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Prediction of Blood Alcohol Concentrations in Human Subjects[1]

Updating the Widmark Equation

Patricia E. Watson, M.H.Sc., Ian D. Watson, Ph.D.
and Richard D. Batt, Ph.D., D.Phil.

SUMMARY. *Equations are derived for expressing the relationship between alcohol intake and blood alcohol concentration in terms of total body water and the blood water fraction. These equations are more exact than Widmark's, and if used in conjunction with regression equations to calculate total body water, will give more accurate predictions of BAC.*

IN RECENT YEARS traffic and health authorities around the world have presented the drinking public with numerous charts and reckoners that aim to inform people of the amount of beverage alcohol they can drink with safety. Most of these are based on calculations that use the Widmark equation (1) to estimate blood alcohol concentration (BAC).

It is nearly 50 years since Widmark first published this important equation, and while still basically correct, to use it in the same form today is to fail to take advantage of the data from numerous studies on body fluids published since 1950 (2). We show herein that the Widmark equation can be recast, with use of these data, to yield more accurate predictions of BAC.

The Widmark Equation

The Widmark equation describes the relationship, under fasting conditions, between the total amount of alcohol ingested (A), the alcohol concentration in blood at zero time (C_0) and the body weight (p):

$$A = r \times p \times C_0. \qquad [1]$$

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Here r is a factor defined as the fraction of the body mass in which alcohol would be present if it were distributed at concentrations equal to that in blood.

The rate of alcohol metabolism in humans is linear under most conditions, particularly at moderate BACS, and under such conditions, the Widmark equation can be modified by substituting the term

$$C_0 = C_t + \beta t, \qquad [2]$$

so that equation 1 becomes

$$A = r \times p(C_t + \beta t) \qquad [3]$$

where C_t is the blood alcohol concentration after time t, and β is the rate of ethanol disappearance from the blood, i.e., the slope of the descending portion of the blood alcohol curve.

Values for r can be determined if all other variables in equation 1 or 3 are known. However, in most situations in which the Widmark equation is used, such as in predicting BACS, all other variables are not known, and r must be assigned a value. From measurements on 30 subjects (20 men), Widmark (1) assigned to r mean values of 0.68 ± 0.085 for men and 0.55 ± 0.055 for women. Since these estimations in 1932, other investigators have reported values ranging from 0.50 to 0.94 (3). In cases in which r was not measured under fasting conditions, values greater than 1.0 have been recorded, presumably due to delayed absorption of alcohol because of food in the gastrointestinal or alimentary tract (4). In such situations, alcohol would not be distributed rapidly to equilibrate throughout the body.

The Alcohol: Total-Body-Water Equation

The decision on what value to ascribe to r can be entirely avoided by reducing the problem to first principles. The composition of the total body mass can be described as the sum of the body fat mass (i.e., ether-soluble lipids) and the lean body mass. The latter may be defined as the total body water mass plus the total lean solids mass. Since alcohol does not dissolve in body fat to any appreciable extent but is freely miscible with water, ingested alcohol will be almost totally associated with the body water. Accordingly,, in any tissue, the alcohol content will be proportional to that tissue's water content. Alcohol is thus suitable for use as a solute to measure total body water volume and, in fact, has been used for this purpose (5–8). If we assume that when alcohol is

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ingested it is absorbed immediately and spreads instantaneously and uniformly throughout the body water, it follows that the concentration of alcohol in the total body water equals that in the blood water. However, alcohol concentrations are normally measured in whole-blood samples and expressed as the weight of alcohol per unit volume of blood. These whole-blood concentrations can be related to the concentration in blood water through the fraction of water in whole blood (B_w), defined as

$$B_w = \frac{\text{volume of water in blood}}{\text{volume of blood}}. \qquad [4]$$

If the weight (in grams) of alcohol ingested by fasting subjects is A, the total volume (in liters) of water in the body is TBW, and the hypothetical zero-time equilibrated blood alcohol concentration (in grams per liter) is C_0, then it follows that

$$\frac{A}{TBW} = \frac{C_0}{B_w} \quad \text{and} \quad A = \frac{TBW}{B_w} \times C_0 \qquad [5]$$

or, using equation 2,

$$A = \frac{TBW}{B_w}(C_t + \beta t). \qquad [6]$$

In deriving these equations it has been assumed that elimination of alcohol from the body follows zero-order kinetics.

Estimation of the Volumes of Body and Blood Water

To solve equation 5 or 6, estimates of TBW and B_w for each subject are necessary. The most precise estimate of TBW is obtained by direct measurement using isotope or other dilution methods which have an accuracy of ± 2 to 5% (9). In alcohol research, however, the time, equipment or expertise for such direct measurements may not be available. In that case, the volume of body water can be estimated with reasonable accuracy (± 9 to 11%) from linear regression equations derived by us (10) from simple anthropometric data. Total body water measurements (using solutes other than ethanol) of 458 men (aged 17 to 86) and 265 women (aged 17 to 84) were collected from the literature and used to construct linear-regression equations relating TBW to age, height and weight. The equations were designed to apply to any healthy Western adult population, from lean to obese. They do not apply to subjects with clinical evidence of edema or malnutrition, or to those receiving diuretic therapy, i.e., conditions where the relationship between *TBW* and body weight is disturbed.

In women, age was found not to be a significant variable, and the linear-regression equation which best fit the reported experimental data (when *TBW* was in liters, height in centimeters and weight in kilograms) was

$$TBW = -2.097 + 0.1069 \text{ Height} + 0.2466 \text{ Weight}. \qquad [7]$$

The total variation (coefficient of determination, CD) explained by this equation was 73.6%, and the standard deviation (SD) of the total body water was 3.6. The following simpler form was almost as satisfactory (CD = 71.7%, SD = 3.72):

$$TBW = 14.46 + 0.2549 \text{ Weight}. \qquad [8]$$

For men, the corresponding equations (including age in years which was found to be a significant variable) were as follows:

$$TBW = 2.447 - 0.09516 \text{ Age} + 0.1074 \text{ Height} + 0.3362 \text{ Weight}, \qquad [9]$$

(CD = 70.4%, SD = 3.76) and the next best equation (CD = 68.9%, SD = 3.86),

$$TBW = 20.03 - 0.1183 \text{ Age} + 0.3626 \text{ Weight}. \qquad [10]$$

The derivation of these equations is fully reported elsewhere (10), together with nomograms[2] for estimating *TBW* in men and women based on these equations. Equations 7 through 10 will need to be revised in the future if a major change in life-style results in a significant shift in the mean *TBW* of a population.

The *TBW* of any person thus can be either measured directly, calculated using one of the above equations or read from the appropriate nomogram. The fraction of water in the blood (B_w) can also be measured directly, or a mean value of .80 (6, 11) can be used, depending on the accuracy required. Normal variations from this mean value are small, and the error introduced by using .80 is acceptable. With this value for B_w, equations 5 and 6 then become

$$A = \frac{TBW}{.80} \times C_0 \qquad [11]$$

and

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[2] Enlarged versions of the nomograms from which *TBW* can be read more easily are available on request from the authors.

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$$A = \frac{TBW}{.80}(C_t + \beta t). \qquad [12]$$

The Accuracy Gained by Using TBW Estimations

The improved accuracy obtained by using the *TBW* estimation equations may be demonstrated if actual measured C_0 values are compared with those predicted by equation 11, and by the Widmark equation, transformed as follows:

$$C_0 = \frac{.80}{TBW} \times A \qquad [13]$$

and

$$C_0 = \frac{A}{r \times p}. \qquad [14]$$

Studies of alcohol consumption by healthy subjects under fasting conditions provided test data on 54 women (12–14) and 85 men (12, 14, 15). In the studies of women, *TBW* was estimated using equation 7 for one group (12), but equation 8 was used for the others (13, 14) because height measurements were missing. Widmark's mean r value of 0.55 was used in equation 14, with measured values for A and p. Alcohol dose varied from 0.4 to 0.9 g per kg of body weight, and the resultant zero-time blood alcohol levels (C_0) ranged from 58 to 136 mg per dl. The mean (± SD) measured C_0 was 91 ± 22 mg per dl; the mean C_0 calculated using the $A:TBW$ equation (i.e., equation 13) was 93 ± 23 and that calculated using the Widmark equation was 104 ± 26 mg per dl. Thus, while the $A:TBW$ equation gave a C_0 value very close to the measured value, Widmark's equation tended to overestimate blood alcohol by 13 mg per dl on average. The discrepancy is illustrated in Figure 1, where a histogram presents the difference between the measured and predicted C_0 values, calculated as a percentage of the measured value. When the $A:TBW$ equation was used, a normal distribution about zero (i.e., the measured C_0 value) resulted, 35% of subjects being within ± 5% of the measured C_0, 63% within ± 10%, and 83% within ± 15%. However, when the Widmark equation was used, the results were positively skewed, and in the majority of subjects the C_0 values were overestimated, many considerably so. Only 17% of subjects were within ± 5%, 31% within ± 10% and 50% within ± 15% of the measured C_0.

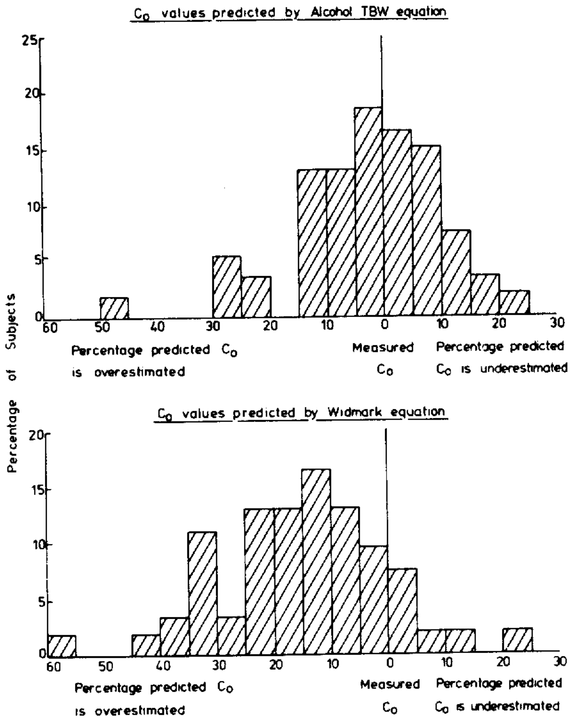

FIGURE 1.—*The Percentage Difference between C_0 Measured in Women and C_0 Predicted by the A : TBW Equation (upper graph) and the Widmark Equation (lower graph).*

In two studies of men (12, 15), equation 9 was used to calculate *TBW*, while in the third (14)—again because of lack of height measurements—*TBW* was calculated from equation 10. Widmark's mean *r* value of 0.68 was used in equation 14. Alcohol intake varied from 0.4 to 1.25 g per kg of body weight, and the resultant C_0 values varied from 48 to 212 mg per dl.

The mean measured C_0 for men was 103 ± 52 mg per dl, the mean C_0 calculated from the $A:TBW$ equation was 101 ± 51 and that calculated from the Widmark equation, 110 ± 54. Again, while the $A:TBW$ equation result was comparable with the mean measured value, the value derived from Widmark's equation was higher. The extent of this overestimation is shown more clearly in the histogram in Figure 2, which illustrates the difference between measured and predicted C_0 values, calculated as percentages of the measured C_0. When the $A:TBW$ equation was used, a normal distribution about zero again resulted, 44% of the subjects being within ± 5%, 62% within ± 10% and 87% within ± 15% of the

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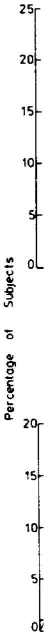

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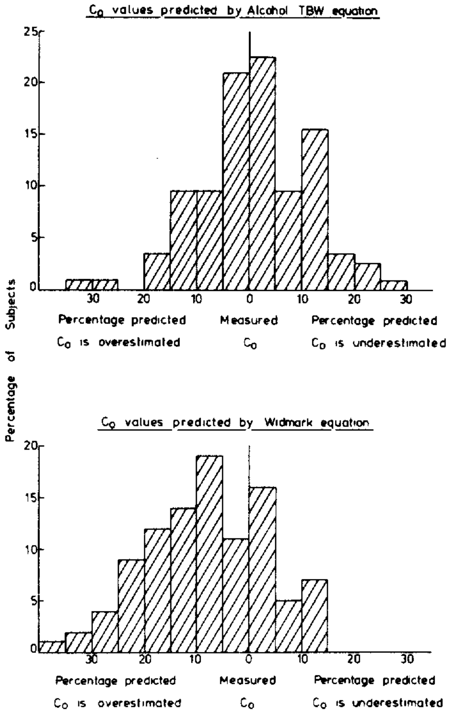

FIGURE 2.—*The Percentage Difference between C_0 Measured in Men and C_0 Predicted by the A : TBW Equation (upper graph) and the Widmark Equation (lower graph).*

measured C_0 value. When the Widmark equation was used, the results were again positively skewed, with most C_0 values overestimated. Here 27% of subjects were within ± 5%, 51% within ± 10% and 72% within ± 15% of the measured C_0.

Consideration of the difference between measured and predicted BACS, rather than C_0s, for both men and women gave results very similar to those in Figure 1 and Figure 2. Furthermore, a plot of measured C_0 against predicted C_0 showed no trend with dose, for either men or women, when the *A* : *TBW* equation was used.

Hence, not only does the Widmark equation overestimate the blood alcohol level in most cases, but it also predicts C_0 values much less precisely, particularly in women.

Practical Consequences of Using the A : TBW *Equation*

The alcohol-loading dose given to an experimental subject to produce a required C_0 is usually calculated in grams of alcohol per kilogram of body weight, with no correction for individual variations of the ratio of body fat to total body mass. Accordingly, there are wide variations in C_0, even when subjects are the same body weight. More uniform C_0 values between subjects will be obtained if the $A:TBW$ equation is used and doses are calculated on the basis of grams of alcohol per liter of body water. Alternatively, doses could be expressed as grams of alcohol per kilogram of lean body mass, since this is directly related to body water by the Pace and Rathbun equation (16):

$$\text{Lean Body Mass} = \frac{TBW}{0.73} \qquad [15]$$

In experimental work two additional factors are frequently estimated: the total amount of alcohol eliminated from the body per hour (b_{60}), and the rate of alcohol metabolism (R), expressed as the amount of alcohol eliminated from the body per kilogram per hour. Widmark calculated these factors using the following formulae:

$$b_{60} = p \times r \times \beta_{60} \qquad [16]$$

and

$$R = \frac{b_{60}}{p} = r \times \beta_{60} \qquad [17]$$

where the rate constant (β_{60}) is expressed per hour.

As methods of measuring body-fluid volume had not been developed in Widmark's time, he used the function $p \times r$ in equation 16 to estimate the body mass in which alcohol would be present if it were distributed at concentrations equal to those in blood. This is not necessary today, and the two factors can be defined more exactly as follows:

$$b_{60} = \frac{TBW \times \beta_{60}}{B_w} \qquad [18]$$

and

$$R' = \frac{b_{60}}{TBW} = \frac{\beta_{60}}{B_w}, \qquad [19]$$

where R' is the weight of alcohol eliminated per liter of body water per hour. However, as alcohol is metabolized primarily in the liver, and liver size is considered to be proportional to lean body mass *(LBM)*, it may be preferable to define R in terms of LBM as follows:

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where *LBM* is calculated using equation 15 and R'' is now expressed as grams of alcohol eliminated per kilogram of *LBM* per hour.

Using either equation 19 or 20 eliminates the confusion over effects of obesity on R which can arise if Widmark's formula 16 with its body-weight factor is used.

CONCLUSION

The major advantage of the $A:TBW$ equation lies in the prediction of BACS or alcohol intake. When Widmark's equation is used, a mean value must be assigned to r, and the resultant values can only be regarded as approximate for the individual. When the $A:TBW$ equation is used, however, with *TBW* estimated from equations 7 through 10, and a value of .80 for B_w, more precise individual results can be obtained. Variations in individual B_w from the mean value of .80 are minimal compared with variations in *TBW*.

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