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Breath-Alcohol Analysis: Uses, Methods, and Some Forensic Problems—Review and Opinion

Presently when one uses the terms "breath analysis," "breath testing," or even the unqualified "chemical testing," people, generally, think of a determination of alcohol in a specimen of breath for medicolegal purposes. (The unmodified term "alcohol" in this article refers to ethanol.) This is because of the notoriety of this application and, perhaps, the strong resentment of many to the police procedures involved. Actually, analysis of breath has been undertaken for a variety of purposes since before the recorded history of man. Thus an almost infinite number of conscious judgments about, or unconscious responses to, components of his *inspired* breath have been made based on odor, taste, and other sensory effects, many of these crucial for well-being or survival of both man and other animals. A striking example is the functioning of pheromones [1].

Much less frequently, direct, planned qualitative testing of *expired* breath of others, using the nose as a sensing device, has been employed for centuries to detect such manifestations as the fruity odor of the breath of the diabetic and the fetid odors of the breaths of subjects with advanced liver disease, uremia, or various acute infections. Especially among Moslems, the presence of the congeners of ethanol was checked by smelling the breath, a positive result being considered a priori evidence of previous consumption of alcoholic beverage—originally a capital offense. In more recent times exposures to a variety of toxic chemicals are recognized or suspected because of abnormal odor of the breath [2].

Studies of the gases in breath (and in blood) were undertaken by pioneers in biochemistry and physiology about the beginning of the 19th century. Relatively precise quantitation of oxygen, carbon dioxide, and nitrogen had to await instrumentation such as that employed by Fitzgerald and Haldane [3] and Haldane and Priestley [4] in the early 1900s. This permitted determination of the average and ranges of variation in the composition of mixed expired breath and alveolar air as well as a variety of other values relevant to the physiology of respiration [5]. The detection of ethanol in breath after consumption of wines was reported at least as early as 1847 [6]. The earliest American paper on breath alcohol analysis in humans appears to be that of Anstie [7] in 1874.

Modern Uses of Breath Analysis

As more sophisticated instrumental methods were developed, examinations of breath comprised chemical compositional studies establishing norms of health and alterations

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induced by disease (including the role of breath in the transmission of infection). Somewhat later the major inquiries dealt with breath volumes, pressures, and rates of movement in health and disease [8,9].

The combined needs of pulmonary physiologists and the National Aeronautics and Space Administration (NASA) resulted in the development (and, often, miniaturization) of several analytical devices capable of rapid responses to changes in sample composition and other properties so that the dynamics of pulmonary function in terms of volumes, composition, and rates of movement of gases during the inspiratory and expiratory phases of respiration might better be studied. In addition, changes in atmospheric composition, particularly contamination by toxic chemicals, may be monitored more adequately. Concomitantly, marked improvements in instrumentation employing mass spectrometry and the interfacing of gas chromatography-mass spectrometry and dedicated computers as production items at lessening "real dollar" prices have greatly increased the number of components which may be detected and studied in breath or in other body effluents. Thus, recent studies on total body effluents report at least 135 compounds identified and two or three times this number as detected but not yet structurally identified [10-13]. The possible forensic use of effluent patterns for individual identification has been suggested [14].

Relatively few components of breath have been studied in depth with respect to their origin and functional significances, if any. Contemporary and "suggested applications [of breath analysis] which are considered practical at present" have been listed by Dubowski [15]. Currently, most breath analyses probably are for determination of ethanol and are undertaken in connection with traffic law enforcement. (The very large number of determinations of partial pressures of oxygen and carbon dioxide made in clinical laboratories of hospitals are mostly calculated from measurements made on blood.)

By 1920 assembly line production techniques and arrangements for installment purchase had put the automobile within reach of the ordinary working man. Traffic densities greatly increased and deaths in vehicular accidents became commonplace [16]. It was soon recognized that many crashes were alcoholic beverage-related and in a number of states statutory restrictions on the right to drive while "under the influence of intoxicating liquor" appeared. Effective prosecution for drunken driving thus came to require statutory definition of a concentration of ethanol in a body fluid (usually whole venous blood) at which driving ability became impaired. It was recognized early that in man the dose-response relationships for ethanol in both central and peripheral nervous system function involving faculties such as judgment, perception, coordination and reaction time were strikingly nonuniform: the effects of ethanol varied greatly from person to person and in the same person at different times or under different circumstances. An extensive series of investigations now support the conclusion that the most important functional defects caused by ethanol are those associated with perception and processing of information received by the special senses [17-19]. Learned motor responses are relatively much less impaired.

Unfortunately and perhaps even irrationally, in actual law enforcement practice prosecution, let alone conviction, became infrequent unless the blood alcohol concentration of the accused was shown to be so high that, on the basis of existing scientific investigative evidence, any individual attaining such a concentration would have demonstrable impairment of nervous system functions relevant to safe and proper driving.

Even when it was commonly considered that a blood alcohol concentration in excess of 0.15% weight/volume (w/v) was prima facie evidence of being under the influence of alcohol, confidence in chemical test evidence was more than occasionally eroded by unwise public demonstrations in which volunteer subjects who had considerably higher concentrations appeared to respond satisfactorily to the tasks (usually poorly chosen) re-

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quested of them. Appropriately sensitive and discriminating tests would not have yielded such misinterpreted, misleading, and highly publicized conclusions as those which often followed these early exhibitions.

Although the gross features of inebriety had already been long established [20-22], there were not many controlled studies of the effects of graded blood alcohol concentrations on actual driving performance. Until about 1940 almost nothing was known about the kinds of defects in driving capability caused by alcohol at blood concentrations often accompanying otherwise generally acceptable behavior, socially. During the last 35 years these medicolegal matters have been extensively explored [17,18,23]. The results of these studies have led, in the United States, to the statutory definition of alcoholic impairment of driving performance shown in Fig. 1.

Until 1968 the National Safety Council (NSC) through its Committee on Tests for Intoxication (established in 1936 and later designated the Committee on Alcohol and Drugs) and the American Medical Association through its House of Delegates and Committee on Medicolegal Problems were largely responsible for recommendations to the various states and to the public generally, regarding alcohol and traffic, especially about technical methods, interpretations of published data, and enforcement procedures. One of the position papers of the NSC [24] provided the basis for action demanded by the federal government when the National Highway Safety Agency was established in 1966. The agency later became the National Highway Safety Bureau (NHSB) which was absorbed into the National Highway Traffic Safety Administration (NHTSA) of the Department of Transportation.

Inasmuch as it appeared that the ethanol concentration in alveolar air or the alveolar component of an expired breath sample was proportional to its concentration in blood (that is, that its distribution between blood and alveolar air obeys Henry's Law), proce-

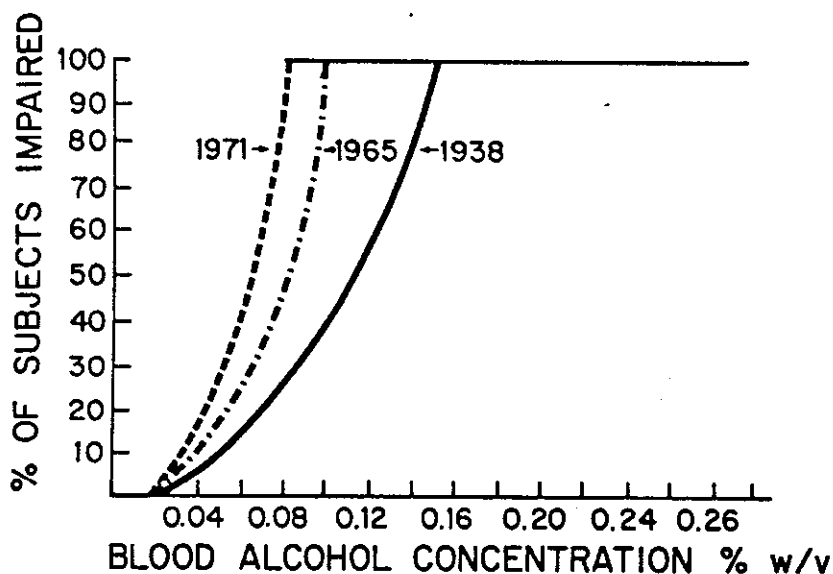


FIG. 1—The relationships shown between blood ethanol concentration and percentage of a population of subjects impaired reflect the positions taken by the National Safety Council (1938, 1965) and the more recent recommendation of its Committee on Alcohol and Drugs (1971). The intermediate values in the slopes of the curves of increasing impairment are approximations but indicate the constraints imposed on the public interest. Thus, for 1971, a subject driving with a blood concentration only three fourths that considered a priori evidence of impairment has a 50% chance of being significantly impaired. At at 0.10% w/v blood alcohol concentration the relative risk of the driver's being in an accident is estimated to increase by a factor of about 6 [21].

dures were devised which used breath as a sample. The quantity of any ethanol found was converted to a *presumed* blood concentration (strictly speaking, a pulmonary venous blood concentration) by *calculation*. The use of breath has the advantage of not requiring the intervention of a physician, nurse, or hospital personnel in the enforcement procedure, but the subsequent calculation employs several presumptions whose validity cannot be assessed in an individual case. This is a significant disadvantage to the value of the result in the criminal justice system of the United States.

In any event, traffic law enforcement came to require facilities, procedures, and specialized instruments for both breath and body fluid analysis for ethanol. The federal standards with which the individual states must comply or run the risk of loss of federal funds for highway construction are specified in a comprehensive manual [25]. By 1974 there had been threats, but no actual instance of withholding of funds. Maryland and Puerto Rico had still not met the requirement of statutorily declaring "that reaching or exceeding 0.10 per cent BAC [blood alcohol concentration] renders a person 'intoxicated' or 'under the influence of alcohol' " [26]. The setting of sanctions hearings (1975) brought about their compliance. Almost all jurisdictions had made technically acceptable, although not uniformly satisfactory, responses to various other traffic-related federal requirements and laggards may require sanctions to obtain compliance [26]. These developments and various related matters are summarized in a recent comprehensive review [27].

Methods of Breath-Alcohol Analysis

A procedure for breath-alcohol analysis for medicolegal purposes was described in 1927 [28], but very little use was made of it. The first state law on admissibility of chemical test evidence was passed in Indiana in 1939 shortly after the first model of the "Drunkometer" for breath-alcohol analysis was described fully by Harger et al [29,30]. The concentration of ethanol in a breath specimen was determined by measuring the volume of the specimen required to reduce a fixed amount of a standard acidic (H_2SO_4) permanganate solution. The alveolar fraction of the volume of expired breath analyzed was estimated by determining the weight of CO_2 present. Using the assumption of a CO_2 content of 5.5% by volume in the alveolar air of a resting subject, without subsequent addition or loss in transit through the bronchial tree, and a blood/breath partition ratio at the mouth of 2000:1, the authors postulated that the amount of ethanol accompanying 190 mg of CO_2 would be the quantity present in 1.0 ml of pulmonary venous blood of average composition. Two variations in the use of the instrument, in respect to the sample used and calculation of the analytical result, were later described [31,32]. About the same time several other devices appeared which differed in design, the character and volume of the analyzed sample, the oxidizing agent employed, and the procedure for calculation of the result. Table 1 summarizes the characteristics of the early and most commonly used instruments in North America up to 1970. Numerous extensive reviews have included discussion of these instruments along with relevant features of the physiology, pharmacology, and pharmacokinetics of ethanol [23,33-37].

Experience has shown that these instruments can analyze or collect alcohol, or both, in a sample of vapor presented from an equilibrator or simulator with quite acceptable accuracy and precision. However, when the results of analyses of nearly simultaneously collected breath and blood samples are compared it is found that the blood concentration *calculated* from the breath quantity not infrequently may show differences unacceptable for use in law enforcement. One of the reasons for this was the fallacious assumption of reasonable constancy of the CO_2 content of expired breath at rest, with estimation of the amount of alveolar air in a breath specimen based on the amount of CO_2 present. Perhaps under the pressures of the advocacy system the validity of the

TABLE I—Features of early instruments for breath-alcohol analysis.

Instrument	Sample	Oxidizing Agent	Calculation of Result
Drunkometer [29]	mixed expired air	KMnO ₄ -H ₂ SO ₄	alcohol accompanying 190 mg of CO ₂ in breath delivered at 34°C = alcohol in 1.0 ml of arterial blood
Drunkometer [31]	mixed expired air	KMnO ₄ -H ₂ SO ₄	alcohol in 3200 ml of sample = alcohol in 1.0 ml of arterial blood (an apparent partition ratio of 3200)
Drunkometer [32]	rebreathed air	KMnO ₄ -H ₂ SO ₄	alcohol in 2100 ml of sample = alcohol in 1.0 ml of arterial blood.
Portable Intoximeter® [128]	mixed expired air	KMnO ₄ -H ₂ SO ₄ for visual test ^a	alcohol accompanying 200 mg of CO ₂ in breath delivered at 34°C = alcohol in 1.0 ml of arterial blood.
Alcometer® [129]	deep lung air ^b	iodine pentoxide	originally alcohol in 1300 ml of sample = alcohol in 1.0 ml of capillary blood [129]; subsequently, alcohol in 2100 ml of sample = alcohol in 1.0 ml of arterial blood.
Photoelectric Intoximeter® [130]	deep lung air ^b	dichromate-H ₂ SO ₄	alcohol in 2100 ml of sample = alcohol in 1.0 ml of arterial blood
DPC Intoximeter [131]	deep lung air ^b	choice by analyst	alcohol in 2100 ml of sample = alcohol in 1.0 ml of arterial blood
Breathalyzer® [40]	deep lung air ^b	dichromate-H ₂ SO ₄	alcohol in 2100 ml of sample = alcohol in 1.0 ml of arterial blood

^a For screening test on a portion of the sample. The remainder is adsorbed on magnesium perchlorate and is subsequently analyzed by any appropriate technique.

^b Substantially alveolar air.

constancy of alveolar CO₂ content became a veritable sacred cow, with copious evidence to the contrary often being totally ignored.

The NSC recommended the discontinuance of the use of CO₂ in estimating alveolar air in 1967 [24], and a year later provided extensive documentation of its position [38]. Recently, further data confirming the considerable variability of CO₂ in expired alveolar air of healthy resting subjects have been presented [39]. The subsequent Federal Program Manual [25] required analysis of a volumetrically measured sample of "substantially alveolar" deep lung air. Other reasons for discrepancies between analyses of nearly simultaneously collected blood and breath specimens have been discussed in detail elsewhere [27]. Some additional pertinent information will be dealt with subsequently.

Following the federal requirement that all states develop programs which promote highway safety and which include specific standards regarding alcohol and traffic [25], the frequency of chemical testing greatly increased, especially breath-testing as compared to analysis of blood. At that time the only widely available instrument meeting existing federal standards was the Breathalyzer® [40,41]. Within a short time various other

instruments and methods made their appearance as prototypes or production items, some lacking sufficient independent confirmation of their operational and analytical capabilities. Consequent to a recommendation by the Committee on Alcohol and Drugs of the NSC [42] the NHTSA required quantitative, evidential breath testers, if purchased with federal funds, to meet federal performance standards which were developed by the National Bureau of Standards, in order to be eligible for use in traffic law-enforcement [43]. A few months later a report by the Committee on Alcohol and Drugs of the NSC commented on and suggested some changes in these requirements [44].

Most of the newer instruments utilize rapid means of measurement which do not involve classical wet chemical oxidation of ethanol in a presented sample. Rather, they employ such techniques as gas chromatography, infrared photometry, and solid state oxidation by the use of electrochemical oxidation, fuel cells, catalytic oxidation devices, and metal oxide semiconductor sensors, the final measurement being that of an amperage or voltage. None of these methods is specific for ethanol in a single operational mode. Gas chromatography provides specificity with high probability for ethanol in terms of an observed retention time identical with that of ethanol in a reference standard obtained in an immediately prior or subsequent analysis. By repetition of the analysis using a different column and operating conditions, identification, at least beyond "reasonable doubt," of the component of interest may be achieved.

Interference by other volatile substances is infrequently (and in many jurisdiction, very rarely) encountered in breath alcohol analyses and when claimed as a defense can easily be checked, providing a portion of the breath is available for re-examination. Presently (1975), although such availability is clearly a necessity implied within the framework of the criminal justice system, a portion of a breath specimen is rarely saved. Any method used should be capable of preserving or trapping all known interfering compounds present in breath with any significant frequency.

Table 2 lists a number of the newer breath-alcohol instruments which have been developed for use by law enforcement agencies. A number of additional instruments not yet available as production items and devices for screening are described in recent documents, one prepared for the Department of Transportation [45,46]. All the quantitative testers

TABLE 2—Recently introduced instruments for traffic-related breath-alcohol analysis in the U.S.^a

Instrument	Method	Portability ^b	Instrument Category
Breathalyzer [®] 1000 [47] ^c	wet oxidation and photometry	no	quantitative evidential
Alco-Tector [48]	wet oxidation and photometry	no	quantitative evidential
Alco-Analyzer [50]	gas chromatography	no	quantitative evidential
G. C. Intoximeter [®] [51] ^c	gas chromatography	no	quantitative evidential
Intoxilyzer [54] ^c	infrared photometry	no	quantitative evidential
Alco-Limiter [®] [56] ^c	electrochemical oxidation	yes	quantitative evidential
Alco-Sensor [60]	fuel cell sensing	yes	screening test
A.L.E.R.T. [®] [61]	metal oxide semiconductor sensing	yes	screening test
Roadside Breath Tester ^c (Alcohol Screening Device) [66,67]	fuel cell sensing	yes	quantitative evidential

^a Nonspecialized gas chromatographs may be employed with samples obtained by any appropriate remote sampling device [125,132-134]. None of these have as yet had performance standards specified as in the case for evidential breath-testing instruments or screening devices.

^b Easily hand-held.

^c Approved for use as evidential breath testers [57].

The Intoxilyzer [54,55] consists of a small infrared photometer designed to measure the infrared absorbance of ethanol at $3.39 \mu\text{m}$ in an open-ended chamber having a volume of 600 ml and through which the subject exhales deeply. The terminal portion of the specimen is presumed by the author to be substantially alveolar if a plateau of absorbance due to ethanol occurs in a beam making multiple passes across a fixed path in the chamber (which is the equivalent of a sample volumetrically measured). Interference filters at the exit end of the chamber isolate relatively monochromatic light of $3.39 \mu\text{m}$ which is directed to a sensitive infrared photoconductor to produce a signal that is processed for digital display of a presumed percent w/v ethanol in blood, using a blood-breath ratio of 2100:1. The instrument is factory-calibrated and the calibration may be confirmed with reference vapors from a simulator or equilibrator.

The few blood breath correlations reported by Harte [54] are somewhat better in terms of accuracy than those in a recent study by Dubowski [39] which gave results averaging about 10% less than those obtained by direct analysis of blood between blood concentration of 0.050 and 0.15% w/v (see Fig. 2).

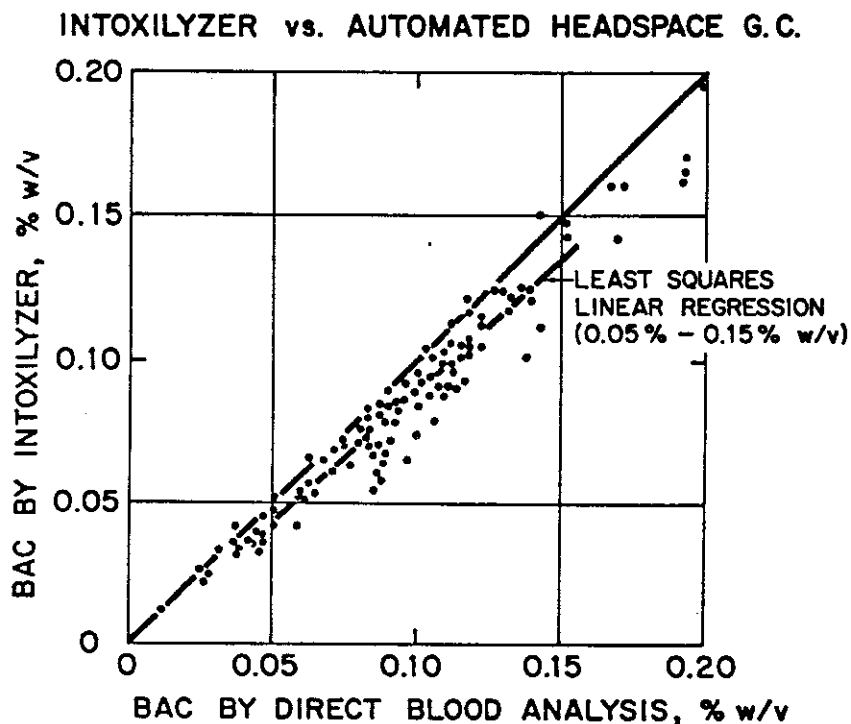


FIG. 2—Correlation between results of analyses for alcohol in 128 pairs of simultaneously collected venous blood and end-expired breath specimens [39]. Some points represent replicate results. The perfect correlation line is shown; the least square linear regression line (not shown) equation for these data is $y = 0.902x - 0.001$ with a correlation coefficient, $r = 0.980$. For data between 0.05% w/v and 0.15% w/v the corresponding values are $y = 0.916x - 0.002$, $r = 0.933$ and the regression line is shown. The regression equation calculated from measurements of data points on the chart was $y = 0.938x - 0.004$ which results in an error of about 0.001 for the value of y when $x = 0.10\%$ w/v. (Breath analyses were performed with an Intoxilyzer apparatus with direct digital BAC readout; blood analyses were performed, in duplicate, by an automated gas chromatographic headspace procedure [68,82].)

require a sample comprised of deep lung air, that is, substantially alveolar in composition, if the instrument calibration is consistently to yield results within presently acceptable limits for the existing arterial blood-ethanol concentration as deduced from analyses of reference standards (within $\pm 0.10\%$ w/v of the blood alcohol concentration-equivalent target value of a reference sample of alcohol vapor). Just how substantially alveolar the sample taken by some of these instruments really is remains to be demonstrated, as it appears unlikely that the sampling techniques employed uniformly permit reaching an alveolar plateau such as has recently been demonstrated for stated conditions [15]. Although not all instruments in Table 2 volumetrically measure the sample presented, the intent of this portion of the federal requirement is met by a "regulated" volume being used, such as a fixed light-path length for a sample at ambient pressure for measurement of infrared absorbance, or trapping by the sampling arrangement of a fixed but not quantitatively measured volume. Special features of the analytical methods employed by these instruments are described in greater detail and with diagrammatic illustrations elsewhere [45].

The Breathalyzer® 1000 [47,45] is a modification of the original Breathalyzer® [40] (see Ref 41 for a detailed discussion of principles, construction, and operation of the latter) to make its operation more automatic, thus decreasing the manipulations the breath-test operator must perform. In addition the manual valve has been replaced by electrically activated valves and a second piston-cylinder has been added to collect and discard at least the first 400 ml of delivered breath, after which 56.5 ml of breath warmed to 50°C (122°F) is collected in a second piston-cylinder and 55.2 ml of this is bubbled through an ampule containing potassium dichromate-sulfuric acid and silver nitrate as a catalyst. As in previous models the initial photometric absorbance is established by equalizing the filtered "blue light" absorbance of a reference and test ampule, using the Bunsen principle. The change in absorbance on analysis of breath appears as a digital readout and a printed record of the presumed blood alcohol concentration, based on assumption of a blood-breath ratio of 2100:1.

It is unlikely, as stated in Ref 45, that (substantially) alveolar air is obtained after discarding only the first 400 ml of exhaled breath [15]. Unless counterbalanced by compensating errors this would tend to provide falsely low values in nearly simultaneous blood-breath comparisons.

The Alco-Tector [48] is almost identical in construction and operation with earlier models of the Breathalyzer® and according to limited published data [49] gives at least as satisfactory analytical results.

The Alco-Analyzer [50] is a specialized gas chromatograph containing two columns, one for direct analysis of blood and the other for analysis of headspace gas or breath. The volume of gas is measured by a sampling loop. Thermistor detectors are employed. That of the unused column serves as a reference detector and the conductivity differential between the two detectors is recorded on a strip-chart during the analysis. A digital readout device is also available. A simulator is used to calibrate the instrument for breath analysis. Available data indicate adequate precision and accuracy is obtained in analysis of vapor samples [50] and nearly simultaneous blood-breath comparisons are comparable with those obtained with other instruments [45].

The G. C. Intoximeter® [51,52] is a specialized gas chromatograph with a flame ionization detector and attached strip-chart recorder. The subject exhales deeply and the first portion of the breath (about 1800 ml) is discarded. The subsequent expiratory fraction, now considered by the authors to be substantially alveolar, is diverted into a gas sampling device which allows 0.25 ml to pass on to the column. The instrumental response may be calibrated by injection of a vapor containing a known amount of ethanol, prepared as such, or by means of a simulator with a blood-breath ratio of 2100:1 being used to convert a breath quantity to a presumed blood concentration.

Alternately indium tubing and a crimping device [51] may be used for "field" (remote) sampling of deep lung air. Capsules of breath believed to be substantially alveolar are thus obtained. Placed in the instrument, a capsule is penetrated by a needling device which allows the content to be conveyed to the gas sampler which admits 0.25 ml onto the column.

Reported nearly simultaneous blood-breath comparisons [45,51-53] show correlation of the order obtaining for various other breath-testing devices (Table 3).

TABLE 3—Blood/breath correlations found in 28 studies with nine breath-testing instruments (1956-1974).^{a,b}

Reference	Year	Instrument	Correlation of Reported Values, %				Mean of Blood/Breath Deviation, %
			Within ± 5%	Within ± 10%	Within ± 15%	Beyond ± 15%	
32	1956	Drunkometer, rebreathed air	54	87	98	2	+1.3
81	1957	Breathalyzer*	38	62	91	9	-6.7
81	1957	Alcometer*	53	78	95	5	-1.3
135	1959	Breathalyzer*	30	51	68	32	-10.0
136	1959	Breathalyzer*	40	68	84	16	-6.1
137	1960	Breathalyzer*	26	52	72	28	-8.5
138	1963	Breathalyzer*	...	...	...	...	-12 (mg/100 ml)
139	1964	Breathalyzer*	5	17	38	62	-17.5 ^b
139	1964	Kitagawa-Wright Hermes system	31	49	68	32	-1.9 ^b
90	1964	Drunkometer, rebreathed air, arterial blood	64	86	93	7	-4.0 ^b
140	1969	Breathalyzer* vs blood	33	59	87	13	-9.7
140	1969	Breathalyzer* vs plasma	28	59	76	24	-9.9
49	1969	Breathalyzer*	42	61	84	16	-0.3
49	1969	G. C. Alco-Analyzer	60	70	75	25	-4.9
49	1969	Alco-Tector	51	78	88	12	+1.7
51	1969	G. C. Intoximeter*	58	61	73	27	-4.3
91	1969	Breathalyzer*	25	61	80	20	-7.1
91	1969	Breathalyzer*, rebreathed air	57	74	92	8	-2.2
141	1970	Alcolinger Automatic	45	66	85	15	+3.6
54	1971	Intoxilyzer	...	...	...	...	-3.2
46	1971	Breathalyzer*	25	57	74	26	-5.2
156	1972	Breathalyzer*	31	58	82	18	-0.7
156	1972	G. C. Alco Analyzer	15	31	66	34	-13.7 ^c
53	1972	G. C. Intoximeter ^b	45	65	82	23	-4.4 ^c
45	1973	G. C. Intoximeter ^b direct analysis	15	63	77	23	-10.2
45	1973	G. C. Intoximeter ^b indium capsules	61	79	97	3	+1.8 ^c
142	1974	Intoxilyzer	28	65	86	14	-10.0 ^c
142	1974	G. C. Intoximeter*	34	82	90	9	-6.6 ^c

^aData taken from presentation by Harger [45]; blood/breath ratio = 2100 (except for Alcometer*). See also Refs 23 and 27 for other reports on and discussions of blood/breath correlation studies.

^bComparisons in which the blood alcohol was less than 0.05% w/v are omitted.

^cData calculated from estimates made from scatter diagrams.

The extent of any interference resulting from the presence of the most frequently encountered volatiles such as methanol, isopropanol, and, particularly, acetone, which also absorb light at $3.39 \mu\text{m}$ has not been adequately documented.

The Alco-Limiter[®] [56] employs an electrochemical oxidation system not considered to be a fuel cell by the authors and measures the current produced as ethanol is oxidized to acetic acid in an electrolyte of concentrated H_2SO_4 . No oxygen or hydrogen is produced at the electrodes and the amperage is proportional to the ethanol concentration of vapor introduced into the instrument over the range occurring in breath. The terminal portion of an expiration is said to be sampled. Presumably performance data more extensive and better than those presently available [45] will appear to support its approval as an evidential breath-testing device by the NHTSA [57] and show that an alveolar plateau is consistently attained in the case of healthy subjects.

A modification and miniaturized version of the Alcoyser FCD (fuel cell detector) [58,59] which is produced in America is the Alco-Sensor [60], designed for use as a roadside screening device. The fuel cell chamber is partitioned by a plastic membrane coated on each side with catalytic chemicals, the cathodic chamber having a volume of 1.0 ml. This is said to be filled after a by-pass discards all but the terminal portion of a forced expiration. The voltage induced is amplified and employed for a display of qualitative results: the relative position of a light indicates a presumed blood alcohol concentration of less than 0.05% w/v; 0.05 to 0.10% w/v; or greater than 0.10% w/v.

Performance studies quoted [45] are those which involve comparisons of results of nearly simultaneous blood-breath analyses with those of other instruments, thus including all of the possible discrepancies due to the conversion of the result to a presumed blood concentration. There is no obvious impediment which would prevent a modified version of this instrument from becoming an acceptable evidential breath-testing device if the breath result were reported on a calibrated voltmeter scale or by a digital readout.

A.L.E.R.T.[®] [61,62] is an instrument employing a semiconductor sensor, the Taguchi Gas-Electric Transducer ("TGS" or Taguchi sensor) invented in 1967 [63] and produced since 1969 in Japan. This minute sensing device has an inherent high electrical resistance in the presence of ordinary air, but if certain combustible vapors are present the conductivity is increased in proportion to their concentrations. Precisely predictable response was not originally claimed by the manufacturers of this TGS sensor; however, a later report states there is increased stability and linearity of response versus concentration for several compounds including ethanol [64,65].

Two coiled iridium-platinum wires pass through and heat a very small block of sintered stannic oxide containing a small amount of gold oxide. Contact of a combustible component in the sample chamber with the sensor decreases the resistance of the block and increases the passage of current, ultimately resulting in an increase in voltage which is measured.

The A.L.E.R.T.[®] instrument is said to be so designed that the distal portion of a continuous exhalation is analyzed and the resulting voltage increase is used to activate the display of three lights as described in the case of the Alco-Sensor. Full performance data have not been published, but a preliminary evaluation report has appeared [62]. It remains to be determined whether the accuracy and precision of analysis of ethanol in vapor is sufficient so that a modified instrument could qualify as an evidential breath testing device.

The Alcohol Screening Device (Roadside Breath Tester) [66,67] is portable and battery-powered and includes a control feature of sample selection which is said to ensure obtaining a deep lung aliquot of breath. A chemoelectric cell generates an electric current upon oxidizing any alcohol present and an adjustable readout permits the result to be displayed as "pass," "warn," or "fail" lights or as a digital readout of the presumed blood alcohol concentration on the basis of a blood/breath ratio of 2100:1 and certain other presumptions [39].

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Another screening device of the sort which may be shown to determine alcohol in breath with suitable accuracy is the Century Systems Breath Alcohol Tester (BAT-111) [67], also a combustion device.

It should be emphasized that these various devices are not specific for ethanol, which points to the need for accompanying accessories for saving a portion of the delivered breath specimen for later re-examination if the issue of specificity is brought up.

By late November 1974 only five devices had met all performance requirements, including those for Mobile Evidential Breath Testers [57]: the Alco-Limiter® (Energetics Science, Inc., New York, N.Y. [56]), Mark II Gas Chromatograph® (Intoximeters, Inc., St. Louis, Mo. [52,69]), Intoxilyzer Model 4011 (Omicron Systems Corp, Palo Alto, California [53]), Breathalyzer® Models 900A and 1000 (Smith & Wesson Electronics Co., Eatontown, N.J. [47]), and Alcohol Screening Device (Roadside Breath Tester) (U.S. Department of Transportation, Washington, D.C. [66,67]). Additional devices meeting all requirements, excluding those for Mobile Evidential Breath Testers were the Alco-Tector, Model 500 [48] and the Photo-Electric Intoximeter® [69].

A compelling case may be made to extend the present federal standard for evidential breath-testers and to delete one key item. The deletion, suggested previously [27,44], is that part dealing with the analysis of nearly simultaneously collected specimens of blood and breath for ethanol and agreement of the results. Rather, this should be replaced by requirements which relate to the capability of the instrument to collect an appropriate breath specimen, which when analyzed with specified accuracy would permit conversion of the breath-alcohol concentration to a presumed blood-alcohol concentration, also within specified limits of accuracy on the basis of the various presumptions necessary. These presumptions, in fact, do not have verified certainty in a given real-world case in traffic law enforcement. The additional requirements should include (1) recording the breath temperature as delivered at the mouth, which also indicates the temperature of the portion becoming the analyzed sample; (2) demonstrating in each case that (with healthy tested subjects) an alveolar plateau is, in fact, reached and that sampling occurs during this portion of the breath-delivery time-sequence, with indication in field use when sampling precedes or succeeds the plateau; (3) including an interlocking system so that once an analysis has been started no part of the procedure can be altered by the subject or breath-test operator; and (4) recording a digital printout of each result that is assigned a number by the act of starting an analysis.

It is likely that the criminal justice system will generate pressures leading to the provision of these sorts of safeguards. Further, it is likely that more certain evidence of proper checking and maintenance of instruments will be demanded along with more stringent enforcement of regulations regarding the licensure and periodic re-examination of breath-test personnel.

Forensic and Technical Problems in Breath-Alcohol Analyses

Various specific problems encountered in the use of a breath-alcohol analysis as trial evidence are mostly related to five matters. The first is that, admittedly, the effects of ethanol on assessable nervous system functions vary a great deal from person to person. One or more jurors may be loath to accept a calculated blood concentration only a little above a statutory limit as proof of inebriation beyond reasonable doubt. This is because it readily may be shown that a reported presumed blood alcohol concentration can be inferred to have a rather large standard deviation, coefficient of variation, or other statistical measure of variability. This may be even more so if obligatory performance monitoring of individual operators and instruments is instituted and the results become matters of public record. In addition, when a narrow margin is involved there is enhancement of a

juror's possible private view that "there but for the grace of God go I" and, occasionally, unwillingness to convict.

Next, the physiology and chemistry of breath testing are actually rather complex, and this can be effectively exploited by cross-examination by a skillful attorney for the defense. There is little that can be done about this creation of distrust in the jury's mind concerning such a complicated matter other than for witnesses for the prosecution to make it abundantly evident that they are aware of and understand the complexities and their bearing, if any, on the analytical result reported. This is not always the case [70]. Thus, a breath-test supervisor, in a recent conversation, was clearly at loss to account for the fact that a reference solution prepared by a 1:50 dilution of a stock standard containing 77.0 ml of absolute ethanol per litre was employed in simulators at 34°C (93°F) to produce the equivalent of breath from a subject with blood containing 0.10% w/v of ethanol, for the purpose of checking the reading of a Breathalyzer®. This aqueous reference standard contains 121.0 mg of ethanol per 100 ml and when equilibrated with air at 34°C yields a vapor which is presumed to be identical in alcohol content to that of deep lung air at 34°C from a subject whose blood alcohol concentration is 0.10% w/v. The difference is mainly due to the lower water content of blood compared to an aqueous reference standard [71].

Third, knowledgeable attorneys have become aware of the details of the present federal recommendations, initially delineated in the Highway Safety Program Manual, Vol. 8 [25], and the responses of their states. These concern the training and certification of operators of breath-testing devices, their supervision and performance monitoring, the use and composition of reference standards in the administration of individual tests and periodic checking of individual instruments. Possible confusion in respect to these technical matters is manifested in a summary [72] of *State v. Ghylin* [73] in which it is reported that the Supreme Court of North Dakota listed five responsibilities of the state in respect to use of breath test evidence. The fourth item is that the known solution for conducting calibration tests is what it purports to be: "a 0.10% solution of alcohol and water"—which it is not because of constraints imposed by using an aqueous solution to calibrate response of an instrument to a vapor tension arising from blood. If shortcuts or omissions have occurred, attempts to obscure these during cross-examination may diminish the credibility of the entire testing procedure in the mind of one or more jurors. These and new interpretations by the courts may result in reversal of a verdict by an appellate body [74-78].

Another recent and troublesome matter especially affecting instrumentation employing wet oxidation (for example the Breathalyzer®) has been the question as to whether the reagents employed in an individual test need be retained and be available for re-examination on demand at a later date. Litigation involving these issues is in quite unfavorable progress [72,79,80] from the point of view of law enforcement agencies, although two recent court decisions and an appellate court decision in New Jersey have recognized the impracticability of such a requirement (*State vs. Williams*, *State vs. Teare*).

The fifth and perhaps most important matter is the existence of considerable published data originating from presumably competent sources showing frequent, unacceptable discrepancies between the results of analyses for ethanol in nearly simultaneous blood and breath samples from the same subject [23,27]. Table 3 presents an accumulation by Harger of data exemplifying this in a report for the Department of Transportation [45].

This form of tabulation, while useful, does not provide individual data points, a suitable visual image, or the necessary information for statistical evaluation of discrepancies such as are to be seen in the form of presentation shown in Fig. 2, and, for example, in Fig. 1 of Ref 31. One exemplar [81] taken from Table 3 is one of the few in which the appropriate raw data, including numerical values, were given for such a display. When no actual numbers are provided, reasonably accurate statistical estimates may be made from the figures (see legend, Fig. 2).

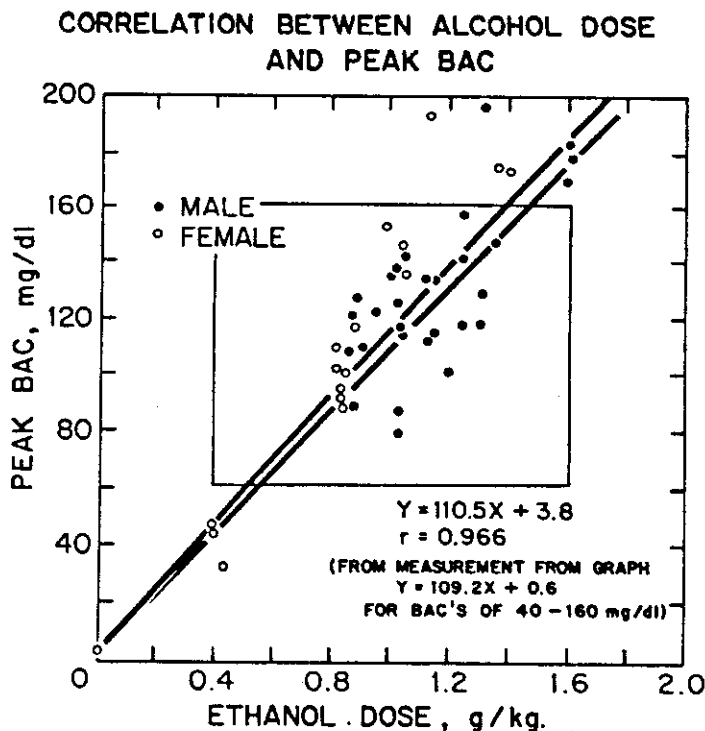


FIG. 3—The data [122] demonstrate part of the hazard attending estimation of the ingested dose of alcohol in response to a hypothetical question involving assumption of a given peak blood alcohol concentration. Similar variations in rate of decline of blood alcohol concentration (not shown) compound the error which may attend retrograde extrapolation.

Most of the various reported studies were made under well-controlled conditions and it is possible, indeed likely, that truly double-blind comparisons under field conditions might show a greater frequency and degree of disagreement. Inasmuch as many generally accepted instruments or analytical procedures can satisfactorily determine ethanol in a vapor sample properly presented to them (as is readily demonstrated by analysis of vapor samples from simulators or equilibrators), other causes must be sought to explain why the conversion of a quantity of ethanol per unit volume of breath to a blood concentration is fraught with possible error. Several of these, which have been dealt with in some detail elsewhere [27], will now be briefly reconsidered and up-dated.

The Validity of the Presumption of an Uncomplicated Obedience to Henry's Law

This question arises because the delivered breath is not a vapor phase that has come to a certain equilibrium as is the case for proper samples from simulators, equilibrators, or in certain kinds of headspace analyses. If (as is surely, though presumptively, the case) substantially complete equilibrium in partition of ethanol between pulmonary capillary

plasma and alveolar and arterial vapor is achieved at the existing temperature, normally about 37.5°C (100°F), that equilibrium is certainly altered during expiration. As the dead space regions of the bronchiolar-bronchial tree are reached there is both cooling and contact with the liquid on epithelial surfaces kept in a state of continuous disequilibrium with the vapor phase by the to and fro movement of that phase by the respiratory process. Indeed, experience with the time required to attain equilibrium in headspace analyses [82-84] suggests strongly that, with the surface area-volume relationships existing in the dead space region, equilibrium of ethanol is *not* almost instantly attained along the bronchial tree during expiration as is frequently assumed or implied. The question is certainly amenable to experimental study with *in vitro* models.

Under these circumstances, as is emphasized by Wright et al [85], it should not be expected that the *in vitro* blood/breath partition ratio at 34.5°C (94°F) as determined by analysis of tonometer-vapor of blood containing known, added amounts of ethanol should be precisely the same as the *in vitro* ratio obtaining in the case of delivered deep lung breath (at the same temperature) which had been in equilibrium with pulmonary venous blood (or its plasma). Further, there is now a question [86] as to whether inorganic anticoagulants added to blood placed in tonometric devices such as simulators, equilibrators, or devices for headspace collection may have significantly increased the vapor phase concentrations of ethanol in studies previously reported.

Also, recent observations have demonstrated both positive and negative fluctuations in arterial-alveolar partial pressures of CO₂ [87]; however, this gas has a much more complex transport system. No observations have been reported in respect to ethanol.

Failure to Obtain a Deep Lung (Substantially Alveolar) Breath Specimen

The difficulties encountered in consistently capturing alveolar air have long been known to physiologists. Pains have been taken in their studies to collect the terminal portion of a prolonged forced expiration. In more recent times, rapidly responding instrumentation has permitted better study of the requirements for reaching an alveolar plateau by prolonging expiration. Ideally, the expiration should be against a minimal increment above ambient pressure and the rate of breath movement should not be limited by the diameter of the orifice of the mouthpiece or lumen of the inlet tube or other obstructions in the breath pathway. However, this imposes difficulties in sampling and fixation of the temperature of the breath at the mouth. It has been found that when a normal subject makes a forced expiration against ambient pressure the temperature of the breath at the mouth tends to rise progressively [88,89]. Imposition of some degree of obstruction to outflow (distal to the mouth) promotes reaching a temperature plateau in the range of 30 to 35°C (86 to 95°F) in the later phase of the expiration. Thus, expirograms obtained by Dubowski [15] from normal adults from 21 to 50 years of age under fixed conditions of flow-rate show that about two thirds of the maximum expiratory volume after a normal inspiration must be discharged to obtain an alveolar plateau in terms of both temperature (34.5°C) and composition.

Some breath-testing devices do not permit sufficiently rapid flow of air without a considerable pressure increase, and a near-terminal sample is difficult to obtain without some practice. In law enforcement practice many subjects are encountered who have structural or functional disorders of respiration limiting their ability to reach an alveolar plateau. Observations of subjects taking breath tests suggests that there is frequent failure to meet the conditions required to obtain a substantially alveolar breath sample. It is unlikely that suitable terminal end-expiratory specimens invariably (or nearly so) are obtained, especially

under field conditions. Devices which capture rebreathed air [32,90,91] may be needed more nearly to attain the sample desired. It should be recognized that rebreathed air is not identical to deep lung or alveolar air. It appears likely that its efficacy will lie in the empirical advantage of providing better agreement of the results of analyses for ethanol in nearly simultaneous blood and breath specimens. This is a result of such air having a partial pressure of ethanol closely corresponding to that which would have been present had a truly alveolar specimen been delivered at the same temperature at the mouth. Fortunately, failure to capture a substantially alveolar specimen leads to a false low result (to the advantage of the tested subject) when the quantity of ethanol found is converted to a presumed blood concentration by *calculation*.

Uncertainty of the Value for the Blood/Breath Ratio for Alcohol

When breath tests were first used in traffic law enforcement the value of the blood/breath ratio employed in converting a concentration of ethanol in an expired alveolar air-component of a breath sample to a presumed arterial (or postabsorptive venous) blood concentration was believed to be about 2000:1, that is the amount of ethanol in 2000 ml of what was alveolar air as delivered at the mouth was equal to that present at the time in 1.0 ml of pulmonary venous (or postabsorptive venous) blood of presumed normal composition [29,92-95]. This clearly was an approximation as the temperature of delivered breath at the mouth was not universally agreed upon; however, it became evident that an earlier estimate of 1150:1 [96] and a later revision of this to 1300:1 [97] were grossly erroneous. A little later the careful and comprehensive study by Harger et al [71], which included determination of the partition of ethanol between air and water, blood, and urine over a range of temperature, found an *in vitro* ratio for blood quite close to 2000:1 at 34°C (93°F), which by then was rather widely accepted as the appropriate temperature of a delivered specimen in breath testing. Similar findings for air and aqueous solutions of ethanol were reported by Grosskopf [98-100]. Figure 6 in Ref 71 illustrates the degree of some of the discrepancies in earlier investigations as well as the technical proficiency exhibited in the study.

Slightly later measurements of the ratio *in vivo* for blood/alveolar air and blood/rebreathed air by Harger and other colleagues [31,32] indicated that in their view 2100:1 was a nearer approximation; however, the data presented in their Fig. 1 in Ref 31 in an earlier study illustrate well the experimental variance in the individual results. In an appendix to a report by the Committee on Tests for Intoxication of the National Safety Council on evaluation of chemical tests [101] the value was stated (as the alveolar air-blood ratio) to be "approximately 1:2100" and this is the value almost invariably employed during the last 22 years. The need for qualifying phraseology is evident on examining the data presented in the report itself and especially those data in Ref 102 that were part of the experimental work upon which the report was based. The spread in individual values for ethanol found in nearly simultaneously collected specimens of blood and breath is of the same order as shown in Table 3 which includes several more recent papers.

These various studies had raised questions regarding the validity of the 2100:1 ratio, but the ratio was reaffirmed after a reconsideration (but not experimental verification) by a group with international representation in 1972 [103].

A rather surprising range of values for the blood/breath ratio for ethanol is to be found in the literature of the last 45 years. Table 4 contains a partial listing of those reported values together with other values for the ratio calculated from published paired blood and breath alcohol concentration data. Note 2, Table 4 identifies references containing data

which may be satisfactorily evaluated statistically. It appears that the true value (with a small inherent biological variation in normal subjects), if indeed there is such, lies somewhere in the range of 1900 to 2400:1.

A report of Jones et al [86] is of particular interest because it presents data which may support the view that the presently used ratio of 2100:1 is somewhat low. They suggested that in the earlier determinations the blood analyzed often contained inorganic anticoagulants in sufficient amounts to increase significantly the ethanol in the vapor phase as a result of enhancement of concentration of nonvolatile solutes in the liquid phase ("salting out"). When heparin is used as an anticoagulant the amount required does not significantly increase the nonvolatile solute concentration. This could explain the higher value of the ratio which they obtained. If confirmed, the effect of the anticoagulant could largely account for the mean low calculated values of blood concentrations found in correlation studies. It does not, however, account for the spread of the discrepancies reported (Table 3) in which several causes may be involved [27,45].

Effects of Temperature on the Concentration of Ethanol in Breath

Temperature affects the value of the blood/breath ratio because between 30 and 40°C (86 to 104°F) the vapor pressure curve of ethanol is rather steep and the partial pressure P_{ak} exhibits an increase such that the air/blood partition coefficient K_{aw} rises to about 1.8 times its initial value. [71].

The temperature of alveolar air is believed to be that of the mean temperature of the blood perfusing the lungs which in turn closely approximates body temperature as determined in the mouth or rectum. Normal body temperature is not a rigid, constant 37.0°C (98.6°F) for all well subjects at all times, nor is it free from modest fluctuations in a given individual [104,105]. Rarely, the "set" of body temperature may be significantly different than 37°C (98.6°F) (usually lower) in an otherwise well person. Mild fever and drug-induced hypothermia (usually from aspirin) are not infrequent occurrences in ambulatory subjects.

The temperature of alveolar air is modified on expiration by mixing with dead-space air whose temperature and heat capacity are in part determined by the temperature and humidity of inspired air, the rate of inspiration, the dimensional architecture of the bronchial tree, the proportion of vital capacity expired, and the rate of expiration. Clearly, even when all of the dead-space air has been swept away there must be some heat transfer to the surfaces of the larger, proximal structures of the bronchial tree, otherwise the temperature upon reaching the alveolar plateau at the mouth would have to be about 37.0°C (98.6°F). In the latter phase of expiration in a comfortable ambient temperature of less than 34.5°C (94°F) (which is usually the case) and against a modest pressure, the temperature of breath, saturated with water vapor, at the mouth is commonly found to be 34 to 34.5°C (93.2 to 94.1°F) [15]. Hence, when instruments are used at such ambient temperatures the inlet tube into which the breath is blown should be heated a few degrees above 34.5°C to avoid condensation of vapor in the tube with loss of ethanol from the sample to be analyzed.

The magnitude of these influences has been the subject of numerous investigations. Early studies made prior to the development of rapidly responding temperature recorders have been reviewed by Winslow et al [106] and report temperatures of expired breath under ordinary ambient conditions of temperature and humidity ranging from about 32 to 35°C (92 to 95°F). Galeotti [107,108] reported expired air temperatures ranging from 34.4 to 34.8°C (93.9 to 94.6°F) in contrast to the lower values given by Liljestrand and Sahlested [109]. The averages of values found prior to 1928 and given by Perwitzschky

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[110] were 33.8°C (92.8°F) for breath expired via the mouth and 33.5°C (92.2°F) via the nose. As might be expected, at very low ambient temperatures, expired breath may be considerably cooled, and a temperature as low as 25°C (77°F) has been reported [111]; the average is 27.2°C (80.9°F) at -8°C (17.6°F). Such might be inferred from the subjective sensations arising in the chest on breathing remarkably cold air. Harger et al [31] reported a range of 31 to 35°C (88 to 95°F) from beginning to end of expiration for subjects inhaling through the nose and exhaling deeply. The effects of these matters on breath ethanol concentration were reported by Wright [88,89,112], who found that after rapid initial rise as the dead-space air was expelled, the breath ethanol continues to rise slowly and continuously during expiration over a range of 10 to 50% during the whole expiration. The rise could be reduced by offering some resistance to expiration or abolished by having the subject keep his mouth closed three to five minutes before testing. These effects were believed to be temperature related and consistent with the findings of Cole [113] regarding expired air temperature and humidity.

The events transpiring in the dead space, related to dimensions, rate of movement, surface liquid film, pressure, and other factors determining the extent to which equilibrium is approached, appear to be more important than modest variations in the partial pressure of ethanol in the alveolar spaces of normal subjects due to small temperature fluctuations. It would be of considerable interest to study temperature changes in the same individual induced by agents such as typhoid vaccine and aspirin to see whether the temperature and compositional changes inferred from Henry's Law are, in fact, reflected in deep lung breath delivered at the mouth.

Thus, in the field use of breath testing, the assumption of the captured sample having a temperature of 34°C (93.2°F) may be an approximation—an average of individual values having considerable variation, the extent also probably depending partly on incidental structural features of the instruments used in accumulating the data. Testing of a subject in a building or in a warmed (or air-conditioned) squad car only partially eliminates potential causes of end-expiratory temperature variation.

It is difficult to escape the conclusion that knowledge of the temperature of the breath sample taken for analysis is needed to detect possible gross changes in body temperature and to ascertain that an alveolar plateau has been attained. It should, therefore, be obligatory to establish the conditions required for reaching the plateau of both temperature and composition for each kind of instrument, with sampling arranged to occur during the period of the combined plateau. The provision of this information, as previously stated, would appear to be desirable, specified standards for evidential breath-testing devices. Under such controlled circumstances there was little individual variation from the mean value of the temperature at the plateau for healthy adults in a recent study [15]. Larger variations if observed in law enforcement practice may be treated with a correction factor as soon as adequate experimental data are available, and thus no longer would contribute significantly to the error in conversion of a breath quantity to a blood concentration.

Effects of Variations in the Cellular Composition of Blood

Ethanol is distributed in the water of blood. The water contents of plasma and cellular components (mostly erythrocytes) differ considerably. Variation in the cellular composition, as revealed by the hematocrit reading, can contribute to discrepancies in results of analyses for ethanol in nearly simultaneous blood-breath specimens regardless of what blood/breath ratio is assumed, as any ratio employed is derived from studies using normal blood presumably with an hematocrit reading of about 47%. Various sources for average normal values give different figures, ranging from 44 to 47% for U.S. and

TABLE 4—Values for the ratio of blood alcohol concentration (BAC) to breath alcohol concentration (BrAC) reported in the literature or computed from published data for paired blood-alcohol and breath-alcohol concentrations.

Study	Author(s)	Date	Refer- ence	BAC/BrAC Ratio				Specimen				Notes
				Mean	Range	SD	Subjects	Sample Pairs	Blood	Breath		
1	Liljestrand and Linde	1930	92	~2000	...	...	...	...	venous	alveolar		1
2	Haggard and Greenberg	1934	96	1142 2098	1117-1170 1833-2139	±19 ±44	1 1	8 8	arterial arterial	alveolar expired		1, 2, 4 2, 4
3	Haggard et al	1941	97	1307	1180-1423	...	100	...	venous	rebreathed		1
4	Harger et al	1950	31	~2100	1583-2927	...	33	...	venous	alveolar		1
5	Akiya et al	1951	143	~2100	1836-2816	...	...	...	venous	rebreathed		1
6	Seiferl and Günther	1951	144	2287	1921-2739	±262	...	21	...	...		2
7	Greenberg and Lester	1954	145	2222	...	...	6	...	capillary	expired		1
8	Harger et al	1956	32	~2100	1909-2450	±157	4	18	...	...		2, 3
9	Coldwell	1957	146	2442	...	...	31	93	capillary, venous	rebreathed		1
10	Brugsch et al	1959	147	3478	...	...	66	253	venous	end-expiratory		2, 3
11	Smith	1959	148	2358	1004-7289	...	26	...	venous	expired		2
12	Lereboullet et al	1961	149	2023	1922-3240	±454	10	10	venous	alveolar		2, 3
13	Begg et al	1962	150	2062	...	...	...	18	...	end-expiratory		3
14	Begg et al	1964	139	2540	2178-2811	±227	18	54	venous	end-expiratory		3

15	Forney et al	1964	90	2226	...	4	9	arterial	rebreathed	2
16	Freund and O'Hollaren	1965	151	2614	2272-2778	2	13	venous	alveolar	2
17	Enticknap and Wright	1965	152	2625	2333-2877	2	...	arterial	alveolar	2, 3
18	Fukui	1969	153	1787	...	36	...	venous	expired	1
19	Noordzij	1969	154	2350	...	...	17	venous	end-expiratory	1, 3
20	Harger and Forney	1969	91	2247	...	49	...	capillary	end-expiratory	3
				2146	...	49	...	capillary	rebreathed	3
21	Franklin	1969	140	2300	...	...	46	venous	end-expiratory	1
22	Prouty and O'Neill	1971	46	2600	...	...	46	venous plasma	end-expiratory	1
23	Jones and Jones	1971	155	2479	1634-3177	...	283	capillary	end-expiratory	1
24	Morales	1972	156	2320	...	...	...	capillary	end-expiratory	2, 3
25	Yamamoto and Ueda	1972	157	2384	...	...	74	venous	end-expiratory	1
26	Morales	1974	158	1950	...	35	170	venous	end-expiratory	3
27	Jones	1974	159	2372	...	18	67	venous	rebreathed	1
				2392	2120-2950	15	84	capillary	end-expiratory	3
				2226	1980-2400	10	22	venous	end-expiratory	2
				1948	1720-2110	10	23	venous	end-expiratory	2
						10			rebreathed	2

1. Indicates that the values in the BAC/BrAC Ratio column are given by the author(s) cited; all other BAC/BrAC values were calculated by the present authors from data in the cited references.
 2. Indicates that the cited reference includes BAC/BrAC data required for the usual statistical correlation analysis.
 3. Indicates that BAC/BrAC computations are based on the assumption that the breath-alcohol apparatus or procedure employed in the cited study was calibrated on a 2100:1 BAC/BrAC basis.
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European populations. If blood from a blood bank is used, the hematocrit reading usually is considerably lowered and the ionic strength increased by the added diluents, preservatives, and hemolysis.

Most deviations in value involve lower percentages of cellular volume so that the ethanol per unit volume of such a blood is slightly higher than would be the case if the hematocrit reading were normal. The potential error due to deviation in cellular volumes in ambulatory drivers is not large, rarely exceeding -2 to $+5\%$ of the calculated value obtained by conversion of a breath quantity. The main difficulty is forensic in that the conversion is based on the assumption that the blood in question had the normal proportions of plasma and cells. In retrospect it is difficult to understand why plasma (or serum) was not chosen as the sample of choice for traffic blood-alcohol analysis as the water contents of plasma or serum vary only slightly in ambulatory subjects. The advantage of plasma or serum for use in a number of analyses in the clinical chemistry laboratory had already been widely recognized by 1935.

Effects of Status of Absorption and Distribution of Ethanol

During absorption and distribution of ethanol into the water of the tissues, the arterial blood has a higher concentration than venous blood because of diffusion of ethanol from capillaries into tissue cells. This occurs until the concentration gradient becomes negligible. Thus, when comparisons are made of the ethanol concentrations in nearly simultaneous venous blood and breath specimens the subjects must be in the postabsorptive state with an insignificant arteriovenous ethanol difference or else arterial blood must be drawn. Capillary blood may approach arterial blood in ethanol concentration but does not equal it. In most such studies it is venous blood that is drawn with a breath specimen, both taken after an interval thought but not always proven sufficient for completion of the distribution.

In law enforcement practice, however, the status of absorption and distribution of ethanol is always uncertain, so that in a given subject the arterial concentration may be higher than the venous concentration. The magnitude of the differences in relation to the time since the last beverage was taken has been studied and discussed elsewhere [27,37,90]. Because of the usual interval between apprehension and the taking of a breath sample, very large arteriovenous differences are no doubt infrequent, but the circumstances of some arrests and their time frames strongly suggest that failure of the subject to be post-absorptive could lead to his breath's yielding a significantly higher calculated blood concentration than that present in venous blood, which is almost invariably taken when blood is sampled in traffic law enforcement.

In some states such as Texas and Oklahoma the subject has a choice between submitting to a blood test or a breath test. If he is not postabsorptive the result of a breath test could be discriminatory compared to a blood test which might have saved him from a charge of driving while intoxicated being filed. However, the choice of a blood test could be against the public interest in that the arterial blood concentration, if correctly reflected by a breath test, is the better indicator of nervous system impairment because of the very rapid diffusion of ethanol into the water of brain tissue.

Examination of trial transcripts reveals that these matters are not always properly clarified by either the prosecution or defense in direct or cross-examination of witnesses. The present trend toward perhaps extreme protection of a defendant's rights in respect to admissibility and interpretation of technical evidence makes it likely that this issue will be dealt with judicially one way or another.

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The "Steeple" Effect and Related Matters

Surprisingly short interval fluctuations in blood ethanol concentration have been reported during monitoring by continuous flow techniques [114,115] and by following the decline of blood alcohol concentration, after attainment of a high value, by frequent discrete analyses [116,117]. Similar fluctuations soon after administration are well-known phenomena with many other drugs [118,119]. These do not appear to be artifactual and if further confirmed they provide another cause of possible discrepancy between the results of analyses for ethanol of nearly simultaneous specimens of blood and breath. The technically more difficult problem of continuous monitoring of ethanol in expired alveolar air, further to confirm "steeping," appears not to have been undertaken to date.

A forensic problem encountered at trial with the results of both breath and blood analyses (and apparently still in some jurisdictions, analyses of urine) is that of a witness being asked to estimate the ethanol concentration which was present in the biological material concerned at a prior time considerably removed from the time of taking of the sample actually analyzed; that is to engage in speculative "retrograde extrapolation." Again, examination of trial transcripts reveals that this is not infrequently undertaken with assignment of a rather precise value, usually one thought to obtain at the time of apprehension.

It is unusual for enough reliable information to be available in a given case to permit a meaningful and fair value to be obtained by retrograde extrapolation. If attempted, it must be based on assumptions of uncertain validity, or the answer must be given in terms of a range of possible values so wide that it is rarely of any use. If retrograde extrapolation of a blood concentration is based on a breath analysis the difficulty is compounded. These conclusions inescapably follow from the biological variation in rates of oxidation of ethanol [23,120-122] as well as uncertainties related to matters discussed above. (See Fig. 3.)

Comments

Dose-Response to Ethanol

The legal difficulties related to individual variation in dose-response to ethanol are further compounded by the large individual differences in quality of driving performance which are due to other factors. These, especially, include inherent features of nervous system function such as reaction time, coordination, quickness and quality of judgments, perception, and matters affecting these, including psychiatric makeup (particularly in respect to aggressive behavior). In addition, deficiencies related to age, state of health, and a variety of environmental features affecting attention, domestic affairs, fatigue, and so forth, all contribute to the quality and, hence, the relative safety of motor vehicle operation.

Measurable impairments of nervous system functions are importantly related to the sensitivity of the testing procedure. Some tests might be capable of invariably demonstrating impairments at concentrations of ethanol in blood as low as 0.03 to 0.05% w/v and this is strongly suggested by the subjective sensations accompanying consumption of a single bottle or can of common beer. For this reason, especially, judgments regarding legally allowable concentrations have been derived from real-life experiences such as the relation of accident frequencies to blood ethanol concentration in the subjects involved and experimental studies of real or simulated driving performances in relation to blood

alcohol concentration [23]. The complex nature of the effects of ethanol relevant to driving are dealt with in the previously mentioned reviews [17-19].

Thus state legislatures, judiciaries, and federal agencies in dealing with these problems have, in general, responded to the demands of public interest by placing statutory limitations on the blood alcohol concentrations allowable for legal operation of a motor vehicle. These concentrations are based on studies indicating that some significant degree of impairment could be demonstrated in any individual attaining a blood alcohol concentration at or above the statutory limit, and not on the basis that the driving skill of the individual has become less competent than that of individuals free from ethanol and legally driving.

The point is that the statutory limitations are arbitrary (but not capricious) and that presently it is considered in the public interest that a motor vehicle may not legally be operated by a driver with a blood alcohol concentration above 0.05, 0.08, or 0.10% w/v, depending on the state concerned. Some states have statutory provision for a lesser offense when a low blood alcohol concentration is found in instances in which other aggravating factors were present in the traffic situation concerned. The arbitrary nature of the limitations makes reasonable accuracy in the determination of whether a violation has occurred all the more desirable.

The Complexity of the Physiology and Chemistry of Breath Testing

Law enforcement personnel engaged in chemical testing must be capable of properly performing the testing procedures with the instrument used in their jurisdictions, including those procedures which are safeguards to assure reliability of results and which are specified in the Highway Safety Program Manual [25]. However, the need for competency in the physiology and chemistry of breath testing could be essentially eliminated by two developments: (1) the already existing federal regulations requiring the use only of instruments that, when properly employed, provide an analytical result for the concentration of ethanol in a vapor phase of acceptable accuracy and precision, and (2) by reporting the analysis in terms of the concentration of ethanol in the breath sample analyzed.

Informational and Forensic Resources

There is a need for improved informational and forensic resources for defense attorneys. This should not impede the administration of justice; rather it is highly desirable in that it increases the likelihood of proper observation of imposed testing, regulatory, and monitoring procedures. In addition it should encourage more careful preparation of cases by prosecutors and better preparation for giving evidence by witnesses for both the state and defense. Such information would also be available to the judiciary for consideration during trial. Thus, justice is more satisfactorily meted out in a given case.

Preservation of Chemicals Used in Analysis

If oncoming judicial decisions require the preservation of chemicals used in analysis, it is likely that instruments employing wet oxidizing agents such as dichromate solutions will decline or disappear from use unless alternate procedural safeguards are found acceptable. For example, the preservation and availability of an aliquot of the breath specimen may be required [123-125]. It is strongly recommended that the federal requirements for approval of an evidential breath tester be amended to provide that a portion of the breath specimen, substantially identical with that actually analyzed, be saved (for example, trapped by an adsorbent) for later confirmatory analysis if such is desirable or necessary. The problem of preservation of reagents is not encountered in

methods involving infrared photometry, electrochemical oxidation, and gas chromatography.

Discrepancies

Frequently there are unacceptable discrepancies between the results of analyses of nearly simultaneous blood and breath specimens from the same subject. It is questionable whether Henry's Law is properly applicable in assessing the composition of breath that has left the shelter of the minute dimensions of the alveolar and atrial spaces. Thus alveolar breath enters a dynamic environment with fluctuating temperature and humidity consequent to the movements and the properties of expired and inspired air, that is, mixing with gas that has not been alveolar air, accompanied by unpredictable alterations in the ethanol concentration in the fluid on the surface of a system having a progressively diminishing and variable surface/volume relationship.

It is possible that in normal subjects there is sufficient biological variation in these respiratory parameters that there is no closely regulated blood/breath ratio as might be anticipated from Henry's Law in a system at equilibrium and which is demonstrable for vapor/liquid phase samples from simulators or equilibrators. It is especially likely that a fixed blood/breath ratio does not obtain in field application of breath testing where the various other requirements for obtaining a proper sample for analysis and the subsequent calculations are not presently being met with certainty.

It is very unlikely that with presently approved instrumentation substantially alveolar expired breath samples, free from inescapable biological perturbations not subject to control, are consistently obtained. While this is a disadvantage in respect to law enforcement it does not unjustly affect the accused because a concentration of ethanol in mixed expired or otherwise compositionally distorted air at proper temperature is less than would be the case if a truly alveolar specimen were obtained. Whether this difficulty can be overcome by instrumentation employing rebreathed air as the sample remains to be shown.

If the present policy of conversion of a found breath quantity to a presumed blood concentration were retained, the value of the blood/breath ratio employed in the calculation becomes critical. A procedure which has been suggested to lessen the possibility of injustice in a given case is to require by statute an arbitrary subtraction from a given calculated value so that the concentration in the blood would be at least that of the corrected value beyond reasonable doubt. Inasmuch as this would probably have to amount to a quantity two or three times the standard deviation of the mean difference found in nearly simultaneous blood-breath comparisons the consequence would be escape of an undesirably large fraction of subjects from a charge.

The effect of temperature on the concentration of ethanol in a breath sample can and should be controlled by measuring the delivered temperature of the aliquot used for analysis. This would aid in determining whether an alveolar plateau had been reached and would also aid in identifying subjects who had significantly abnormal body temperatures or who had been given a test under improper ambient conditions. If documented as feasible by appropriate investigation, the conversion of a found value to a corrected value at a standard temperature (34.5°C or 94.1°F) might be undertaken.

There is no solution to the matter of variations in cellular content of the blood except that of determining the hematocrit reading. As the effects on the calculated blood concentration of variations found in ambulatory subjects are small they could be ignored. A forensically more defensible procedure would be the subtraction from a reported calculated value of the maximum positive error due to anemia which might be expected to occur with any significant frequency. To define by statute the allowable plasma or serum concentration (which would be 0.112% w/v for a jurisdiction having a

whole blood limit of 0.1% w/v) and to analyze plasma or serum would minimize this cause of error in conversion of a breath concentration to a presumed concentration in a component of circulating fluid.

The status of absorption and distribution does not affect the presumed blood concentration obtained by calculation if the value calculated is specified as that obtaining in pulmonary venous blood. Any value reported is that presumed present in the sample when obtained, and no estimate of the value at any earlier time should be attempted. Such retrograde extrapolation is not needed if the offense is defined by statute in terms of a quantity found at the time the specimen was taken with appropriate limitation on the time lag allowed.

Data are not presently available to permit an opinion as to whether the steeping effect presents a forensic problem for breath analysis except in the comparison of results of analysis for ethanol in nearly simultaneous blood and breath specimens. Continuous monitoring of breath in the trachea and proximal portion of the bronchial tree (easily undertaken in experimental animals but more difficult in human subjects, even those with tracheostomies) in performing blood/breath comparisons would perhaps also settle the question whether the blood/breath ratio in normal subjects is a constant with a relatively small standard deviation.

All of these vexing matters are avoided by the expedient of reporting only the quantity of ethanol found per unit volume of delivered breath within a specified range of temperature and defining the offense by statute in terms of the amount of ethanol allowable per unit volume of the sample analyzed [27]. Many data have already established what the amount should be to conform with present standards dealing with blood. Thus, for those states using the federal standard of 0.1% w/v blood alcohol concentration, a convenient corresponding breath quantity would be 0.1 g/210 l (476 $\mu\text{g/l}$), at 34.5°C (94.1°F) and saturated with water vapor. Ambient barometric pressure need not be considered in direct breath-alcohol analysis [126] or when remote sampling involves adsorption of ethanol onto a surface [123] as in column chromatography. In statutory revision it would be wise to stipulate the corresponding equivalent for plasma and serum concentrations and also to delineate the corresponding values in the International System of Units (SI units), which, like complete acceptance of the metric system, is making rather slow but inexorable progress toward general use.

In a previous communication [27] dealing in part with the imponderables encountered in the conversion of a breath quantity to presumed blood concentration a portion of a summarizing statement was "that in actual law-enforcement practice, when a breath-sample is analyzed for alcohol, the quantity found cannot be used to calculate the simultaneously existing actual blood concentration without making assumptions having uncertain validities in any given case because they have not been assessed."

Informal discussions with a number of scientists who have had lengthy experiences with the technical, administrative, and forensic aspects of breath-testing did not bring forth any significant disagreement with the factual information on which that statement was based and which has been reviewed and extended here. In spite of this, most of those consulted initially did not favor immediately implementing steps necessary to place breath-testing on a firmer technical and juridical foundation. A few, in essence, were distinctly unsympathetic with the idea of "rocking the boat" in an area of traffic law enforcement which, from their point of view, seems to be working well enough as it is. The most commonly presented objections have been that the various states have just finished amending their statutes and passing new legislation to conform with the federal requirements which direct that a breath alcohol analysis be reported as its presumed blood concentration equivalent; that a vast amount of effort has been spent on blood-breath correlation studies which have been used to support the validity of the transmogrification of a breath quantity to a blood concentration; that the Uniform Vehicle Code has been amended to meet the

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present federal guidelines; and that grave forensic problems would follow any change which implies that breath testing, as applied for many years, actually suffers from unacceptable flaws.

These objections seem to imply an inflexibility in the law and its applications of a degree hardly supported by the facts. Especially in recent times rapid change has been a striking feature of operational, procedural, and interpretive details of our legal system in respect to both social questions and matters of criminality. The control of alcohol in traffic safety has both social and criminal aspects.

During 1974 the proposal to report breath-ethanol concentration as such evidently gained considerable acceptance. In February 1975, the Executive Board of the Committee on Alcohol and Drugs of the NSC adopted a resolution recommending revision of the Uniform Vehicle Code so that blood and breath analyses for alcohol are dealt with separately but in parallel [127]. Thus for breath, in a given jurisdiction, the quantity of ethanol present in 210 litres of substantially alveolar air (0.10 g in the case of states using the limit of 0.10% w/v for blood and 0.08 g/210 l for states using the 0.08% w/v standard for blood), could define by statute the alcohol-related element of the offense of driving while under the influence of alcohol. It is hoped that the NHTSA will give sympathetic consideration to including the recommendation in the forthcoming revision of the Highway Safety Program Manual. If such were the case it is likely that application in actual traffic law enforcement could begin within about two years.

This would be a significant step forward. Certainly it is worthwhile to make changes in any facet of regulations of human behavior when such changes are clearly perceived as right on the basis of information available at the time. In the law-science relationship it is inconceivable that recognizably faulty science should be employed to bolster good law.

Summary

Breath analysis for ethanol, especially in respect to the forensic aspects, has been reviewed. Included are matters dealing with instrumentation, physiological factors involved in the elimination of ethanol via the breath, and, especially, the uncertainties in the calculation of a whole blood concentration of ethanol from the quantity found in breath.

We believe that the conversion of a breath quantity to a blood concentration of ethanol, for forensic purposes, should be abandoned and that the offense of driving while under the influence of alcohol should be statutorily defined in terms of the concentration of ethanol found in the breath in jurisdictions employing breath analysis. The breath sample should be obtained and analyzed only with instruments having capabilities which would require some extension of present federal standards for evidential breath-testing devices.

Events in early 1975 indicate that implementation of some of these proposals may soon be undertaken.

APPENDIX

The following summary of applications of regression analysis to data from blood/breath measurements for ethanol was very kindly provided by Mr. Brian O'Neill, Vice President, Research, Insurance Institute for Highway Safety, Washington, D.C.

Fitting a Regression Line to Blood/Breath Measurements

Consider a set of n pairs of simultaneous or nearly simultaneous measurements x_i, y_i , where x_i is the blood-alcohol concentration (BAC) as measured from blood samples and y_i is the corresponding BAC as measured from breath analysis.

The variable x is referred to as the independent or regressor variable and is assumed to be measured without appreciable error. If we assume a linear relationship between the variables x and y of the form

$$y = a + bx \quad (1)$$

then the usual least squares estimators are

$$b = (n \sum_{i=1}^n x_i y_i - \sum x_i \sum y_i) / (n \sum x_i^2 - (\sum x_i)^2) \quad (2)$$

$$a = (\sum y_i - b \sum x_i) / n \quad (3)$$

The inverse relationship is

$$x = (y - a) / b \quad (4)$$

If the widely used blood/breath partition ratio of 2100:1 is used in the breath apparatus to convert an intermediate breath alcohol concentration to a blood alcohol concentration, then $y = 2100Z$ where Z = breath alcohol concentration. Therefore substituting in Eq 4 we have

$$x = (2100/b)Z - a/b \quad (5)$$

Accuracy

The estimated values of a and b for the regression equation can be used to make inferences concerning the accuracy of both the apparatus and the blood/breath partition ratio. To separate the two sources of inaccuracy we must assume that apparatus biases cause constant errors; if there are design reasons to suspect percentage errors due to apparatus biases, it is not possible to separate the two sources of inaccuracy.

An estimate of the accuracy of the apparatus can be obtained from the estimated values of a , the intercept in Eq 1. An unbiased apparatus should have a very small or zero value for this parameter.

Thus in the three regressions presented in Prouty and O'Neill [Appendix A of Ref 46] the values for a were 0.007, 0.002, and 0.005, relatively small numbers indicating that the Breathalyzers® used in those experiments were essentially unbiased.

If the breath apparatus is unbiased then it is clear from Eq 5 that an estimate of the ratio that would have produced unbiased results from the breath apparatus that was used is $2100/b:1$.

Thus in the three regressions presented in Prouty and O'Neill the values for b were 0.832, 0.861, and 0.847, yielding ratios of 2524:1, 2439:1, and 2479:1 that would have produced accurate blood alcohol concentrations from the Breathalyzers® used in those experiments.

The variances of both a and b can be computed and used to provide more objective information concerning the accuracy; however, for the purposes of this elementary exposition, the details of these calculations have been omitted.

Precision

It is not possible using a single regression equation derived from BAC measurements from several subjects to separate the measurement variation due to the apparatus and due to the blood/breath partition ratio varying among individuals. Separation of these two sources of variation would require regression equations to be computed for each individual subject.

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If we note the earlier assumption that x_i is measured without appreciable error and we assume that the observed y_i (BACs measured from breath analysis) are distributed normally about some expected value with variance $S^2_{y|x}$ then

$$S^2_{y|x} = [(n - 1)/(n - 2)](S^2 - b^2S^2_x)$$

where

$$S^2_x = \frac{n \sum x^2 - (\sum x)^2}{n(n - 1)},$$

$$S^2_y = \frac{n \sum y^2 - (\sum y)^2}{n(n - 1)},$$

The quantity $S^2_{y|x}$ estimates that part of the variance of y left unexplained by the regression of y on x and is a measure of the precision of the measurements. The positive square root $S_{y|x}$ is sometimes called the standard error of estimate.

In the three regressions presented in Prouty and O'Neill [46] the values for $S_{y|x}$ were 0.0097, 0.0107, and 0.0103.

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