition ratio and cause as much as ±14% error in the apparent blood alcohol concentration.

Hematocrit is a term describing normal blood. Blood is a mixture of cells, mostly red cells but also some white cells and platelets. These cells are contained in a watery solution called plasma. The hematocrit describes the relative volume of blood made up of cells. The average hematocrit in a male is 0.47 (29), but this value varies from 0.42 to 0.52 (±2 standard deviations, SD). Females have a slightly lower hematocrit with a mean value of .42 and a range of .37 to .47 (±2 SD). This broad range of hematocrit exists even in normal individuals. In addition, there are various types of diseases which can cause an increase or decrease in hematocrit.

The red blood cells (erythrocytes) are densely packed with hemoglobin, a protein which carries oxygen and gives blood its red color. There is less room for water within the red cell. Therefore, red cells can hold less alcohol. In any blood sample with alcohol, the alcohol concentration within the red cells is lower than the alcohol concentration in plasma. An increase in hematocrit will result in a decrease in the blood-air partition ratio. This would result in a greater concentration of alcohol in the alveolar air for a given BAC. According to Frajola (5), and Payne et al (21), the normal variation in hematocrit can result in an error in the breath test reading of as much as 14% (±2 SD). However, Jones (13) showed plasma alcohol partition ratio of 2022 at 37°C and a whole blood (Hct = .45) alcohol partition ratio of 1756 at 37°C. A calculation with these numbers shows a normal hematocrit variation of ±2.6% (±2 SD).

Respiratory Diseases

If the subject has some degree of respiratory disease, there may be even greater error due to the airway interaction problem. Both obstructive (difficult to blow out) and restrictive (small lungs) respiratory diseases, in general, contribute to a worsened distribution of ventilation (air flow) in the lung. The matching of air flow rate (V) to blood flow rate (Q) in the lung is altered by disease (10,12) and the emptying of air from different regions of the lung becomes more and more irregular resulting in a changing gas concentration during exhalation (3). Some important diseases affecting the air flow pattern include asthma, chronic bronchitis, emphysema, asbestosis, silicosis; to name a few.

Most of the respiratory diseases cause an alteration of the matching of air flow to blood flow (called V_A/Q distribution). The worsened matching of V_A/Q will have a minimal effect on the slope (the change in breath alcohol concentration per unit of exhaled breath volume) of the alcohol alveolar plateau because the alcohol partition ratio is so much higher than the normal range of ventilation to blood flow ratio in the normal lung (10). However, if there are a significant number of regions with a high ventilation and/or low blood flow created with the disease process, there may be a significant difference in alveolar alcohol concentration among different alveoli (10). With the normal sequencing of exhalation from different regions (28), there will be an increased change in alcohol concentration during exhalation and an increased error caused by taking a sample from the end of the breath (11). However the changing alcohol concentration is not primarily caused by V_A/Q distribution as reported by Russell and Jones (25), but is in large part due to the interaction of alcohol with the airways.

Another factor causing the increased change in alcohol concentration in disease is the worsened distribution of sequencing of exhalation of different lung regions. Even in the normal individual, it has been shown that the respiratory dead space contributes to later stages of exhalation (27). In respiratory disease, this sequencing is worsened (17), causing an increased change in alcohol concentration. There is also an increased likelihood of air-airway interaction because of the increased mucous production often associated with obstructive lung disease.

Conclusion

Breath testing, as currently used, is a very inaccurate method for measuring BAC. Even if the breath testing instrument is working perfectly, the physiological variables listed herein prevent any reasonable accuracy. The physiology of the lung causes large errors of greater than ±50% when using the breath to measure blood alcohol concentration because key factors such as body temperature, hematocrit, exhaled breath volume, inspired air temperature and humidity are not measured during the test. Breath testing for alcohol using a single breath method should not be used for scientific, medical or legal purposes where accuracy is important.

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