Forensic Science, Medicine, and Pathology

ISSN 1547-769X/07/3:33–40/$30.00 (Online) 1556-2891
DOI: 10.1385/Forensic Sci. Med. Pathol.:3:1:33

ORIGINAL ARTICLE

The Estimation of Blood Alcohol Concentration

Widmark Revisited

Douglas Posey[1] *and Ashraf Mozayani*[2]

[1]Georgia Bureau of Investigation, Decatur, GA;
[2]Harris Country Medical Examiner's Office, Houston, TX

Address for correspondence and reprints:

Douglas Posey
Georgia Bureau of Investigation
3121 Panthersville Road
Decatur, GA, 30037
E-mail:
Douglas.Posey@gbi.state.ga.us

Accepted for publication:
July 21, 2006

Abstract

Expert witnesses and others involved in toxicology are frequently asked to perform retrograde extrapolation of blood alcohol concentration (BAC) or to estimate BAC based on a proposed drinking scenario. Although many individuals are reluctant to perform these calculations and some jurisdictions expressly prohibit them, a significant number of practitioners routinely estimate BAC based on this type of calculation, using as a basis the fundamental work of Widmark. Although improvements to the Widmark formula and other data pertaining to the pharmacology of alcohol have been published, these improvements are frequently ignored when estimating BAC. This article summarizes five published models for the estimation of BAC and proposes a sixth model that incorporates recent data on the rate of absorption of alcohol from the GI tract into the existing five models. The five improved models can be computerized and used to construct comparative snapshots of the BACs calculated by the different algorithms. This will allow practitioners to provide a more balanced picture of the variability in BAC calculations.

Key Words: Forensic toxicology; Widmark; extrapolation; alcohol; ethanol; blood.

(DOI: 10.1385/Forensic Sci. Med. Pathol.:3:1:33)

INTRODUCTION

Driving under the influence of alcohol (DUI) is a persistent worldwide problem. Violators are subject to monetary fines, loss of driving privileges, arrest, and imprisonment. Owing to the potential serious consequences of DUI, many of these cases require appearances in court. A significant percentage of DUI trials involve the testimony of expert witnesses who in many instances are asked to extrapolate blood alcohol concentration (BAC) at a previous time based on laboratory BAC results (retrograde extrapolation), or to predict a BAC based on a particular drinking scenario.

Although some experts in the field discourage the practice of predicting BAC levels, the fact is that virtually every expert witness who testifies in DUI cases has been asked to do just that, and most of those that agree to perform the calculation rely on the Widmark equation *(1)*. This equation is based on elimination rates and a factor known as the "Widmark factor," ***r***, that were established by E. M. P. Widmark in 1932 by examining a number of men and women and determining average values for the elimination rate and ***r***.

The purpose of this article is to discuss the use of the Widmark equation in BAC calculations and to suggest improvements to the use of that equation.

ALCOHOL PHARMACOKINETICS

Absorption

The absorption of alcohol from the stomach has been recently studied *(2)*. The first order rate constant for the absorption of alcohol from an empty stomach was found to average 6.5 ± 1.5 hours^{-1} which translates to a half-life of 0.1066 hours and would indicate that 99% of the alcohol is absorbed in about 0.75 hours (45 minutes). At the other extreme, assuming that the absorption of 99% of the alcohol from a full stomach takes 2 hours, the rate constant is about 2.3 hours^{-1} and the half-life about 0.3009 hours. Many calculations are based on a general rule of thumb that says that alcohol is completely absorbed somewhere between 30 minutes and 2 hours after the ingestion of the alcohol. This assumption is valid if the time since the last drink is more than 2 hours, but is of little help for recent ingestions of alcohol (i.e., within the past hour).

Distribution

Most BAC calculations are based on the Widmark formula,

$$C = \frac{A}{rW} - (\beta t) \quad (1)$$

where C is the blood alcohol concentration; A is the mass of alcohol consumed; ***r*** is the Widmark factor; W is body weight; t is elapsed time since the start of drinking; and β is the elimination rate.

The Widmark factor ***r*** is variable and depends on body mass, percentage body fat, age, and sex. Widmark tested a large number of individuals and found that the average value of ***r*** for males is 0.68 ± 0.17 and for females is 0.55 ± 0.11. Researchers after Widmark *(3–6)* attempted to improve the Widmark formula, primarily by developing methods to more accurately estimate the value of ***r***.

Watson *(6)* calculated the total body water (TBW) of males and females using their age in years (G), weight (W), and height (H). In order to avoid confusion with the letter W, the symbol Q will be used to represent Watson's TBW. Thus, the BAC based on Watson's data can be determined according to the formula

$$Q(\text{females}) = 0.2466W + 10.69H - 2.097$$
$$Q(\text{males}) = 0.3362W + 10.74H - 0.09516G + 2.447$$

where W is in kilograms and H is in meters. After correcting for the specific gravity of blood, the adapted Widmark formula becomes

$$C = \frac{0.844A}{Q} - \beta t \quad (2)$$

where 0.844 is the average weight/volume ratio of water in blood. Since ***r*** = Q/0.844W, the Watson Q value can be converted to

$$r_{Watson}\,(\text{females}) = 0.29218 + \frac{12.666H}{W} - \frac{2.4846}{W}$$

$$r_{Watson}\,(\text{males}) = 0.39834 + \frac{12.725H}{W} - \frac{0.11275G}{W} + \frac{2.8993}{W}$$

Forrest *(7)* calculated the value of ***r*** using a formula that relies on the body mass index (BMI) in order to more accurately address the issue of percentage body fat. He assumed that the water content of blood is 80% *(7)* and that the water content of the body's fat-free mass is 72.4%. *(8)* When W is body weight in kilograms and H is height in meters,

$$r_{Forrest}\,(\text{females}) = 0.8736 - \frac{0.0124W}{H^2}$$

$$r_{Forrest}\,(\text{males}) = 1.0178 - \frac{0.012127W}{H^2}$$

which can then be used to calculate the BAC using Eq. 1.

Seidl et al. *(8)* gathered height (in centimeters), weight (in kilograms), blood water content, and TBW data for 256 women and 273 men and used the data to fine tune the Widmark equation according to the formulae

$$r_{Seidl}\,(\text{female}) = 0.31223 - 0.006446W + 0.4466H$$
$$r_{Seidl}\,(\text{male}) = 0.31608 - 0.004821W + 0.4632H$$

Ulrich, Cramer, and Zink *(9)* developed an equation to determine the Widmark ***r*** value based on experiments with 386 males (weight in kilograms and height in meters), viz.

$$r_{Ulrich}(\text{male}) = 0.715 - 0.00462W + 0.22H$$

Ulrich used only male subjects, so the resulting BAC parameters are not applicable to calculations of BAC in females.

Elimination

The three factors that are by far the primary contributors to the calculation of BAC are the rate of absorption of the alcohol from the gastrointestinal (GI) tract, the distribution of the alcohol in the body (reflected by ***r***) and the rate of elimination from the body. Widmark measured the elimination rate, β, in a large number of individuals and found it to average about 0.018 g% per hour^{-1} *(1)*. Elimination rate has also been found to vary significantly among individuals. The average elimination rate is about 0.018 g% per hour^{-1}, with the range between 0.009 and 0.035 g% per hour^{-1} *(9–11)*. BAC calculations are frequently based on an estimated elimination rate between 0.017 and 0.020 g% per hour^{-1}.

All five of the methods listed here calculate an ***r*** value that can be plugged into the Widmark equation (Eq. 1) in order to arrive at an estimated BAC value. A review of the variables contributing to the differences observed when using the various methods has been presented *(12)*.

Average r Value

Because all of these methods ultimately arrive at an ***r*** value or a value that can easily be converted to ***r***, it is possible to calculate an average ***r*** value from the several different methods, thus

$$r_{avg(male)} = 0.2\left(r_{Widmark} + r_{Watson} + r_{Forrest} + r_{Seidl} + r_{Ulrich}\right)$$
$$r_{avg(female)} = 0.25\left(r_{Widmark} + r_{Watson} + r_{Forrest} + r_{Seidl}\right)$$

One way to arrive at the r_{avg} value is to calculate each of the individual ***r*** values and determine the mean. This method has the advantage of allowing for the determination of a standard deviation. A second method uses the fact that all of the ***r*** values are derived from the same variables (i.e., age, sex, height, and weight). As a result, all of the equations contain the same variables and can be algebraically combined, resulting in a single formula that calculates an r_{avg} that can be directly substituted into the Widmark equation. Thus, if the value of $r_{Widmark}$ is taken to be the average of 0.68 for males and 0.55 for females,

$$r_{avg\ (male)} = 0.62544 + 0.13664H - W(0.00189 + 0.002425/H^2) + 1/W(0.57986 + 2.545H - 0.02255G)$$

$$r_{avg\ (female)} = 0.50766 + 0.11165H - W(0.001612 + 0.0031/H^2) - 1/W(0.62115 - 3.1665H)$$

MULTIPOINT BAC CURVE GENERATION

The method outlined thus far allows for an estimation of the BAC based on an r_{avg} calculated by a number of different algorithms that take into account such personal variables as age, sex, weight, and height. As such, it is adequate for a rough estimation of BAC. However, none of the equations address the rate of absorption from the GI tract, although the inclusion of that parameter is relatively easy. The rate equation governing the absorption is first order and can be written as

$$A_{absorbed} = A_{ingested}(1 - e^{-t \ln 2/t_{1/2}})$$

or

$$A_{absorbed} = A_{ingested}(1 - e^{-kt})$$

where $A_{absorbed}$ is the total amount of alcohol absorbed from one ingestion; $A_{ingested}$ is the amount of alcohol contained on the drink; t is the elapsed time since the ingestion; and $t_{1/2}$ is the absorption half-life; and k is the absorption rate constant.

This value for $A_{absorbed}$ can be substituted into either Eq. 1 or Eq. 2 to provide a more accurate reflection of the rate of absorption on the final BAC value at a given time. From Eq. 1, the contribution to the total BAC from the *n*th drink is

$$BAC_n = \underset{r\mathrm{W}}{A_{ingested}(1 - e^{-kt_n})} - (\beta t_n) \quad (3)$$

or from Eq. 2

$$BAC_n = \underset{\mathrm{Q}}{0.8[A_{ingested}(1 - e^{-kt_n})]} - (\beta\, t_n) \quad (4)$$

where t_n is the time of the *n*th drink and k is the absorption rate constant. If $t_n > 7 \cdot t_{1/2}$, more than 90% of the ingested alcohol will have been absorbed. The presence of food in the stomach can be dealt with by inserting the rate constant for an empty stomach (6.5 hours^{-1}) or a full stomach (2.3 hours^{-1}).

The total observed BAC is the sum of the BACs for each individual drink. Thus,

$$BAC_{total} = \sum_0^n BAC_n$$

DISCUSSION

For the purpose of estimating the BAC, the absorption of alcohol from the gut is assumed to be first order, with a first-order rate constant of about 0.1 for an empty stomach and about 0.3 for a full stomach.

The elimination of alcohol in humans is known to follow Michaelis-Menten kinetics, that is, the rate of elimination is not a constant as suggested by Widmark but is actually determined by the relationship

$$\text{Rate} = \frac{V_{\max}[BAC]}{K_m + [BAC]}$$

where V_{max} is the maximum rate of elimination, K_m is the Michaelis constant and, [BAC] is the blood alcohol concentration.

K_m is the BAC at which $V = {}_{1/2}\, V_{max}$. V_{max} is determined by the specific alcohol dehydrogenase (ADH) isozymes present and the amounts of those isozymes in of a given individual. The specific ADH isozymes are determined by the genetic makeup of the individual, whereas the amount of each isozyme is determined by genetics and also by drinking history. Thus, V_{max} is approximately constant for a given individual at a given time, as is K_m.

It can be seen from the Michaelis-Menten expression that if the BAC is much greater than K_m, the enzyme is completely saturated and the rate expression reduces to

$$\text{Rate} = -V_{\max}$$

where the elimination is zero order and linear. This linear portion of the curve where Michaelis–Menten kinetics are less significant and where the application of a linear elimination model seems justified occurs in those situations where the BAC is greater than about 0.015–0.020 g%.

Using the equations outlined above for the determination of ***r***, calculations of total BAC utilizing all three major contributors can be performed to provide a more balanced view of the range of possible BAC values in a given situation, including those in which all of the alcohol has not yet been absorbed from the gut. The manual calculation of BAC curves by this method is tedious since it requires a calculation of the BAC_{total} at regular short intervals during the course of the absorption, distribution, and elimination process. The following examples were calculated using the method outlined here by using a time interval of 6 minutes (i.e., the BAC_{total} was calculated every 6 minutes until the alcohol was completely eliminated from the system). In order to emphasize the variability among the BAC calculated from the several ***r*** values, the BAC curve for the ***r*** value from each algorithm is displayed, as well as the average BAC curve.

EXAMPLE 1

A 23-year-old male, 6′2″ (188 cm), 231 pounds (105 kg) consumed one drink containing 2.5 ounces of 151-proof liquor. Assuming an absorption half-life of 0.1066 hours^{-1} and using Eqs. 3 and 4, the BAC can be calculated at selected intervals (e.g., every 6 minutes) for each of the mathematical models. The results are shown in Table 1.

Table 1
Comparison of BAC Values Calculated by Five Different Models

Time since drink (minutes)	*Widmark (1)*	*Watson et al. (3)*	*Forrest (4)*	*Seidl et al. (5)*	*Ulrich et al. (6)*
6	0.0259	0.0283	0.0269	0.0259	0.0276
12	0.0395	0.0431	0.0410	0.0395	0.0421
18	0.0457	0.0500	0.0475	0.0456	0.0487
24	0.0480	0.0526	0.0499	0.0479	0.0512
30	0.0483	0.0531	0.0503	0.0482	0.0517
36	0.0475	0.0524	0.0496	0.0475	0.0510
42	0.0462	0.0512	0.0483	0.0461	0.0497
48	0.0446	0.0496	0.0467	0.0446	0.0481
54	0.0429	0.0479	0.0450	0.0428	0.0464
60	0.0410	0.0461	0.0432	0.0410	0.0446

Legend: Upper curve = BAC calculated from r_{avg} using Widmark parameters
Middle curve = BAC calculated from r_{avg} using Watson parameters
Lower curve = BAC calculated from r_{avg} using Forrest and Seidl parameters. The Forrest and Seidl curves are nearly coincident.

Fig. 1. BAC curves for example 2. Legend: Upper curve = BAC calculated from $\boldsymbol{r_{avg}}$ using Widmark parameters Middle curve = BAC calculated from $\boldsymbol{r_{avg}}$ using Watson parameters Lower curve = BAC calculated from $\boldsymbol{r_{avg}}$ using Forrest and Seidl parameters. The Forrest and Seidl curves are nearly coincident.

EXAMPLE 2

A 23-year-old female, height 5′4″ (163 cm) and weight 126 pounds (57.3 kg) consumed one shot of 80 proof liquor every 6 minutes for 1 hour, beginning at 9 PM, for a total of 11 shots. Each shot was assumed to contain 1.25 ounces of liquor. Figure 1 shows the result of calculating the BAC using an elimination rate of 0.018 g% hour^{-1}, an absorption rate constant of 6.5 hours^{-1} and Widmark's average $\boldsymbol{r}$ value for females of 0.55. Table 2 shows the magnitude and time of the peak BAC. The lower curve on Fig. 1 is composed of both the Seidl

Table 2
Comparison of Time of Example 2 Peak BAC by Five Models

Peak BAC (g%)	*Time of peak*	*Method*
0.376	10:30 PM	Widmark *(1)*
0.338	10:30 PM	Watson et al. *(3)*
0.306	10:30 PM	Forrest *(4)*
0.305	10:30 PM	Seidl et al. *(5)*
N/A for females		Ulrich et al. *(6)*

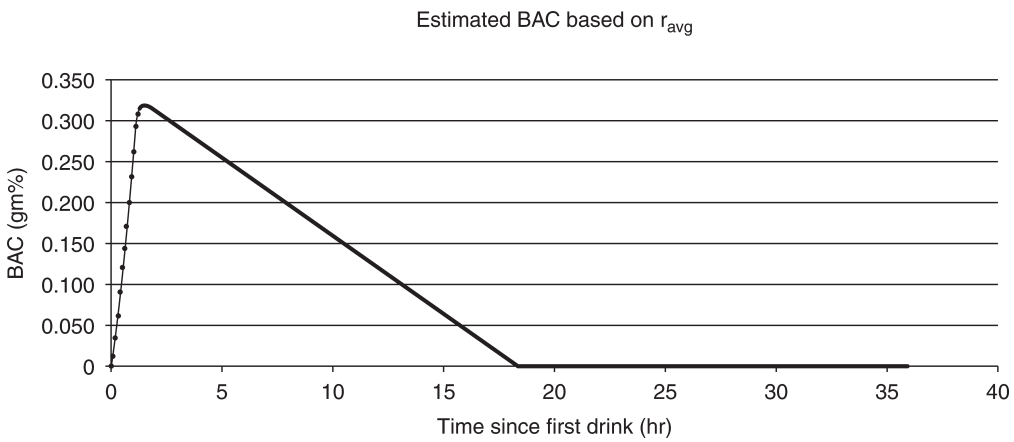
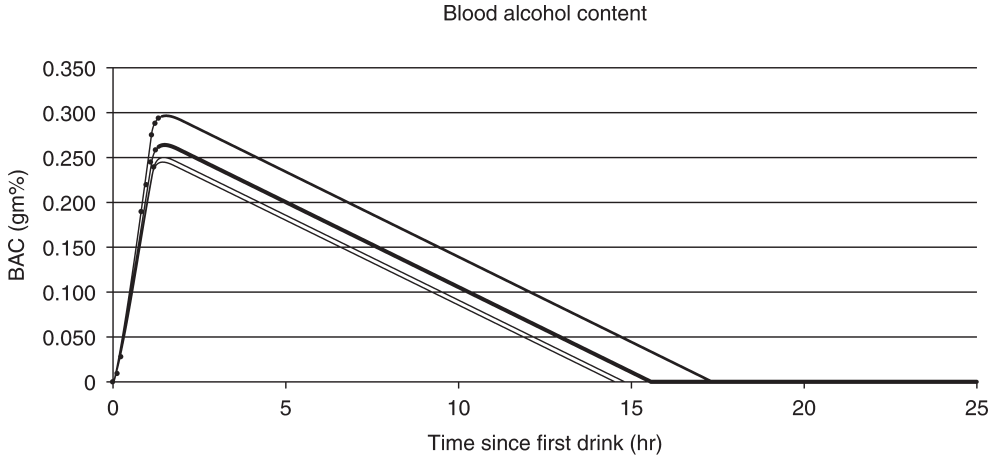


Fig. 2. BAC curve for example 2 generated from $\boldsymbol{r_{avg}}$.



Legend: Upper curve = BAC calculated using Widmark parameters
Second curve = BAC calculated using Forrest and Watson parameters. The two curves are nearly coincident
Third curve = BAC calculated using Seidl parameters
Lower curve = BAC calculated using Ulrich parameters.

Fig. 3. BAC curves for example 3. Legend: Upper curve = BAC calculated using Widmark parameters, Second curve = BAC calculated using Forrest and Watson parameters. The two curves are nearly coincident, Third curve = BAC calculated using Seidl parameters, Lower curve = BAC calculated using Ulrich parameters.

and Forrest curves, which are nearly coincident. The Ulrich parameters do not apply to females and do not appear on this graph. Figure 2 is the BAC curve generated from $\boldsymbol{r_{avg}}$.

EXAMPLE 3

The parameters utilized in this example will be identical to Example 1, except the sex will be changed to male and Widmark's ***r*** value will be the average for males of 0.68. Figure 3 shows the BAC curve and Fig. 4 shows the magnitude and time of the peak BAC. The center curve on this chart is composed of both the Watson and Forrest curves, which are nearly coincident. The Ulrich and Seidl curves appear quite close together as the lower two curves.

From these examples and the previous discussion, it seems apparent that the major contributors to the estimation of BAC are the selection of the elimination rate, the rate of absorption from the gut and the selection of the ***r*** value. The method provided here addresses the latter two contributors. By utilizing $\boldsymbol{r}_{\text{average}}$, the arbitrariness of the selection of a particular model is eliminated, as well as providing a method for the consideration of lean body mass. The selection of elimination rate remains somewhat arbitrary, but a maximum and minimum can be determined by inserting extreme values of the elimination rate in the above equations.

This method works best when the calculations are performed by computer, allowing for the simple generation of

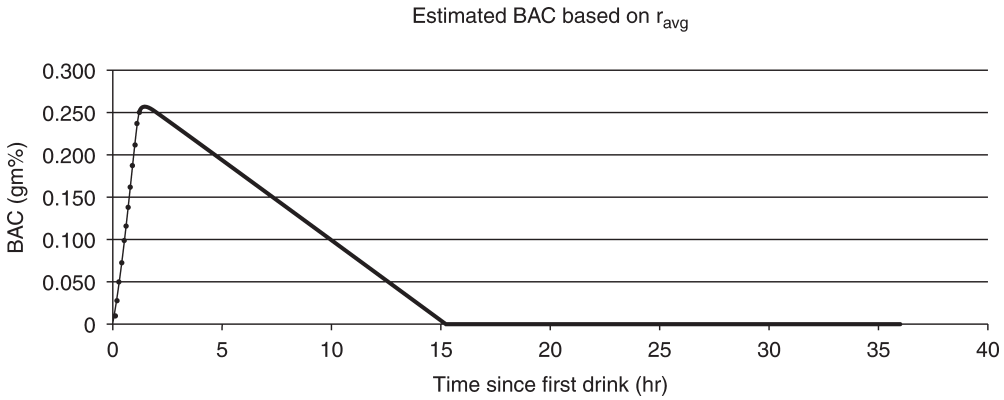


Fig. 4. BAC curve for example 2 generated from $r_{avg.}$

BAC curves by calculating BAC at frequent small time intervals. The computer can also easily incorporate the first-order absorption of ethanol from the gut.

CONCLUSION

From these examples, two significant phenomena are obvious. The first is that the sex (and thus the Widmark value) contribute to a significant difference in the calculated BAC value and thus the magnitude of the Widmark value must be accurately estimated. The second is that the simple Widmark calculation used by many experts results in a higher BAC than any of the other methods, whereas the other methods tend to agree with each other and not with Widmark. The primary reason for the elevated numbers obtained when using the Widmark ***r*** value is that the other methods calculate ***r*** based on measured parameters rather than relying on the average value obtained from a small group of individuals in 1932.

Many alcohol experts are reluctant to perform retrograde extrapolations or calculate estimated BAC values. For those that do perform these calculations, however, it seems apparent that a "one equation fits all" approach is inadequate in an adversarial legal proceeding. Expert witnesses and any other individual who calculates BAC values should look at several different methods for calculating BAC. Any necessary assumptions should be based as much as possible on scientific data and any calculations should include all three factors affecting the final BAC (i.e., absorption, distribution, and elimination). The utilization of an average ***r*** value provides a more balanced prediction of the BAC at a given time, whereas the utilization of a computer program that calculates the BAC at intervals of six minutes provides a simple, accurate way to predict the magnitude of the estimated BAC at any particular time, based on easily available physical measurements. Although the approach may be somewhat more mathematically challenging, it is easily computerized and will result in a more uniform, and perhaps more accurate, reflection of the true BAC at the time in question.

Educational Message

1. Improved algorithm for the estimation of BAC at relatively high concentrations.
2. Expression of the need to include several established methods when estimating BAC.

ACKNOWLEDGMENTS

The authors would like to acknowledge Farrokh Tabeee for his mathematical and computer assistance.

The authors have stated that they do not have a significant financial interest or other relationship with any product manufacturer or provider of services discussed in this article.

REFERENCES

1. Widmark EMP. Die theoretischen Grundlagen und the praktische Verwendbarkeit der gerichtlich-medizinischen Alkoholbestimmung. Berlin: Urban & Schwarzenberg, 1932.
2. Uemura K, Fujimiya T, Ohbora Y, Yashuhara M, Yoshida K. Individual differences in the kinetics of alcohol absorption and elimination:A human study, Forensic Sci Med Pathol, 2005;1:24–27.
3. Watson PE, Watson ID, Batt RD. Prediction of blood alcohol concentrations in human subjects:updating the Widmark equation. J Stud Alcohol 1989;42:547–556.
4. Forrest ARW. The estimation of Widmark's factor. J For Sci Soc1986;26:249–252.
5. Seidl S, Jensen U, Alt A. The calculation of blood ethanol concentrations in males and females. Int J Legal Med 2000;114: 71–77.
6. Ulrich L, Cramer Y, Zink P. Relevance of individual parameters in the calculation of blood alcohol levels in relation to the volume of intake. Blutalkohol 1987;24:192–198.
7. Altman PL, Dittmer DS, eds. Blood and Other Body Fluids.Washington DC: Federation of American Societies for Experimental Biology, 1961.

8. Durnin JVGA, Womersly J. Body fat assessed from total body density and its estimation from skin fold thickness. Br J Nutr 1974;32:77–97.
9. Dubowski KM. Human pharmacokinetics of ethanol: I. Peak blood concentrations and elimination in male and female subjects. Alcohol Tech Rep 5, 1976:55–63.
10. Shajani NK, Dinn HM. Blood alcohol concentrations reached in human subjects after consumption of alcoholic beverages in a social setting. Can Soc Forensic Sci J 1985; 18:38–48.
11. Tam TW, Yang CT, Fung WK, Mok VK. Alcohol metabolism of local Chinese in Hong Kong: a statistical determination on the effects of various physiological factors. Forensic Sci Int 2006;156:95–101.
12. Zuba D, Piekoszewski W. Uncertainty in Theoretical Calculations of Alcohol Concentration. Presented at the 17th International Conference on Alcohol, Drugs and Traffic Safety (ICADTS), Glasgow, UK, 2004. Available at: http://www.icadts.org/T2004/O22.html.