

THE ALCOHOL BREATH TEST – A PARADIGM SHIFT

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Over the years, breath testing has become a widely used method for quantitative determination of the level of intoxication of individuals suspected of driving while under the influence of alcohol. After recognition of the need for quantitative assessment of intoxication, blood alcohol concentration was considered as the single most important variable. However concern about the invasiveness requirements of drawing a blood sample led to the development of the breath test as a non-invasive means of assessing level of intoxication. The breath test is an indirect test, but has been considered to be a good estimate of the blood alcohol concentration because of the assumption that an end-exhaled breath sample accurately reflects the alveolar (or deep-lung) air which is in equilibrium with the blood. In spite of the great deal of effort that has gone into the studies attempting to validate the breath test, forensic scientists and toxicologists still have a very limited understanding of the breath alcohol test and its limitations.

ANATOMY OF THE LUNGS

The lungs are located within the chest. This organ allows inspired air to come into close proximity with the blood so gases (such as oxygen and carbon dioxide) can exchange between the air and the blood. The lung 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" (going to the left and right lungs) which divide further into the "lobar bronchi". This division goes on about 23 times until the alveoli are reached. Actually, some alveoli begin to appear at about the 17th generation airways. Surrounding each alveolus 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 readily between the blood and air. Because of the large number of very small alveoli, there is a very large surface area (70 square meters) for this gas exchange process. For more details regarding the basics of lung physiology, see Hlastala and Berger.

SCIENTIFIC REVOLUTION

The evolution of scientific understanding depends on the continuous development of new ideas that form the bases for experimentation. This concept has been termed "scientific revolution" by Kuhn [Kuhn, 1970 #119], who sees science as the shift from one paradigm to another (Figure 1). The term, "paradigm" refers to a set of universally recognized scientific achievements that for a time provide a

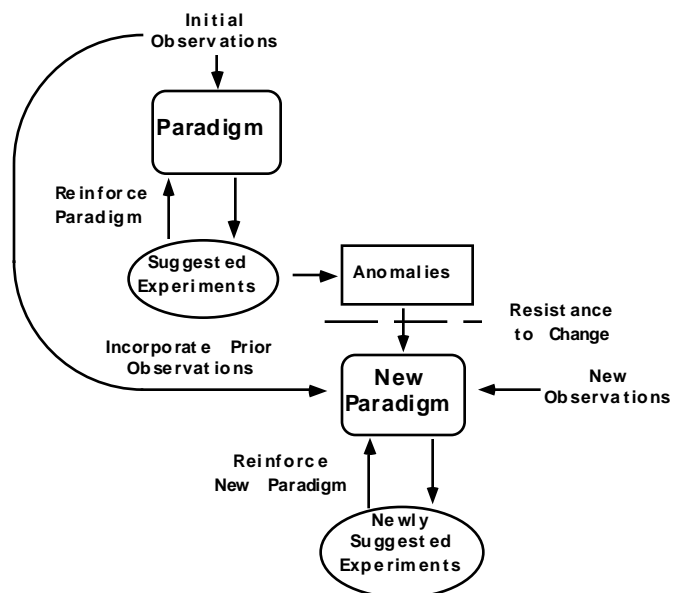


Figure 1. Kuhn's model of scientific revolution.

model or conceptual framework for a phenomenon. This paradigm represents the core principles that define the scientific understanding.

A paradigm is established after a number of initial observations are obtained. Experiments are then carried out to test hypotheses related to the paradigm. Usually, these experiments provide data that reinforce the paradigm. Occasionally, these experiments result in anomalies, or results that do not fit within the framework of the original paradigm, and are inconsistent with the predictions of the paradigm.

The accumulation of anomalies leads the scientist to develop a new paradigm which provides a new framework for interpreting experimental results which accounts for the anomalies of the old paradigm as well as new observations. At that point, the new paradigm undergoes scrutiny through newly suggested experiments that provide data to reinforce the new paradigm. The new paradigm must account for the new observations as well as the prior observations. The transition from the old paradigm anomalies to the new paradigm always encounters enormous resistance to change. This resistance is crucial for this scientific progress to occur.

Eventually, it is likely that another set of anomalies with the new paradigm will lead to yet a third paradigm. This will occur as new technologies reveal new anomalies. Kuhn, a physicist turned philosopher, cites a number of paradigms that have evolved in his field in the form of scientific revolutions: Copernican astronomy, Newtonian physics, the wave theory of light, and quantum physics. These same ideas apply to different fields in very different scales. The concept of the paradigm can also be applied to the Alcohol Breath Test.

THE OLD PARADIGM

Development of the single breath test for alcohol (3, 10) took place in the early 1950's when the field of respiratory physiology was just beginning. At that time, it was generally understood that the first air exhaled from the lungs contained air from the airways and had little "alveolar air". It was thought that further exhalation would result in exhalation of air from the alveoli containing gas in equilibrium with pulmonary capillary blood (Figure 2). These concepts were held in the respiratory physiology community [Fowler, 1948 #108][Rahn, 1946 #130] and followed from data obtained with low solubility gases, such as nitrogen. Without the advantage of having present-day analytical equipment, the profile of exhaled alcohol could not be measured, but was expected to be identical to nitrogen (after a single breath of oxygen) and to appear as shown in Figure 3. The first part of the exhaled air was thought to come from the airways and was called the anatomic dead space and the later part of the exhaled air (with higher gas concentration) was thought to come from the alveolar regions. This later part of the exhaled gas profile was termed the alveolar plateau [Fowler, 1948

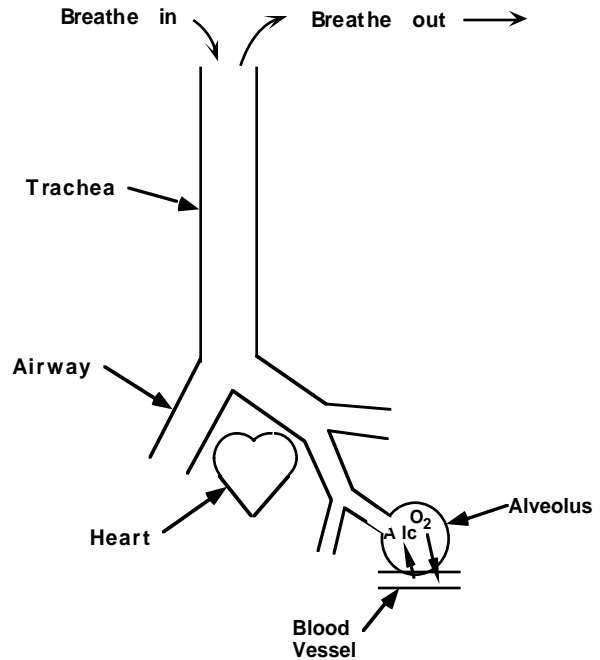


Figure 2. Old paradigm of alcohol exchange in the lung.

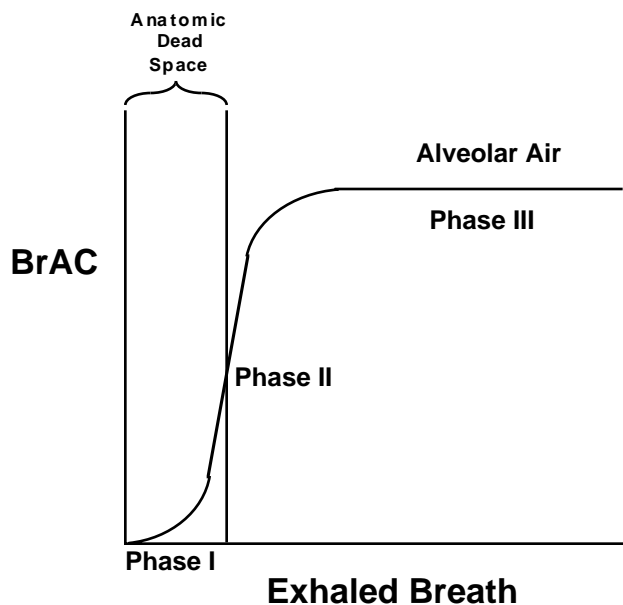


Figure 3. Assumed exhaled alcohol profile in the 1950's.

#108][Rahn, 1946 #130]. With a presumed flat exhaled alcohol profile, it was thought that end-exhaled alcohol concentration would be independent of exhaled volume after exhalation beyond anatomic dead space volume. It was further assumed that alveolar alcohol concentration was precisely related to the arterial blood alcohol concentration by virtue of the physical-chemical relationship known as the partition coefficient [Henry, 1803 #131]. The implicit assumption was that the alcohol concentration remained unchanged as alveolar air passed through the airways. Viewed through the limited perspective of respiratory physiology of the 1940's, the breath alcohol test seemed to be reasonable in principle and further development as a non-invasive measure of blood alcohol concentration was justifiable.

ANOMALIES

Since 1950, many studies have been performed to quantify the relationship between breath alcohol concentration (BrAC) and blood alcohol concentration (BAC) with the goal of defining a precise relationship between the two for accurate non-invasive determination of BAC. These studies, undertaken to validate the use of breath tests by comparing BrAC and BAC in normal subjects, have shown a surprising amount of variability (cf; [Emerson, 1980 #106][Jones, 1978 #115][Mason, 1976 #120] which has not been improved ([Simpson, 1987 #125][Simpson, 1987 #126]) in spite of advances in instrument technology. The physiology of lungs and of the body as a whole remains as the primary explanation for this variability ([Hlastala, 1985 #112][Jones, 1990 #118]).

The alcohol breath test is a single exhalation maneuver. The subject is asked to inhale (preferably a full inhalation to total lung capacity, TLC) and then exhale (preferably a full exhalation to residual volume, RV) into the breath testing instrument. Very few restrictions (i.e., exhaled volume, exhaled flow rate, inhaled volume, pre-test breathing pattern, air temperature, etc.) are placed on the breathing maneuver. The constraints applied vary among the different breath testing instruments and among the operators

administering the test, and the level of cooperation varies among subjects, resulting in substantial uncontrolled variation in the precise maneuver used for the breath test.

The lungs have a relatively simple, but non-uniform, anatomical structure. The airways are a branching, tree-like arrangement of tubes. Inspired air moves through progressively shorter, narrower and more numerous airways [Weibel, 1963 #8]. These airways are lined with mucus at a temperature varying between approximately 34°C at the mouth and 37°C in the very smallest airways. However, this temperature range varies depending on the breathing pattern [McFadden, 1983 #1]. The membranes separating the air in the alveoli and the blood in the capillaries are so thin that inert gases such as alcohol equilibrate between blood and air very rapidly [Wagner, 1977 #162]. With exhalation, air within the alveoli is conducted along the airways to the mouth.

During inspiration, air is heated and humidified as it passes through the upper airways (25, 36). Some water within the mucous layer or watery sub-mucous layer will vaporize and heat stored in the airways will be picked up by the inspired gas and taken to the alveoli (16, 30, 36). During exhalation, the process reverses; fully humidified air at core body temperature is cooled by the cooler airway mucosa and water vapor condenses on the mucosa. This water and heat exchange process is vital because it conditions the inspired air to avoid damaging the delicate alveolar cells while conserving water and heat from major loss in the exhaled air. Under normal environmental conditions, exhaled gas has less heat and less water vapor than does alveolar air.

The dynamics of soluble gas exchange are similar to the dynamics of heat and water exchange. These processes are analyzed using analogous equations (2). The fact that respired air exchanges heat and water with the airways implies similar soluble gas exchange processes (15). This interaction of soluble gases with airway mucosa is well documented (1, 4, 5, 32). The degree of interaction is directly related to the solubility of the gas in the airway mucosa and mucous lining (1, 32). The very high solubility of alcohol in water guarantees its strong interaction with airway tissue. Because this interaction depends on temperature and airflow characteristics, variations in tidal volume

and frequency can have a substantial effect on the alcohol concentration in the breath sample (20, 37). This variation is affected by the difference in temperature between the outside air and the alveolar air (18).

The exchanges of heat and of gas with the airways are complex and interactive processes. The relative significance of this exchange depends on the effective solubility of the gas in the mucosa. For the respiratory gases, oxygen and carbon dioxide, airway tissue solubility is small. For both water and alcohol airway solubility is quite large. Moreover, the exchange processes are interactive. During inspiration, heat, water and alcohol are transported from the mucosa to the air. The exchange of heat cools the mucosa causing an increase in its alcohol solubility and, hence, a decrease in the partial pressure of alcohol in the mucosa and a reduction in alcohol flux into the airway lumen. These various processes have been integrated into a mathematical model developed by Tsu et al (37) and further refined by George et al (8) which shows that during normal breathing, the inspired air is equilibrated with alcohol, picking it up from the airways, before reaching the seventeenth generation airways (start of the alveolar region). Upon reaching the alveoli a small amount of additional alcohol is picked up because the solubility of alcohol in blood is lower than the solubility of alcohol in water (21). The equilibrium partial pressure of alcohol in vapor above blood is greater than in vapor above water at the same temperature. With exhalation, the excess alcohol picked up in the alveoli is rapidly lost to the airways within the sixteenth or fifteenth generation. Along the airway, more alcohol is lost to the airways. The alcohol that arrives at the mouth comes essentially from the airways and not from the alveoli. This is also the case for water vapor. The humidification of inspired air is performed by the airways.

The flux of alcohol from the mucus surface into the air (positive values) during inspiration and the flux of alcohol from the air to the mucus surface (negative values) during expiration is demonstrated in Figure 4. This figure was calculated using a mathematical model of the human airway structure (8). During inspiration, alcohol is taken up into the inspired air immediately at the mouth. The greatest alcohol uptake occurs in the trachea and generations 6 through 13. During expiration, the redeposition

of alcohol occurs primarily at these same airway generations. The important conclusion from this work is that all of the alcohol that comes out of the mouth in the breath comes from the airway surfaces rather than from the alveolar regions.

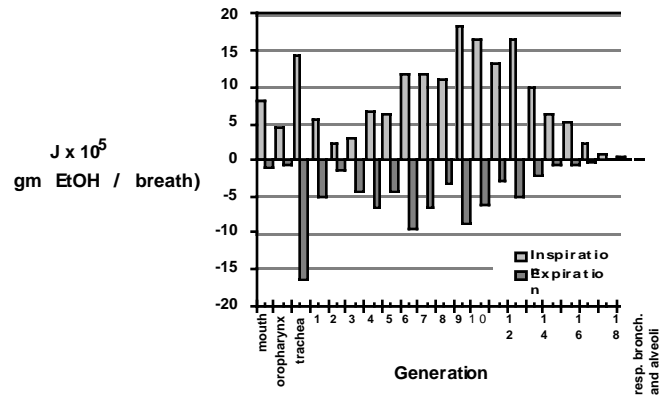


Figure 4. Airway alcohol exchange.

The early basic assumption of the breath alcohol test was that the breath alcohol concentration was the same irrespective of the exhaled volume as long as the dead space volume is exhaled (as shown in Figure 3). However, Jones (20), and others (26, 35) have shown that the breath alcohol concentration depends on exhaled volume. The breath testing instrument takes a sample of air from the end of the breath whenever the subject stops but the volume of breath exhaled is neither controlled nor measured. Therefore, the apparent breath alcohol concentration depends on the volume of air delivered to the breath testing instrument. The last part of the breath can be well above the average single breath alcohol level because the alveolar plateau has a positive slope that is dependent on air temperature (29).

A sloping alveolar plateau for various low solubility gases has been explained by several factors including stratified inhomogeneity (gas phase diffusion limitation) (31), convection-diffusion interaction (27), sequential exhalation from regions with differing \dot{V}_A/\dot{Q} (31) and continuing gas exchange (9). None of these factors contribute substantially to the slope of the exhaled alcohol profile. Continuing gas exchange will contribute to the slope of the exhaled profile for respiratory gases (CO₂ and O₂), but not inert gases (9, 12, 31).

Further variation in BrAC will result from changing the breathing pattern immediately before delivering the sample breath. Hyperventilation for 20 seconds prior to delivering a sample breath to the breath tester causes an 11% reduction in BrAC (19). Three deep

breaths prior to the sample breath reduces BrAC by 4% (26). After breath-holding for 15 seconds prior to exhalation, the BrAC increases by 12% (for a minimum exhalation) and 6% (for a maximum exhalation) (26). A 30 second breathhold prior to exhalation increases BrAC by 16% (19). These effects are caused by the respective cooling or warming of the airways and the data further support the airway surface interaction of alcohol as the mechanism causing the changing alcohol concentration during exhalation.

THE NEW PARADIGM

The conclusions of the above studies are that alcohol leaves the lungs by diffusing from the bronchial circulation through the airway tissue where it is picked up by the inspired air (Figure 5). By the time it reaches the alveoli, it has picked-up as much alcohol as is possible. Therefore, no additional alcohol can be picked up in the alveoli. On exhalation, some of the alcohol is redeposited on the airway surfaces. All of the alcohol exhaled at the mouth comes from the airway surface via the bronchial circulation. No alcohol originates from the pulmonary circulation in the alveoli. The fact that alcohol comes primarily from the airways is why the breath alcohol concentration can be so easily changed by changing the breathing pattern. This contributes to the very large variation in the alcohol breath test readings obtained from actual subjects.

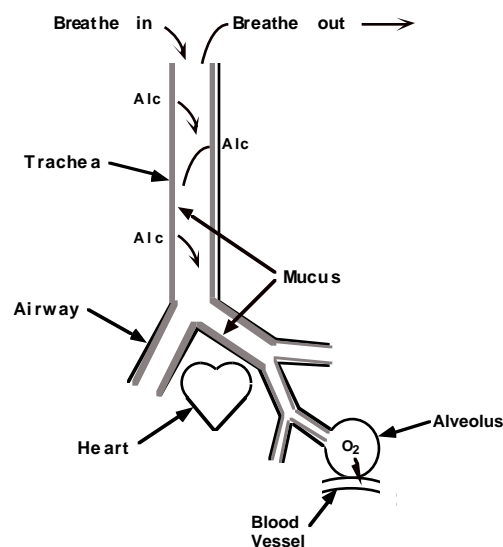


Figure 5. New paradigm of alcohol exchange.

BREATH ALCOHOL CONCENTRATION

In many states, it is illegal to drive a motor vehicle with a breath alcohol concentration of 0.08 gm/210 liters or more. Have you ever considered what is meant by "breath"? What is the breath and to what part of the breath is the statute referring? Webster's New

World Dictionary has several definitions of breath, but the most relevant is "air taken into the lungs and then let out". Air becomes breath when it goes into the lungs AND is exhaled from the lungs. The only air that fulfills that criteria is the air that is exhaled from the mouth or nose. Any air within the lungs is not breath. Only that which is exhaled can be considered as breath.

The exhaled alcohol profile is shown in Figure 6. At the beginning of exhalation, the breath has a zero or near zero BrAC. As exhalation progresses, the BrAC increases, initially quite rapidly, but eventually the rate of increase of BrAC slows down. It does not level off until the subject stops exhalation. All of this is "breath". Since the specific portion of the breath that is sought to determine alcohol concentration is not defined, we can only surmise that the average of the breath is meant. The average of the breath would include some initial breath with lower EtOH and some of the later breath with a higher concentration. The average of the breath alcohol will be a value that is near the 5 second point of exhalation (Figure 7). If a subject exhales for five seconds and then stops, the BrAC will be close to the average of the entire breath. Any exhalation beyond this approximate time will result in a value that will be higher than the average BrAC. Therefore the average BrAC is ALWAYS less than the breath test machine reading.

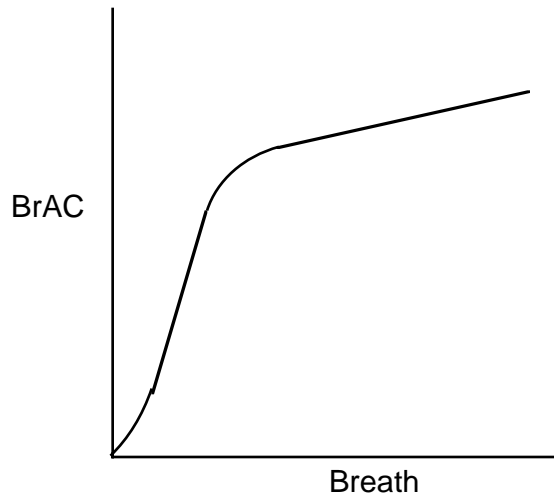


Figure 6. Exhaled breath alcohol profile.

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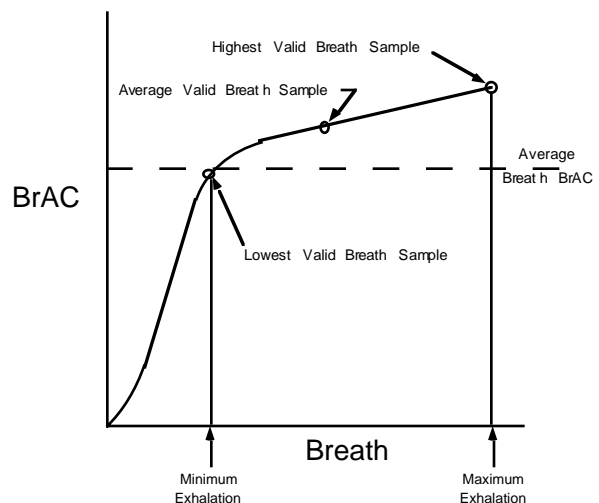


Figure 7. Exhaled breath alcohol profile with valid breath samples identified.

Beware of the over-eager prosecution expert who may say that the part of the breath that the state wants is the "deep-lung air". This is incorrect and must be vigorously opposed. First of all the deep-lung air is not breath (by Webster's definition). The technician will say this because he/she believes (correctly so) that any sample of breath is usually lower than a deep-lung (alveolar) sample. When we had a blood standard (illegal to drive with a BAC of 0.10 mg/dl or more, as measured by the breath), this would be a reasonable argument. However, we now have a breath standard and, therefore, the deep-lung air is not relevant.

BIAS IN THE BREATH ALCOHOL TEST

The initial intent of the legislature was to provide a law that could make it much easier to prosecute by taking away the possibility of defense arguments concerning the variability between BrAC and BAC. In fact, the passage of the "breath per se" law has made it much more difficult for prosecution by virtue of a lack of definition of breath. In fact the average BrAC is actually much lower than any breath alcohol test machine reading. In effect, the legislature has dealt a blow to the prosecution because it is now impossible for the prosecution to prove that the average BrAC is greater than or equal to a given standard, whether it is 0.08 gm/210 L or 0.10 gm/210L.

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