Accuracy and Precision of Breath Alcohol Measurements for Subjects in the Absorptive State

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Published data are analyzed in order to estimate the accuracy of breath-alcohol measurements for subjects during absorption of orally ingested ethanol. Simultaneous measurements of breath alcohol concentration (BrAC) and venous blood alcohol concentration (VBAC) show that actual VBAC can be overestimated by more than 100% for a significant amount of time after drinking stops. The maximum error found for four individual subjects is +230%, +190%, +60%, and +30%. The magnitude of these errors indicates that results from quantitative evidential breath alcohol analyzers are far less accurate for the absorptive state than they are during the postabsorptive state, but the specifications for accuracy and precision given by manufacturers of these instruments do not reflect this. The results also indicate that there is a significant likelihood that subjects will be in the absorptive state when tested under field conditions. I conclude that estimates of BAC based on BrAC measurements are not reliable in the absorptive state and that the uncertainty associated with such estimates should be accounted for, particularly when the results are used in connection with law enforcement.

Additional Keyphrases: forensic medicine, analytical error, instrumental error, blood alcohol concentration

How accurately is the blood alcohol concentration (BAC) in a given subject estimated from measurement of breath alcohol concentration (BrAC) by a typical quantitative evidential breath alcohol analyzer? The answer depends strongly on whether the subject is in the absorptive or postabsorptive state of alcohol distribution, i.e., whether the BAC is increasing or declining. In a recent article, the accuracy and precision of breath analyzer results were estimated for a random subject in the postabsorptive state (1), and it was found that the relative uncertainty in these results is ±15%, ±19%, or ±27%, depending on how it is expressed. These results were based on data in the literature for healthy men in the postabsorptive state under controlled laboratory conditions. Unfortunately, few data have been published regarding the accuracy of BAC estimates from BrAC measurements in the absorptive state, which perhaps reflects the traditional view that the absorptive state has little practical effect on the outcome of breath-testing results. The few data that are available suggest that the magnitude of the error is far greater in the absorptive state than in the postabsorptive state, and that it is far greater than generally appreciated (2, 3). It is the purpose of this article to estimate the amount of error in breath testing results in the absorptive state, and to discuss some of the implications and consequences of this error.

Data in the literature for the absorptive state have been collected and analyzed. Numerical results were estimated from the graphical data of Martin et al. (3), and the estimated uncertainty in these values is about ±10%. Calculations of the standard deviation (SD), coefficient of variation (CV), and the determination of areas under normal error curves were also carried out.

The absorptive state is defined, after Sedman at al. (4), as the period of time from the beginning of alcohol absorption to the intersection of the curves for capillary BAC and venous BAC (VBAC) vs time. The postabsorptive state is defined as the period of time after the intersection of these curves until VBAC decreases to zero. Capillary BAC is that in a sample taken from a finger prick; VBAC is that for a sample from a cubital vein. Where not specified, it is assumed that breath analyzer results are obtained from instruments in which the value 2100:1 is used for the blood-breath ratio. ABAC is arterial BAC and AAC is the BAC result from a quantitative evidential breath alcohol analyzer (AAC = BrAC × 2100).

Measurements of BrAC are commonly converted to BAC by use of the 2100:1 conversion factor (AAC), which is derived from the ratio of the concentration of alcohol in the blood to that in the breath (1, 2, 5). The blood-breath ratio has been measured in many studies (5), although some authors have chosen not to report detailed results for the absorptive state. Data in Table 2 in the article by Jones (2) indicate that the mean, ±SD, CV, and range for the blood-breath ratio, with samples taken 30, 60, and 90 min after the end of drinking, are 1998, ±156, 7.8%, and 990–2404. Calculations based on the graphical data from Figure 1 in the article by Martin et al. (3) yield 1793, ±200, 11%, and 1100–2100, at the same 30-min intervals. However, data collected at 15-min intervals for 90 min after the end of drinking yield 1569, ±400, 25%, and 630–2100.

By calculating areas under these normal error curves it is found that the results of Jones indicate that 75% of his subjects had their actual BAC overestimated by breath test results in the first 90 min after the end of drinking, while the data of Martin et al. indicate that about 90% of their subjects had their actual BAC overestimated. For the first 60 min after drinking stopped, the data of Jones indicate that 80% of his subjects had their actual BAC overestimated, and the results of Schmidt et al. (6) show that about 65% to 80% of their subjects had their actual BACs overestimated.

These results can also be expressed in terms of error,
which is defined as $E = O - A$, where $E$ is the absolute error, $O$ is the observed or measured value, and $A$ is the actual or accepted value; the relative error is given by $(|O - A|/A) \times 100 \, \%$. If an arrested driver chooses a blood test, his or her actual BAC would be determined by measuring venous BAC (VBAC), or in some cases capillary BAC, and the results would be used and accepted as evidence for law enforcement purposes. Then, using the data of Martin et al. (3), O is AAC and A is VBAC. In Figure 2 of Martin et al. (3) results are presented as the difference between AAC and VBAC, which is actually a plot of absolute error vs time. The mean, ±SD, CV, and range of this absolute error for the four subjects in their Figure 1, at 15-min intervals for the first 90 min after the end of drinking, is found to be 0.15 g/L, ±0.1 g/L, 67%, and 0–0.4 g/L. The maximum relative error during the first 90 min for subjects 27, 34, 36, and 6 is found to be +190%, +230%, +30%, and +60%, respectively. For subject 34, relative error in excess of +100% lasted from 5 to 25 min after the end of drinking, as determined from the half-height of the AAC–VBAC curve in their Figure 2, while for subjects 28, 25, and 7, the half-heights of these curves lasted from 5–90, 15–70, and 5–50 min, respectively. The average relative error, for the four subjects in Figure 1, for samples taken at 15-min intervals over the first 90 min, is +60%, +80%, +20%, and +10%, respectively, and the average for all four subjects, expressed as a percentage of the mean peak VBAC, is +15%.

To assess the effects of these errors, it is important to know how long the absorptive state lasts. Dubowski (8) presented six typical curves for BrAC vs time, and in three of the four, the height of the curves constitutes a large fraction of the entire curve. In one curve, it took about 185 min after the end of drinking for the curve to peak; the time required to reach the intersection of capillary and venous BAC curves would be even greater. Tabulated results from Dubowski (8) and Martin et al. (3) show that the absorptive state lasts from 12 to 166 min and from 20 to almost 120 min (peak VBAC), respectively, for fasting subjects. Jones (2, 9) did not consider his fasting subjects to be postabsorptive until 120 min after drinking stopped, while Payne et al. (10) found considerable variation in absorption times in 24 subjects. The results of Forney et al. (11) show a range of 15 to 120 min to reach the peak VBAC for eight subjects who had eaten breakfast within 90 min of the start of testing. Tsukamoto et al. (12), on the other hand, found absorption to be complete within 30 min after the end of drinking for 10 subjects. Forney and Hughes (13) concluded that about 60 min is required for equilibrium to be established, and Widmark (14) reported over 50 years ago that 50–80 min are required for abstraction to be complete in fasting subjects.

**Discussion**

The mean, ±SD, CV, and range from the results of Jones (2) and Martin et al. (3), involving data obtained 30, 60, and 90 min after the end of drinking, are similar. Probably, the difference in the mean values is largely ascribable to the use of capillary blood by Jones and venous blood by Martin et al. While the ranges reported by Jones and those calculated from the results of Martin et al. are substantial, the SDs indicate that only a small part of the sample accounts for these ranges. However, results from Martin et al., based on data obtained at 15-min intervals, yield quite different values for the mean, ±SD, CV, and range as compared with the results for samples collected at 30-min intervals.

If the fraction of subjects having their actual BAC overestimated by AAC results is considered, it is apparent that a substantial proportion of subjects have their actual BAC overestimated in the first 90 min. This is further confirmed by the results expressed as absolute error from the data of Martin et al., for which the CV is 67%. The overestimates of BAC are even more striking if the maximum relative errors of +190%, +230%, +30%, and +60% for individual subjects are considered. Taking the average over 90 min greatly reduces these maximum errors, especially if the data from all four subjects are pooled. The average is usually used, because it is a more reliable indicator of an unknown value than any individual measurement in a set; however, the converse is not true, i.e., the average cannot be used to estimate reliably some individual value in a set. In law-enforcement applications, it is the error in an AAC result for an individual that is important, and use of population average values for an individual's value can greatly underestimate this error (1, 15, 16).

The source of these large individual errors in AAC results is the variability of the blood–breath ratio during absorption. That this variability can be large for all subjects is illustrated by plotting VBAC and BrAC (in grams per liter) vs time. Both quantities are zero at $t = 0$ (the time just before the onset of absorption of alcohol). As absorption begins, BrAC increases first, with VBAC lagging behind because of the concentration gradient between ABAC and VBAC* (3, 9–11, 13, 14, 18). VBAC then begins to increase until it intersects the BrAC curve, at which time the value of the VBAC/BrAC ratio is unity. BrAC continues to increase and then peaks, as does VBAC, but VBAC peaks at a later time (3, 9–11, 13, 14, 18). At the peak value for VBAC, the VBAC/BrAC ratio is about 2100, and it has thus taken on values from 0 to 2100 over the time required for absorption. Experimental results broadly confirm this time dependence, although few data are available on the interval from 0 to 15 min after the end of drinking. For example, the lower limits of the range of blood–breath ratios reported by Jones (2) at 30, 60, and 90 min after the end of drinking are 990, 1794, and 1797, respectively. From the data of Martin et al. (3), for subjects 27, 34, 36, and 6, samples taken 15, 30, 45, 60, and 90 min after the end of drinking, the lower limits of the range are 688, 1100, 1260, 1220, and 1700, respectively. This demonstrates that, for at least some subjects, a significant amount of time is required for the blood–breath ratio to change from 0 to 2100. This is further confirmed by the plots of AAC–VBAC vs time—i.e., absolute error vs time—in Figure 2 of Martin et al. and by the observation that the rate constants for absorption are both highly variable and unpredictable, even under controlled laboratory conditions (3).

Despite large individual errors in AAC measurements, Jones has concluded from the results presented here (2), and from other more recent results (9), that AAC measurements will be somewhat higher than BAC results during active absorption. Yet the overestimates of actual BAC associated with the blood–breath ratio of 990 reported by Jones (2) exceed 100%. Similarly, Martin et al. (3) concluded, "Many

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\[ \text{Forney (17) reported 50–100% differences in ABAC and VBAC during absorption, and Forney and Hughes (14) concluded that these differences last for at least 30 min after absorption begins.} \]

\[ \text{If relative error in AAC results is plotted vs VBAC/BrAC there is an error of about } +200 \text{–} 1000\% \text{ when } \text{VBAC/BrAC} = 1, +300\% \text{ when } \text{VBAC/BrAC} = 100, +100\% \text{ when } \text{VBAC/BrAC} = 1000, \text{ and } 0\% \text{ when } \text{VBAC/BrAC} = 2100. \]
investigators found large discrepancies between the results obtained by simultaneous breath and blood analysis and therefore have questioned the applicability of AAC measurements in medicolegal practice. Our AAC measurements with the Alcolinger Automatic breath analyzer, however, yielded accurate and highly reproducible results (Table 1). It is not clear which parameter in Table 1 is being referred to as a measure of this accuracy and reproducibility, but it is surprising that measurements that can involve relative error in excess of +100% for significant periods of time, or even +30% for that matter, would be regarded as accurate. Furthermore, the cause of these large individual errors has little to do with the Alcolinger Automatic breath analyzer; instead, they result from use of the 2100:1 ratio to calibrate the instrument (I).

It might seem that the large differences between AAC results and actual VBAC—i.e., large absolute errors—would impose certain restrictions on the quantitative use of AAC results. However, these errors have been rationalized by the assumption that arrested drivers are not likely to be in the absorptive state when tested (2, 11, 19, 20). Or, even if some might be so, it is argued that the errors are not really important because AAC results reflect ABAC, and ABAC is a better indicator of impairment than is VBAC during absorption (3, 9–11, 18). It is, however, questionable whether these assumptions and arguments are valid.

To estimate the likelihood that a subject will be in the absorptive state when tested, the proportion of arrested drivers who are absorptive under field conditions should be known. Since this is not known, available data from laboratory studies of absorption times must be relied upon. The common claim that absorption is complete in 30 min is unfounded (8). While a range of absorption times has been reported from 12 to 195 min (2, 3, 6, 8–14), the data of Jones (2, 9), Schmidt et al. (6) and Dubowski (8) (95% confidence limits, dose 1 g/kg) suggest convincingly that an interval of about 120 min from the end of drinking is required for absorption to be complete in fasting subjects. Clearly, many arrested drivers are tested within 120 min after the end of drinking, and this is supported by the results from the field study by Adrian (21), in which very few of the 243 arrested drivers were found to be postabsorptive. It therefore appears that there is a significant likelihood that a subject will be absorptive when tested under field conditions.

It has been known for some time that AAC results reflect ABAC and impairment better than VBAC does during absorption (11, 14, 18). However, this does not necessarily mean that AAC results are a reliable measure of ABAC or impairment. While Dubowski (25, 26) has stated that breath testing results reflect the alcohol content of the arterial circulation, he cites no references to support this, and such a conclusion requires that the value of the ABAC/BrAC ratio be 2100:1 during absorption. Actually, there have been an insufficient number of in vivo studies involving simultaneous ABAC and AAC measurements to establish the value of the ABAC/BrAC ratio during absorption. The available studies involving ABAC by Enticknap and Wright (27), Forney et al. (11), Payne et al. (10), and Martin et al. (3) involved only two, three, 14, and eight subjects, respectively, and no large-scale studies appear to have been done to help determine the mean, ±SD, CV, and range of the in vivo ABAC/BrAC ratio. While the uncertainty in the ABAC/BrAC ratio has not been established, it might well be similar to the ±15% minimum found for estimates of VBAC in the postabsorptive state (I). But, because arterial blood is virtually never the sample used to determine the BAC of a conscious arrested driver, it is never possible to determine the accuracy of an AAC result for an absorptive subject under field conditions.

Even if the in vivo value of the ABAC/BrAC ratio were known, a serious problem remains. Assuming that AAC results do accurately reflect ABAC, an arrested driver who selects a breath test will have his or her BAC determined from estimates of ABAC. While, if this subject selects a blood test, his or her BAC will be determined by measurement of VBAC. This means that even though the two methods yield different BAC results, the two results are used interchangeably to establish a subject’s BAC. Consequently, subjects in the absorptive state who select a blood test will have consistently lower BAC results than those who select a breath test, and this means that the group of people selecting a breath test will not receive the same protection under the law as the group selecting a blood test.

In order to eliminate the problems arising from variability in the blood-breath ratio, Dubowski (5, 8, 26) has advocated for many years that breath test results be reported in terms of direct BrAC, instead of converting them to BAC results. However, such a simplistic approach cannot provide an acceptable solution to these problems (1, 29). The variability of the blood-breath ratio produces uncertainty in AAC results for a given subject, and the uncertainty must be reported along with these results. The 2100:1 conversion factor is of questionable reliability, even for estimating the BAC of subjects in the postabsorptive state, because its use results in overestimates of BAC for at least 23% of subjects in the general population (I) and because, at best, its use results in a relative uncertainty estimated by ±2CV = ±15% (I). If contributions from the uncertainty in the VBAC/BrAC ratio in the absorptive state are to be included, a value even larger than ±15% should be reported with the AAC results.

The variability of the blood-breath ratio during absorption has also not been adequately accounted for by the manufacturers of breath analyzers. They commonly specify accuracy and precision to be "better than" 0.01% BAC (25, 30), which is equivalent to 10 mg per 100 mL of blood, or 10 mg per 210 L of breath (8). However, no distinction is made between the absorptive and postabsorptive states. It was shown previously that manufacturers’ specifications are too optimistic, even for subjects in the postabsorptive state (I), so the specified accuracy as applied to the absorptive state is completely unrealistic. Manufacturers have ignored their responsibility to the scientific community and to the public to publish instrument specifications that are reliable and consistent with results in the published scientific literature.

There is general agreement that it is very important to
identify the state of alcohol absorption for proper interpretation of breath test results (2, 3, 8, 11, 14, 28, 31); to do this reliably, BAC should be measured at regular intervals for several hours (8, 31). Yet, when an individual submits to breath tests for law enforcement purposes, it is virtually never known whether he or she is in the absorptive or the postabsorptive state, because sufficient objective data are not gathered to make such a determination (8, 31). If this is not known, then the common assumption that most subjects are postabsorptive (2, 11, 19, 20) is not justifiable. If the state of alcohol absorption has not been established by some objective method, then the assumption should be made that the subject is in the absorptive state, so that a greater amount of uncertainty can be applied to the AAC result. But more important, if it is not known whether a subject is in the absorptive or postabsorptive state, then it is not possible to know how reliable the AAC result is. Overestimates of actual BAC can be anywhere from 15% to more than 100%. Errors of this magnitude raise questions about satisfying legal criteria for due process.

Conclusions

Too few data are available to establish statistical limits for the accuracy and precision of breath testing results in the absorptive state. However, results from data in the literature indicate that breath testing is not a reliable means of estimating a subject's BAC during absorption. The results also indicate that there is a significant likelihood that a given subject will be in the absorptive state when tested under field conditions. Because of large differences in arterial BAC and venous BAC during absorption, breath test results consistently overestimate the result that would be obtained from a blood test—by as much as 100% or more. In order to have some idea of the reliability of a given breath test result, it is essential to determine by some objective means whether the subject is in the absorptive or postabsorptive state. In the absence of such information, an appropriate value for the uncertainty associated with the absorptive state should be applied to all breath test results.

References


*Note added in proof: Unfortunately, ref. 1 contains the following typographical errors. On p. 265 (right column), "0.01% BAC or 0.10 g/210 L" should read "... or 0.01 g/210 L." On p. 267 (left column), "0.80 g/deciliter" should read "0.08 g/deciliter."