The calculation of blood ethanol concentrations in males and females

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ORIGINAL ARTICLE

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Abstract In German-speaking countries, blood ethanol concentrations (BECs) are usually calculated using Widmark's equation. The distribution factor *r* of this equation is a correction factor needed to obtain a reduced body mass and corresponds to the ratio of total body water and blood water content. To enhance the reliability of Widmark's model equation, the body weight, body height, blood water content and total body water of 256 women and 273 men were measured. The ratio of body water to blood water ranged from 0.44 to 0.80 in women and from 0.60 to 0.87 in men. For both sexes equations were developed by multiple regression analysis which allow the determination of the individual, more realistic distribution factors r_{FI} (for females) and r_{MI} (for males) even when only body height and body weight are known. Drinking experiments revealed a clearly higher congruence of calculated and measured blood ethanol concentrations when r_{FI} or r_{MI} were used instead of rigid distribution factors, i.e. 0.6 for women and 0.7 for men with or without the assumption of a 10% so-called resorption deficit. Additionally, Widmark's equation in combination with r_{FI} or r_{MI} allows a more accurate prediction of blood ethanol concentrations than the equations of Watson and Ulrich.

Key words Bioelectric impedance analysis · Total body water · Widmark's equation · Watson's equation

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Introduction

Forensic expert opinions for courts concerning alcohol offences often require the calculation of blood ethanol concentrations (BEC) from given quantities of alcoholic beverages consumed, especially when blood samples have not been taken. In German-speaking countries courts and scientists therefore use Widmark's equation $C_o = A/[p \times r]$ where C_o is the extrapolated, theoretical maximum concentration of alcohol in blood (mg/g), assuming instantaneous absorption and distribution but without consideration of elimination [2, 3], A is the amount of alcohol in the body (g), and *p* the body weight (kg). Widmark defined the correction factor *r* as the ratio of total body ethanol and BEC [1]. Due to the close relationship between the ethanol content and the water content of organs, tissues and body fluids, *r* also corresponds to the ratio of total body water and blood water [4, 5, 6].

Numerous investigations have shown a tendency to overestimate blood ethanol concentrations using Widmark's equation in combination with rigid values for *r*, i.e., 0.6 for women and 0.7 for men and without consideration of a so-called resorption deficit [i.e. 7]. This fact was observed by Widmark in cases of food intake before, during or after the consumption of alcohol [1] and is especially noticeable after the intake of low concentrations of alcohol such as in beer. Due to the assumption of a general bioavailability of less than 100%, experts in German-speaking countries who calculate BECs, must in general consider a minimum resorption deficit of 10%, which may rise to 30% in cases such as those mentioned.

However, another reason might be that the values of the commonly used distribution factor *r* (0.7 for males, 0.6 for females) are too low in numerous cases. Widmark obtained these values from drinking experiments with 20 males and 10 females, with intake of high-proof alcohol (cognac, brandy) in short drinking times and without intake of food. Without the assumption of a resorption deficit, Widmark found a mean *r* value of 0.68 (range 0.51–0.85) in males and a mean *r* value of 0.55 (range 0.47–0.64) in females and reported considerable variations of *r* in different individuals [1]. Therefore, the main source of the bias between calculated and measured BECs might be that the use of rigid distribution factors does not reflect reality because of considerable interindividual variations of the total body water (TBW) [8, 9, 10, 11]. In cases where the bodily constitution is considered to differ from the norm, this fact can be taken into account in expert testimonies and alternative calculations can be made in court, using lower distribution factors as a rough estimate (i.e., 0.5 for females or 0.6 for males).

Since it is not feasible to find the values for TBW and blood water content (BWC) in individual cases [4, 9], some researchers have tried to determine the individual TBW using easily obtainable anthropometric data such as body height, body weight and age [7, 12, 13]. In most cases the equations proposed by Watson et al. [7] allow a more precise prediction of BECs than Widmark's equation. However, due to an underestimation of TBW by Watson's equations [14], considerable discrepancies of up to 50% between measured and predicted BECs can occur.

In 1987 an individual distribution factor called ρ_i was presented [15] which was derived by mathematical evaluation of more than 300 BEC graphs. The applicability of this individual distribution factor in court is restricted, however, as the study design only focused on males, short drinking times and a low to medium alcohol consumption.

Until recently, the measurement of TBW and body fat was time-consuming and expensive. This particularly applied to hydrodensitometry, a very accurate, but strenuous method for the test persons. A further development of the standard hydrodensitometry was the so-called Ulm vat system, which is a high-precision scale for the measurement of the body mass and a whole body bath for the measurement of the gas-free body volume [16]. Using the equation of Siri [17], body mass and gas-free body volume lead to very exact calculations of total body fat and fat-free mass but densitometric methods as well as rather imprecise skin-fold caliper measurements require additional assumptions for the estimation of the TBW. In contrast, D_2O stable isotope dilution allows a direct approach to the TBW compartment and is therefore a universally accepted reference substance for TBW [6, 18]. One disadvantage of this method is the reduction of the deuterium concentration in body water by H/D exchange with the acidic protons of organic molecules. Therefore the D_2O distribution compartment appears larger, corresponding to the actual size of TBW [18]. For this reason, Grüner and Endres performed dilution experiments with orally administered ethanol (0.8 g/kg body weight) [6, 18] which were compared with D_2O dilutions and revealed the ethanol compartments to be 2.3–3% smaller than those of D_2O. In these experiments, the ratio of blood water content/TBW ethanol (*r* values) ranged from 0.61 to 0.68 in women (mean: 0.63, SD ± 0.03) and from 0.70 to 0.80 in men (mean: 0.74, SD ± 0.03).

In terms of practicability especially in larger study groups, the bioelectric impedance analysis (BIA) seems to be a superior method to determine the extent of TBW. Bell et al. compared TBW predictions ascertained with the foot-to-foot BIA system TBF-305 with D_2O dilution TBW measurements [19] and found very close mean values for TBW D_2O (40.8 l) and TBW BIA (40.2 l) without a significant difference between the bias found for 29 males (–0.7 l) and 28 females (0.0 l), resulting in an overall bias for the cohort of –0.7 l. Compared with D_2O dilution, the authors found an underestimation of the TBW predicted by BIA which tended to increase at larger TBW volumes. Other authors reported standard errors of the TBW estimate by carefully performed BIA of generally less than 2 l of water, or less than 4% error for a nominal 50 l of TBW, while lower predictive values and higher standard errors were found in predicting the percentage of body fat [20, 21]. However, in cases of body mass indices higher than 30, standard errors up to 10% in predicting the percentage of TBW may occur [8, 16] but these are errors by chance and not systematic errors, making BIA suitable for TBW prediction in larger study groups [19].

In 1998 we published an equation to obtain individual distribution factors for females [8] and reported some preliminary evaluation data. The aim of the present study was to develop an equation for males, based on the ratio of TBW content and BWC thus permitting the determination of individual distribution factors and making an individual use of Widmark's equation easier. Furthermore, underlying physiological data of the equations are presented as well as an evaluation of data from drinking experiments in both males and females.

Material and methods

Measurements of TBW and BWC

After obtaining informed consent, the body weight, body height, TBW and BWC were measured in 256 healthy women (between 18 and 77 years of age, mean: 35.1 years) and 273 healthy men (between 18 and 81 years of age, mean: 34.4 years). Venous blood samples were drawn from an antecubital vein for every test person. BWC was determined by double gravimetric measurements. The studies were approved by the ethics committee of the University of Ulm.

Body weight and TBW were measured with the professional body fat analyser TBF-305 (Tanita Europe, Sindelfingen, Germany), using the BIA technology. For the measurements, the persons have to stand on a platform and place their feet on four electrodes. A current of 800 µA and 50 kHz is introduced into the body and flows through all conducting material present in the body in the path between the electrodes. The conductivity of body fluids such as blood and urine is high, that of muscle is intermediate and that of bone, fat, or air is low [22]. The actual parameter measured is the voltage that is produced between the two electrodes located at sites near to the sites where the current is introduced [21]. The measurement is expressed as the ratio V/I, called impedance *Z* which has two components, resistance (*R*) and reactance (*X*) [21, 23, 24, 25]. The resistance is equivalent to the square of the length of the conductor divided by its volume. The reactance of an object depends on its intrinsic electrical properties, i.e. cell membranes are poor conductors but good capacitors [22, 26]. In BIA the resistance is nominally about 250 Ω and reactance averages to only about 10% of this value, therefore, the value of Z is similar to that of R [21]. From the data obtained by this method and combined with body weight, body height and sex, the body fat analyser software calculates the individual total body water.

For multiple regression analysis, the ratio TBW/BWC was considered as a dependent variable r_{FI} or r_{MI}, body weight and body height were considered as independent variables X_1 and X_2. The parameters α, β_1 and β_2 in the equation r_{FI} (or r_{MI}) = $\alpha + \beta_1 X_1 + \beta_2 X_2$ were estimated by the least squares method. Statistical evaluation was performed with the software system SAS, version 6.12.

Drinking experiments

To verify the calculated blood ethanol concentrations, drinking experiments were performed with 30 volunteer women and 30 volunteer men. The studies were approved by the ethics committee of the University of Ulm and all persons gave their informed consent prior to the start of the experiments. Between the last meal and the start of drinking, a minimum time period of 2 h had elapsed and shortly before commencing drinking, body height and body weight were measured. In order to simulate social drinking conditions, the test persons consumed beer or wine according to choice within a 2.5 h time period but were not allowed to consume food. The BEC graph was monitored by breath alcohol testing (Alcomat, Siemens, Germany) and during the unequivocal ethanol elimination stage, four venous blood samples were taken at intervals of 30 min. BEC was measured by gas chromatography (head space method) in serum. The results were converted to whole blood ethanol concentrations ($^o/_{oo}$ w/w) with a constant conversion factor of 1.2, following the official guidelines for forensic ethanol analysis in Germany [27].

The differences between the four BECs measured for every test person showed a regular decrease, allowing the calculation of individual elimination rates which is the requirement for the determination of theoretical maximum ethanol concentrations C_o by extrapolation. These values were compared with expected C_o values, one resulting from calculations using Watson's equations, and four resulting from Widmark's equation with the individual reduction factor ρ_i, with rigid distribution factors (r = 0.6 for women, r = 0.7 for men) with and without a so-called resorption deficit of 10%, and with the individual distribution factors r_{FI} and r_{MI}, determined in this study.

Results

The anthropometric data body height, body weight, body mass index (BMI), blood water content and total body water are shown in Table 1. The ratio TBW/BWC (r) ranged from 0.44 to 0.80 in women (mean: 0.65, SD ± 0.06) and from 0.60 to 0.87 in men (mean: 0.76, SD ± 0.05).

No correlation was found between the parameter pairs age/BWC, age/TBW, body weight/BWC, BMI/BWC, body height/BWC and body height/TBW (Tables 2, 3). A slight correlation existed between body weight and TBW, a strong correlation between BMI and TBW (Tables 2, 3, Fig. 1 a, b) as well as between BMI and r (= TBW content/BWC, Tables 2, 3, Fig. 2 a, b). Using the method of least squares, the estimation of the parameters α, β_1 and β_2 of the equation $r = \alpha + \beta_1 X_1 + \beta_2 X_2$ gave the following results: α = 0.312230 (standard error 0.04269), β_1 = –0.006446 (stan-

Table 1 Anthropometric measurements from the 256 women and 273 men in this study

Parameter	Women (n = 256)			Men (n = 273)		
	Mean	SD ±	Range	Mean	SD ±	Range
Body height (cm)	165.5	6.2	149–181	179.1	6.5	161–200
Body weight (kg)	62.5	8.9	40–97.6	80.5	10.2	56.8–121.6
Body mass index (BMI)	22.8	3.2	15.2–34.9	25.1	2.9	18.5–34.5
Blood water content (BWC) (%)	79.5	0.97	77 –82.8	78.0	1.14	73.3–87.7
Total body water (TBW) (%)	51.5	4.9	35.4–64.9	59.0	3.8	46.6–68.0

Table 2 Spearman's correlation coefficients of the different parameters measured in 256 women

Parameter	Age	Body height	Body weight	BMI	BWC	TBW
Age	1.0	–0.302	0.248	0.397	0.249	–0.294
Body height	–0.302	1.0	0.265	–0.229	–0.045	0.177
Body weight	0.248	0.265	1.0	0.852	0.011	–0.796
BMI	0.397	–0.229	0.852	1.0	0.043	–0.906
BWC	0.249	–0.045	0.011	0.043	1.0	0.116
TBW	–0.294	0.177	–0.796	–0.906	0.116	1.0
TBW/BWC (= r)	–0.327	0.185	–0.803	–0.917	–0.022	0.987

Table 3 Spearman's correlation coefficients of the different parameters measured in 273 men

Parameter	Age	Body height	Body weight	BMI	BWC	TBW
Age	1.0	–0.295	0.192	0.428	0.187	–0.403
Body height	–0.295	1.0	0.437	–0.160	–0.059	0.138
Body weight	0.192	0.437	1.0	0.783	–0.141	–0.753
BMI	0.428	–0.160	0.783	1.0	–0.106	–0.941
BWC	0.187	–0.059	–0.141	–0.106	1.0	0.164
TBW	–0.403	0.138	–0.753	–0.941	0.164	1.0
TBW/BWC (= r)	–0.444	0.156	–0.732	–0.933	–0.012	0.979

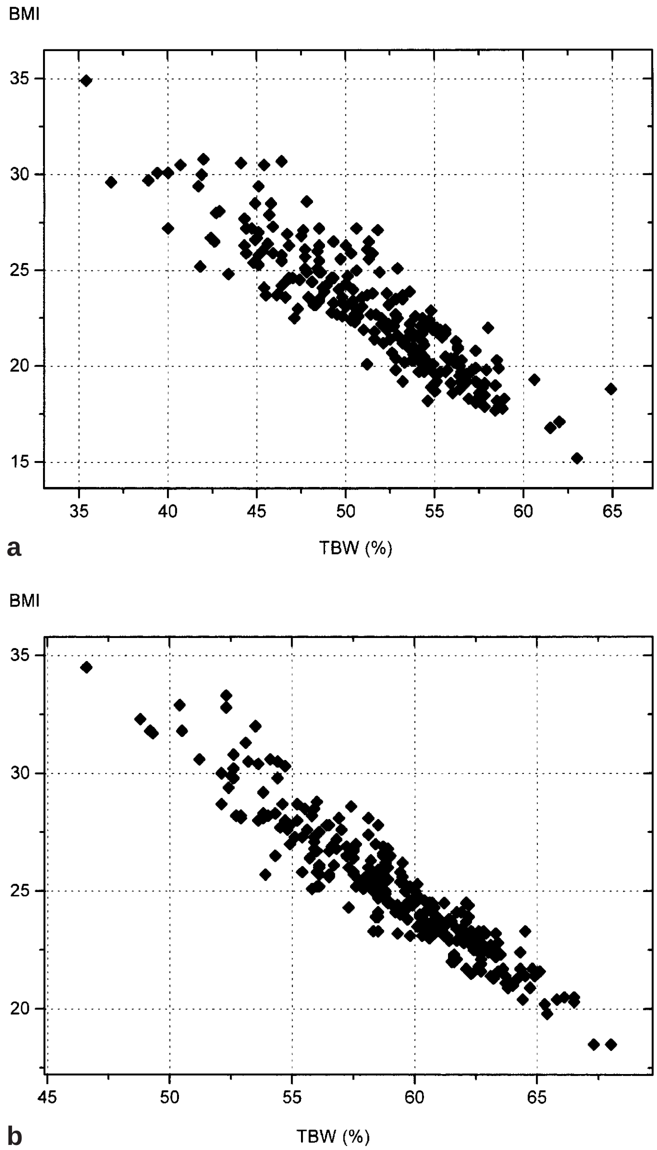

Fig. 1 **a** Correlation between body mass index and total body water in 256 women (Spearman's correlation coefficient = –0.906). **b** Correlation between body mass index and total body water in 273 men (Spearman's correlation coefficient = –0.941)

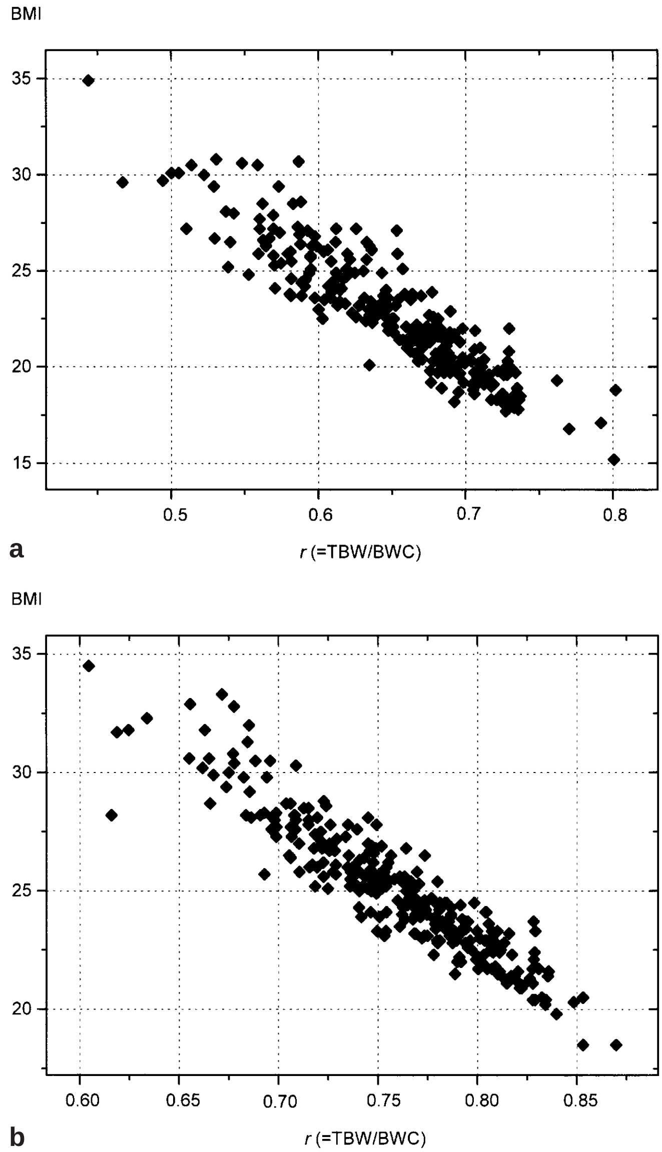

Fig. 2 **a** Correlation between body mass index and the ratio of total body water to blood water (= r) in 256 women (Spearman's correlation coefficient = –0.917). **b** Correlation between body mass index and the ratio of total body water to blood water (= r) in 273 women (Spearman's correlation coefficient = –0.933)

dard error 0.00019) and β_2 = 0.004466 (standard error 0.00027) for women and α = 0.31608 (standard error 0.03148), β_1 = –0.004821 (standard error 0.00012) and β_2 = 0.004632 (standard error 0.00019) for men.

It is now possible to formulate the following multiple linear regression equations:

$$r_{FI} = 0.31223 - 0.006446 \times \text{body weight (kg)} + 0.004466 \times \text{body height (cm)} \quad (1)$$

for women and

$$r_{MI} = 0.31608 - 0.004821 \times \text{body weight (kg)} + 0.004632 \times \text{body height (cm)} \quad (2)$$

for men.

The validity of these equations was proven in drinking experiments in which 30 women (body weight 47.4–

Table 4 Mean, standard deviation (*SD*), median, minimum, maximum and range of C_o (‰). Results from drinking experiments with 30 women

	C_o Measured	C_o Widmark (r = 0.6)	C_o Widmark (r = 0.6) resorption deficit 10%	C_o Watson	C_o Widmark r_{FI}
Mean	1.46	1.68	1.51	1.57	1.52
SD	0.30	0.38	0.34	0.31	0.30
Median	1.57	1.63	1.47	1.61	1.57
Minimum	1.04	1.19	1.07	1.15	1.09
Maximum	1.92	2.40	2.16	2.08	2.00
Range	0.88	1.21	1.09	0.93	0.91

Table 5 Mean, standard deviation (*SD*), median, minimum, maximum and range of C_o (‰). Results from drinking experiments with 30 men

	C_o Measured	C_o Widmark $r = 0.7$	C_o Widmark $r = 0.7$ resorption deficit 10%	C_o Watson	C_o Ulrich ρ_i	C_o Widmark r_{MI}
Mean	1.39	1.50	1.35	1.48	1.45	1.41
SD	0.22	0.29	0.26	0.29	0.25	0.24
Median	1.35	1.49	1.34	1.44	1.40	1.37
Minimum	1.16	1.07	0.96	1.14	1.14	1.18
Maximum	1.78	2.04	1.84	1.90	1.83	1.80
Range	0.62	0.97	0.88	0.76	0.69	0.62

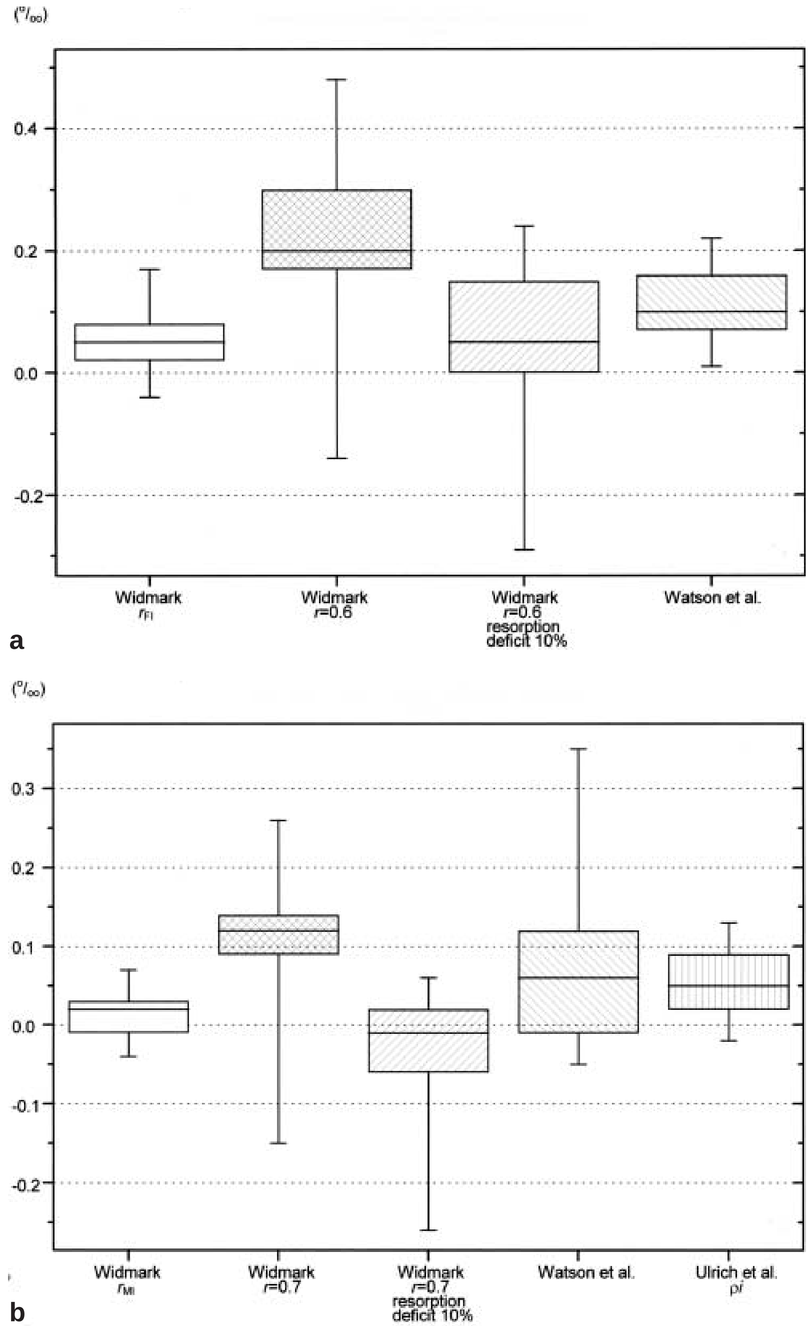

Fig. 3 **a** Divergences between C_o predicted and measured in women. *From left to right* Widmark's equation with individual distribution factors (r_{FI}), Widmark's equation with the rigid distribution factor 0.6, Widmark's equation with the rigid distribution factor 0.6 after subtraction of a 10% resorption deficit, Watson's equation for women (Median, 50%-box, minimum and maximum, results from drinking experiments $n = 30$). **b** Divergences between C_o predicted and measured in men. *From left to right* Widmark's equation with individual distribution factors (r_{MI}), Widmark's equation with the rigid distribution factor 0.7, Widmark's equation with the rigid distribution factor 0.7 after subtraction of a 10% resorption deficit, Watson's equation, Widmark's equation with the individual factor ρ_i (Median, 50%-box, minimum and maximum, results from drinking experiments $n = 30$)

76.4 kg, body height 155–176 cm) and 30 men (body weight 67.4–114.5 kg, body height 173–200 cm) participated. The individual reduction factor (r_{FI}) of the female test persons in this group ranged from 0.52 to 0.72 (mean 0.66, SD ± 0.05) and the individual reduction factor of the male test group (r_{MI}) ranged from 0.60 to 0.82 (mean 0.75, SD ± 0.05). The mean ethanol elimination rate per hour (β_{60} value) was 0.156‰ (SD ± 0.018) for males and 0.159‰ (SD ± 0.015) for females. We observed clearly lower deviations from measured and extrapolated C_o levels, when individual distribution factors r_{FI} or r_{MI} were used for the calculation of BECs instead of the commonly used rigid distribution factors 0.6 and 0.7. However, the mean differences were nearly equal when a 10% resorption deficit was taken into consideration. Slightly lower divergences were obtained using Widmark's equation with r_{FI} or r_{MI} instead of Ulrich's ρ_i in males or Watson's equations (Tables 4, 5). In females, calculations with the "standard" *r* resulted in deviations between –0.14‰ and 0.48‰ and when taking a resorption deficit of 10% into consideration, between –0.29‰ and 0.24‰. Calculations with Watson's equations showed divergences from 0.01‰ to 0.22‰, whereas estimations with r_{FI} resulted in BEC deviations from –0.04‰ to +0.17‰ (Fig. 3 a). The results of the drinking experiments were similar in males: using a rigid *r* factor of 0.7, we found divergences from –0.15‰ up to 0.26‰ and with a 10% resorption deficit between –0.26‰ and 0.06‰. Calculations with Watson's equations showed divergences from –0.05‰ to 0.35‰, and BEC deviations from –0.02‰ up to 0.13‰ were observed when the predictions were performed with Widmark's equation, using Ulrich's individual *r* factor ρ_i. Again, divergences between C_o measured and predicted were clearly lower (between –0.04‰ and 0.07‰), when individual factors r_{MI} were used (Fig. 3 b).

Discussion

The denominator of Widmark's equation, referred to as the reduced body mass ($p \times r$), is commonly obtained using standardised reduction factors (i.e. 0.6 for women, 0.7 for men). Owing to considerable variations of the total body water and the fact that *r* expresses the ratio of body water and blood water, rigid distribution factors can never really meet the high level of accuracy required in jurisprudence. The fact that blood water content and body water content are usually not known in the course of a court trial, made it necessary to develop a regression equation with which these parameters could be determined from easily obtainable and usually known anthropometric measurements.

As expected, the BWC proved to be a relatively constant parameter and did not correlate with the other parameters measured (e.g. TBW, height, weight) but in contrast, TBW correlated with body weight and the body mass index. Interestingly, the correlation between BMI and TBW was clearly higher than the correlation between body weight and TBW which might be ascribed to a very slight positive connection between body height and TBW, increasing the correlation between TBW and BMI by influencing BMI.

Consequently, as in previous studies by other authors [7, 13, 15], the parameters body weight and body height were defined as independent variables for multiple regression analysis. However, no conclusive physiological explanation seems to exist for the inclusion of the individual's age in Watson's equation for men, but not in the equation for women. We found no correlation between age and TBW in women or in men.

While hitherto published equations evolved from predominantly theoretical considerations, our equation is based on actual measurements of BWC and TBW. In this context it is known that the gravimetric determination of BWC is extremely precise, while the standard error of TBW measured by BIA can amount to 4% [21]. Owing to the nonsystematic character of this deviation and the large data base, this error can nevertheless be neglected. TBW can furthermore vary within an individual for various reasons, especially physical training and, in females, menstruation and pregnancy have to be mentioned. In order to be able to apply the developed equation to a broad spectrum of individuals, the factors physical activity and menstruation did not represent an exclusion criterion in our study, especially since the influence can be considered as rather minor. In contrast, pregnancy may affect the body water balance to a much larger extent, explaining why we decided to exclude pregnant women from the study group. The validity of the foot-to-foot BIA technique for TBW prediction, especially in larger study groups, was shown by Bell et al. in comparison with the D_2O dilution method [19]. Interestingly, they found an underestimation of TBW by BIA of approximately 1.5%, while Grüner and Endres reported an overestimation of TBW by D_2O dilution methods of 2.3–3%, compared with the ethanol dilution technique [6, 18]. Therefore, foot-to-foot BIA seems to allow a precise prediction of the size of TBW compartments.

Our study shows that the commonly used distribution factors of 0.6 for women and 0.7 for men are too low in most cases. Calculating the factor according to Widmark's definition of *r* as the ratio of body water and blood water, 25% of the women had *r* values of up to 0.6, while another 25% had *r* values exceeding 0.7. More than 80% of the men showed *r* values exceeding the "standard factor" of 0.7. The mean *r* values derived from our large study groups are in good accordance with *r* values reported by Endres et al. [18]. In contrast, the mean *r* values found by Widmark are clearly lower [1]. This fact might be caused by the very small test group of only 20 males and 10 females used by Widmark. Another reason might be that these experiments were performed approximately 70 years ago and body composition might have changed significantly during this time. Of greater importance, however, is the fact that even Widmark reported considerable variations of *r*. The need to apply Widmark's equation in combination with individual *r* factors is impressively illustrated in Fig. 3 a, b. While r_{MI}, r_{FI}, ρ_i and Watson's equation (in women) lead to slight differences between measured and calculated BECs, the differences are considerable when

Widmark's equation is used in combination with rigid *r* values for the calculation of BEC.

While the use of rigid *r* factors causes a wide range of deviations, calculations with incorrectly low *r* values will inevitably lead to exaggerated BECs. To prevent this and with regard to a bioavailability of ethanol of less than 100%, a so-called resorption deficit of 10–30% has previously been subtracted from the calculated BEC. As shown in Fig. 3 a, b, the subtraction of a 10% resorption deficit only causes an average reduction of the differences between measured and calculated BECs, without any effect on the wide deviation range. Therefore we recommend the use of Widmark's equation in combination with the individual factors r_{MI} and r_{FI} presented in this study. In analogy to the use of the individual reduction factor ρ_i, the subtraction of a standard resorption deficit of 10% is not necessary under similar drinking conditions as in this study (drinking time up to 2.5 h, medium ethanol concentrations and no food intake). In cases of very long drinking times or rich food intake, the subtraction of a 10% or 20% resorption deficit might be more appropriate rather than the hitherto performed practice of subtracting a resorption deficit of 20% or 30%. In this context, however, it has to be pointed out that individual *r* values are independent of the amount and concentration of ethanol consumed and from food intake [1].

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