

Improving uncertainty in Widmark equation calculations: alcohol volume, strength and density

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2 **Improving Uncertainty in Widmark equation**
3 **calculations: Alcohol volume, Strength and Density**

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3 **Abstract**

4 The Widmark equation is probably the most commonly used calculation for
5 medicolegal purposes. Recently the National Research Council (USA) and the
6 Forensic Science Regulator (UK) have called for the uncertainty of all results to be
7 given with all forensic measurements and calculations. To improve the uncertainty of
8 measurement of results from Widmark calculations we have concentrated on the
9 uncertainties of measurement involved in the calculation of alcohol, that of the volume
10 of alcohol, the concentration of alcohol and the density of alcohol as previous studies
11 have investigated some of the other factors involved . Using experimental studies, the
12 scientific literature and legal statutes, we have determined revised and improved
13 uncertainties of the concentration of ethanol for Widmark calculations for both the USA
14 and UK. Based on the calculations that we have performed we recommend the use of
15 Monte Carlo Simulation for the determination of uncertainty of measurement for
16 Widmark Calculations.

17

18 **Keywords**

19 Widmark, Alcohol Technical Defence, Back Calculation, Uncertainty of Measurement

1 Introduction

Calculations using the Widmark equation [1] for medicolegal purposes, such as determining the blood alcohol concentration of a defendant at the time of an incident from a blood sample taken after the incident, are probably the most common calculations performed in forensic toxicology. As with all measurements and estimates that arise both in and from calculations there is a level of “uncertainty”. Knowing the uncertainty of measurement allows us to have a level of certainty around a result and thus a better estimate of the true result [2]. The uncertainty of measurement is becoming increasingly important in forensic science allowing juries and non-experts to understand how accurate (and thus reliable) the results of the calculations and analysis are that they are being asked to evaluate. This is particularly important in cases where there are statutory limits (such as blood alcohol concentration) above which an offence has been committed [3]. Previously it has not been common practice to have uncertainty of measurement quoted with forensic analytical and calculated results within forensic reports and witness statements. However, in the past few years it is now becoming a requirement. As stated in the National Research Council (NAS) report on strengthening forensic science in the USA “All results for every forensic science method should indicate the uncertainty in the measurements that are made, and studies must be conducted that enable the estimation” [4]. In the UK the forensic science regulator expects “...all staff who provide factual evidence based on scientific methodology are additionally able to demonstrate, if required...the impact that the uncertainty of measurement associated with the application of a given method could have on any conclusion” [5]. With regard to the forensic calculations using the Widmark equation, Gulberg states “the only forensically appropriate way to present and interpret Widmark estimates is to include an assessment of their uncertainty” [6].

Prof. Eric Widmark initially studied the pharmacokinetics of alcohol consumption and the equation that he derived now carries his name. When using metric units the most common form of the Widmark equation (as described by Searle [7]) is:-

$$Ct = \frac{100vzdF}{rM} - \beta t \quad (1)$$

The mass of alcohol taken into the body can be separated out and expressed as: -

$$A = vzdF \quad (2)$$

Which then gives a revised Widmark equation (if the mass of alcohol consumed is calculated separately) of: -

$$Ct = \frac{100A}{rM} - \beta t \quad (3)$$

36

37 Ct = blood alcohol (ethanol) concentration at time t (mg/100ml)

38 A = mass of alcohol (ethanol) consumed (g)

39 M = mass of the subject (Kg)

- 1 r = Widmark factor (L/Kg)
2 β = alcohol elimination rate (mg/100ml/h)
3 t = time since the drinking began (h)
4 v = volume of the drink (ml)
5 F = bioavailability of the alcohol (ethanol)
6 d = density of alcohol ethanol at 20°C (a constant)
7 z = the strength of the drink Alcohol by Volume (ABV) %v/v divided by 100.

8
9

10 In order to determine the uncertainty of any results calculated it is important to have
11 the best estimations possible of the uncertainty of the various terms in the Widmark
12 equation. Three relatively recent publications have both investigated and discussed
13 the uncertainty around alcohol calculations [6-8] and offered suggestions for methods
14 of calculation and the uncertainty that is inherent in those calculations. It is important
15 to have reliable sources for the given uncertainty for each term in an equation. Unlike
16 Zuba and Piekoszewski [8], Gullberg [6] gives some referenced estimates for the
17 uncertainty (standard deviation (SD)) of various of the factors of the Widmark equation
18 such as mass of the subject (M), alcohol elimination rate (β), the Widmark factor (r)
19 and the concentration of blood alcohol at time t (C_t). However, none of the publications
20 give referenced error (standard deviation (SD) or coefficient of variance (CV)) for the
21 calculation of the mass of ethanol consumed (A). There is also no referenced
22 information for the variables that make up the calculation of A , that of volume of ethanol
23 consumed (v), the ABV of the alcoholic beverage (z) and finally the fraction of alcohol
24 that is absorbed from the stomach (F). As mentioned by all of the authors of the recent
25 papers [6-8] determining the uncertainty of alcohol calculations improves the
26 calculated estimates and further knowledge of the uncertainty of measurement of the
27 individual variables would allow increased reliability of the results of any calculation
28 using the Widmark equation.

29 The aim of this study is to determine, from the literature, published information and
30 experimental data, improved estimates of the SD of measurements of alcohol density
31 (d), alcohol strength (z) and alcohol volume (v). As the number of drinks (and overall
32 volume of alcohol consumed in a "session") have been shown to have one of the
33 largest contributions to the uncertainty of measurement (~13-21 % depending on the
34 calculation being performed [6-8]), we will also discuss an individual's "memory" of
35 how much they have had to drink compared to their actual consumption. Due to the
36 differing laws in the United States of America (USA) and United Kingdom (UK) we will
37 discuss these regions separately where necessary.

2. Density of Ethanol (d)

The density of ethanol (at 20 °C) is commonly quoted at 0.789 g/cm³ in the forensic literature [9] and 0.78945 g/cm³ in chemistry literature [10, 11]. They do not nevertheless give an estimation of uncertainty. Numerous publications have analytically measured the density of ethanol at 20 °C [11-18]. From these we calculated that the mean density (\pm Standard deviation (SD)) of ethanol is 0.78974 ± 0.00059 g/cm³ (% coefficient of variance (CV) = 0.07481). Thus, it would be more accurate to use these values both in calculations using the Widmark factor and for calculation of uncertainty when using the Widmark equation.

3. Variation on the Strength of Alcohol (z)

3.1 Labelling Requirements of ABV for alcoholic beverages

The strength of alcohol (ethanol) is commonly measured as the percentage of alcohol by volume (%v/v or ABV) and is defined as the number of millilitres of pure ethanol present in 100 millilitres of solution at 20 °C. In the UK and EU it is a legal requirement to give the ABV on the label of any packaged alcoholic beverage, and also to advertise the ABV of alcoholic beverages, such as those sold in a pub or bar [19]. In the USA there is no legal requirement for the labelling of alcoholic beverages with the ABV for either packages alcoholic beverages or off-sales [20]. Some packaged beverages in the USA are labelled (around 17% based on the most up-to-date study from 1999 [21]). The allowable error of ABV in the USA and EU are presented in Table 1.

3.2 Variation in the labelled ABV and actual ABV

Although there are legally allowable variations from the labelled ABV, it is possible that the actual ABV in alcoholic beverage may be more accurate than the allowable legal variations of ABV. To determine if the published ABV measurements are likely to be more accurate than required by law we investigated the methodology to determine ABV from a set of brewing data. The most common method of determining the alcohol content of alcoholic beverages in breweries is that of measurement of the attenuation in the specific gravity by measuring the gravity at the start of fermentation (original gravity (OG)) and then after fermentation has been completed (final gravity (FG)) [22]. Apparent specific gravity is defined as “the density of a sample at 20°C divided by the apparent density of an equal amount of water at 20°C”. Water has an apparent specific gravity of 1.0000 at 20°C. [23]. Specific gravity measurements are not the only methods of determination of alcohol content further methods are given in [24].

For measurements of specific gravity, a number of empirical equations are available depending on the mathematic prowess of the brewer.

1 The simplest is [25]:

$$2 \quad ABV = (OG - FG) * 131.25 \quad (4)$$

3 ABV = alcohol by volume (%v/v)

4 OG = original gravity (before fermentation has commenced)

5 FG = final gravity (after fermentation has finished)

6 In the UK, the original and final gravities are multiplied by 1000 and a mandated
7 specific factor (f) (0.125 - 0.135) replaces the 131.25 when calculating the ABV this
8 factor is dependent on the value of OG – FG and is used for the purpose of calculating
9 the ABV for the determination of the excise duty (Excise notice 226: beer duty):-

$$10 \quad ABV = (OG - FG) * f \quad (5)$$

11 In the USA a beer table allows the calculation of ABV using a hydrometer for excise
12 purposes (Code of Federal Regulations (Title 27 of the CFR PART 30))

13 Another relation based on the Balling equation [26] but expressed in terms of specific
14 gravity rather than °Plato (roughly equivalent to % sugar) [27] can be used:

$$15 \quad ABV = \frac{76.08(OG-FG)}{1.775-OG} \times \left(\frac{FG}{0.794}\right) \quad (6)$$

16

17 Aside from the use of specific gravity values to measure the starting wort (a
18 carbohydrate rich liquid which is fermented into beer) and final beer densities much of
19 the industry uses the °Plato scale. A fluid of 'density' of 1.0 °P is roughly equivalent to
20 a sugar solution of 1.0 on a %w/w basis. Aside from equations 4, 5 and 6, a more
21 exact empirical equation based on the difference between the starting and final
22 densities expressed in °Plato was recently updated and the accuracy much improved
23 by Cutaia et al. [28]

24

$$25 \quad ABV = (0.38726x(OE - AE) + 0.00307x(OE - AE)^2) \times \left(\frac{FG}{0.794}\right) \quad (7)$$

26

27 OE = original extract in °Plato (before fermentation has commenced)

28 AE = apparent extract in °Plato (after fermentation has finished)

29 An expression to convert extract values (i.e., OE or AE) to specific gravities (OG or
30 FG respectively) has also been reported by Cutaia et al. (eq. 10), [34].

1 In order to determine the accuracy of equations 4, 5 and 6 in determining ABV we
2 used industrial data sets from fermentations where measurements of OE, AE and
3 alcohol (% w/w) were converted to OG, FG and ABV by equations 10 and 14 from the
4 paper by Cutaia *et al.* [34]. An estimate of ABV was also determined using OE and
5 AE values and equation 7 reported above. These values were the same fermentation
6 data sets as detailed in [28] and further information on them and their origin can be
7 found therein. The predicted ABV was regressed on the true ABV using Systat Ver 11
8 (Systat Software Inc., San Jose, CA) and forcing the estimate of ABV through the
9 origin. The coefficient of determination and the standard error were calculated. The
10 results (not shown) showed a clear linear relationship between the predicted %v/v
11 calculated and the actual alcohol content using equations 4-7 (r^2 0.99). As expected,
12 the use of equation 7 from Cutaia *et al.* [28] gave the least amount of error (\pm 0.130
13 %ABV) when predicting the actual %ABV from gravity data. Equation (5) gave a similar
14 amount of error (\pm 0.131 %ABV), the largest error was observed with equation (4) that
15 of (\pm 0.141 %ABV). Although these errors for determination of ABV are well within the
16 error allowed by HMRC in the UK, it would be advisable to use the largest error in ABV
17 in the calculation of uncertainties. In large breweries (such as the top global breweries)
18 that use high gravity brewing [29] where the beer is brewed at a higher ABV than it will
19 be sold at, then diluted to the required ABV using water, there is likely to be a greater
20 accuracy in the final ABV. Due to the use of IR-ATD with a measurement accuracy of
21 \pm 0.01 %ABV.

22

23 **3.3 ABV variation in alcoholic beverages in the USA**

24 In the USA it is not a federal requirement to label with the ABV, it is also not a legal
25 requirement to give the ABV of alcohol when served in bars. When there is no specific
26 information on the brand of alcoholic beverage consumed, there are limited sources
27 of information. It is possible to make some general assumptions based on the alcohol
28 beverage consumed. In the USA in 2002, the last year for published compiled data,
29 wine had an average strength of 11.45% [30, 31], spirits 37% [30] and beer in 2005
30 had an average ABV of 4.5%. [32] Unfortunately no error was given with these results.
31 These results were also compiled from industry data rather than direct measurement.
32 The last year where data is available for beer ABV from direct measurement is 1997
33 where beers for sale in Washington state were analysed [21]. The study investigated
34 ales ($n = 256$), lagers ($n = 113$) and various sub-groups of these categories. Ales had
35 a mean \pm SD ABV of 5.51 ± 1.23 % (Median 5.25 %; Range 2.29 % - 12.69 %). Lagers
36 had a mean ABV of 5.32 ± 1.43 % (Median 5.00 %; Range 4.02 % - 15.66 %). The
37 study gives more detail on the subgroups of the ale and lager classes for those that
38 are interested and require more accurate calculations of uncertainty. It is to be noted
39 that the average ABV of beers across the USA has decreased in recent years from
40 4.72 % in 1997 to 4.5 % in 2005 [32], suggesting that a new study investigating the
41 average ABV of beer (with standard deviation) would be beneficial in the estimation of
42 uncertainty for forensic calculations.

1

2 **3.3.1 Deviations from the labelled ABV**

3 Even when beverages are labelled with ABV there will be deviations in the labelled
4 and actual ABV. In the study by Logan and colleagues for beverages labelled with
5 ABV the average difference between the labelled ABV and the actual ABV was 0.03
6 ± 0.40 % (mean \pm SD) less than labelled (range 0.98 % below - 1.62% above) [21].
7 For wine a systematic study was carried out on the ABV on wine labels data from over
8 100,000 wines entering Canada between 1992 and 2009 [33]. This study found that
9 there was an underreporting of the label ABV on average (mean) by 0.13% ABV. For
10 the wines that were underreported the average (mean) underreporting was 0.42%
11 ABV (57.1% of total number sampled). 32.2% of the wines samples over reported the
12 ABV of an average (mean) of 0.32% ABV [33]. Further information into the variation
13 of labelled ABV and actual ABV in the USA can be found from the annual Alcohol
14 Beverage Sampling Program (ABSP) (<https://www.ttb.gov/sampling/>) carried out by
15 the USA Alcohol and Tobacco Tax and Trade Bureau (TTB) in order to determine if
16 the labelling is likely to mislead customers. The TTB randomly sample alcoholic
17 beverage to check compliance. Table 2 gives an up-to-date summary on the TTB
18 compliance program and suggest that currently there may be less variation in ABV
19 than suggested by the Logan study [21]. There is a greater level of certainty in the UK
20 with ABV due to the labelling regulations than in the USA.

21

22 **3.4 ABV variation in alcoholic beverages in the UK**

23 In the UK all alcoholic beverage for sale must be labelled with the ABV. If the type and
24 brand of drink can be remembered by the individual then it can be reasonably simple
25 to determine ABV for calculation. If the exact beverage type is not available there are
26 various sources that can be used for a reasonable estimate. Table 3 gives data of the
27 ABV (\pm standard deviation) of various common alcohol types from Tesco.com the
28 largest supermarket in the UK [34] and from LWC drinks the UKs largest Independent
29 drinks wholesaler [35]. For the craft type beer there are two sources of data. The
30 Society of Independent Breweries (SIBA, www.siba.co.uk) publish the results of a
31 survey of members each year. This survey usually has data from ~ 35 % of the
32 membership (~ 350 breweries) and publishes the average ABV of the beers brewed by
33 members. In 2015 the average ABV (mean \pm SD) was $4.17\% \pm 0.521\%$ ($n=266$) [36]
34 this was similar in 2016 where the average ABV again was (mean \pm SD) $4.17\% \pm$
35 0.44% ($n=295$) [37]. Further information on the variation of ABV for various types of
36 UK beer can be estimated from data obtained from the Great British beer festival, an
37 annual beer festival in the UK with over 300 different beers. Table 4 shows the average
38 (mean, mode), Standard deviation and %CV of the various beer types (as defined by
39 CAMRA) of golden ale, bitter, indian pale ale (IPA), mild, porter, stout and "speciality"
40 [38] from the 2016 Beer festival. Overall the mean ABV of all the beers at the festival

1 (n = 386) was 4.4 ± 0.7 % (Range 3.0 – 7.5 %). From these data it was possible to
2 calculate the mean ABV (\pm SD) of beer (4.5 ± 0.8 %, n = 552); wine (12.4 ± 1.5 , n =
3 399) and spirits (39.3 ± 4.1 , n = 147) in the UK. This information can be used when
4 only limited information about the beverage type is known.

5

6 **4. Variations in the volume(s) of Alcoholic Beverage (v)**

7 **4.1 UK and USA Drinks Measures for on-sale purchases.**

8 As with concentration of alcohol content in alcoholic beverages there is also an
9 uncertainty of measurement with the labelled or dispensed volume of alcoholic
10 beverages. Alcoholic beverages are sold in three forms where volume is important.
11 Pre-packaged (for example buying a bottle of an alcoholic beverage), a serving
12 measure (for example buying a dispensed beer at a bar) and a transfer measure (for
13 example a “shot” measure when making cocktails). Table 5 outlines the variations in
14 volume that are allowed under US and EU regulations. In the EU legislation covers all
15 of the forms of alcoholic beverage that are sold (European Commission Directive
16 (87/250/EEC) article 3 ABV). However, in the US the only specific weights and
17 measures legislation cover pre-packaged drinks. There is no direct legislation covering
18 serving measures apart from those that protect against deceptive trade, so commonly
19 in the USA when purchasing a beverage at a bar neither the volume nor ABV will be
20 known [20].

21 In the UK the standard dispensed unit for beer is a pint (~568 ml), whereas in the US
22 the standard pint is 16 fluid oz (~ 473 ml) and pint glasses are not required to be legally
23 stamped to confirm the volume. This has led to reports of restaurants replacing 16 fl
24 oz glasses with 14 fl oz glasses with similar profiles and also of overly large “heads”
25 of foam on beers leading to pints of significantly less volume than 16 fl oz. Studies in
26 the USA have shown that the average size of a glass of wine (\pm 95% CI) was 6.18 fl oz
27 (5.95, 6.41), n = 131; the average glass of beer was 14.10 fl oz (13.50, 14.70), n = 56;
28 the average glass of spirits was 5.28 fl oz (5.06, 5.50), n = 288. Further sub divisions
29 (such as red wine, white wine etc.) of the various beverages are given in the paper
30 [20]. Further study in this area would be beneficial.

31 In the UK even though there is a legal requirement to provide a full pint (Weights and
32 Measures Act 1985) a 1982 court ruling (Bennett v Markham [1982] 3 AllER 641)
33 allows a “reasonable” head of foam. Industry regulations allow a 5% head of foam on
34 a beer, although a full pint should be provided if asked [39]. Studies have shown the
35 mean volume of liquid was 96.06% of a pint. (3.94% short) (n=88) however in one pub
36 it was found to be 11.8% short [40]. In the UK it is possible to purchase pint glasses
37 that are either a pint to the brim or to the line. The line measured glasses allow a head
38 to be included without the dispensing of less than a full pint. Pubs and bars in the UK
39 can choose which pint glasses they use; unfortunately there is no data available on
40 the commonality of each glass type in the UK.

4.2 Variations in fill volumes of packaged alcoholic beverages

In the EU pre-packaged alcoholic beverages must not on average be below the nominated volume in a single batch. There is a set tolerable negative error (TNE) (see table 5) that is either a set volume or percentage of volume and packers must set limits on the number in a batch that can be short by the TNE (Weights and Measures (Packaged Goods) Regulations 2006). No package should be short by twice the TNE. In the USA, as can be seen in table 5 the allowable fill variation depends on the size of the bottle and varies between 1.5 to 4.5% of the labelled volume (27 CFR 19.356). Confirmation on fill volume around the world is either measured by fill height, weight or dispensed amount [41]. There is limited information on the actual variation in packaged fill volume. A survey of industry suggested on average an overfill on packaging lines between 0.5 and 4 % [42], suggesting that beverages are unlikely to be under-filled in the UK even though the packaging technology should theoretically allow variations of less than 1 ml [43]. A study in 2012 investigated fill volume variation and gives the best example of real fill data from a large brewery producing 1.9 million litres per day. The target fill was 750 ml, based on the values provided the average fill was found to be 752 ml \pm 8.13 ml (range 705 ml – 775 ml) [44]. The average and the standard deviation are within both the required EU and USA regulations (EU 735 ml - 765 ml; US 762 ml – 745 ml), however the ranges are not within the legal limits. Automated bottling plants, like the one outlined in [44], are likely to have a greater reliability than those in smaller breweries/distilleries that use may use manual methods of filling. The TTB study (table 2) shows that in the USA there have been no recorded incidences of deviation from the filling legislation in the past 4 years that data is available.

5. Number of drinks consumed

Depending on the type of Widmark calculation being carried out it can be important to know the number of alcoholic beverages that have been consumed by the subject. This can be problematic in that the drinker may not a) remember how many “drinks” they have consumed b) they may lie about the amount of alcohol they have consumed and c) they may have been at home and not poured measures that alcoholic beverages are commonly sold in. In this section we review the studies that have been conducted in order to give a better understanding of the uncertainty that may be involved with the self-reported recall of the number of drinks consumed.

5.1 Accuracy of self-reporting of alcohol consumption

A limited number of studies have been performed in order to try to determine the accuracy of self-reporting of alcohol consumption (in terms of the number of “drinks” (as defined by the drinker)) vs. the actual number of drinks consumed.

1 There have been a number of different approaches to this question. 1) Observation of
2 the subject(s) either in a controlled environment or in “the wild” [45-47]; 2) Comparison
3 of measured blood alcohol concentration (BAC) compared to estimated BAC based
4 on reported self-drinking on emergency department admissions [48, 49] or 3)
5 Comparison of “real time” recording of consumption vs. retrospective self-reports [50].
6 All of these types of reporting methods have pros and cons that are discussed further
7 in the individual publications, however, some salient points that are of importance in
8 alcohol calculations were obvious.

9 In all of the studies there was a difference in the alcohol consumed and the alcohol
10 reportedly consumed. In the study where the subjects were observed consuming
11 alcoholic “drinks” in a simulated social environment there were 58 males (age 25-54)
12 that drank in groups of 4. The subjects were able to drink *ad libitum* for 6 h then either
13 1 or 2 days later they were interviewed to see the number of alcoholic drinks they had
14 consumed. The mean number of drinks actually drunk was 11.4 (range 7-16) with the
15 number recalled being less at 10.5 (range 6 – 15.5). When divided into “light” drinkers
16 (7-11 drinks) the mean consumed was 9.76 drinks with an actual of consumption of
17 9.40 drinks. The heavy drinkers (12-16 drinks) actually consumed a mean of 13.37
18 drinks with the recalled amount being 11.72 drinks [46]. This trend of the “heavier”
19 drinkers having less accurate recall of consumption is confirmed in a study in a more
20 realistic drinking environment where data was collected by volunteers shadowing
21 participants (n=62; 30 male, 32 female; age 18 – 25) in normal social settings. The
22 participants were again interviewed 1 – 2 days after the drinking. These results show
23 that participants tend to be accurate at remembering the number of drinks consumed
24 when consuming up to 8 drinks. When looking in more detail at the data subjects
25 overestimated when consuming up to 4 drinks (mean observed drinks 1.7, mean
26 reported drinks 1.8, n = 31) and this was repeated with up to 5 – 8 drinks with a slight
27 overestimation of drink consumption (mean observed drinks 5.8, mean reported drinks
28 6.0, n = 50). When subjects drank more than 8 drinks (9 - 12 drinks) the participants
29 underreported the number of drinks consumed (mean observed drinks 9.0, mean
30 reported drinks 8.3, n = 33). When the subjects consumed >12 drinks they under
31 estimated their consumption by around 2 drinks (mean observed drinks 14.8, mean
32 reported drinks 12.8, n = 15). [45] A further study where the 69 participants (18 - 36
33 years; 59 % male) logged their drinking on a night out in real time using a phone app
34 and were then asked to recall how much they had drunk 24h later, again shows that
35 participants underreport their drinking that increased with the number of drinks
36 consumed. The participants logged an average (mean \pm SD) of 8.45 ± 5.97 drinks
37 during the evening whilst only recalling consuming 4.17 ± 3.02 drinks a mean
38 difference of 4.28 drinks less than actually consumed, a 49.3% difference [50]. When
39 looking at longer term recall of alcoholic beverage consumption (average 27 days) a
40 study again shows an underreporting of alcohol consumption. This study investigated
41 141 drivers who were recruited on arrival at a selection of bars in an 80 km radius of
42 Vermont, New England USA. The drivers were not aware their drinking was being
43 observed and recorded. They again showed that recall of the number of drinks

1 consumed worsened with increasing number of drinks. Light to medium drinkers (1 –
2 5 drinks) all tended to estimate 2 – 3 drinks. They reported light drinkers (1 – 2 drinks)
3 tend to overestimate and medium to heavy drinkers (<4 drinks) tend to overestimate
4 [47]. Unfortunately, the study gave no more detail on the drinking. The underestimation
5 in these studies could be due to a number of reasons; the well know effects of ethanol
6 consumption on memory [51], the phenomena of people tending to underestimate the
7 number of items as their quantity increases [52], social stigma [49] and actually
8 deliberately distorting the results due to possible legal consequences [49]. The final
9 approach to self-reported drinking was investigating the correlation of estimated ABV
10 (based on self-reported drinking) compared to measured ABV after admission to the
11 emergency department (BAC). In the two studies [48, 49] they found that drivers
12 under-reported more than non-drivers and men under-reported more than women.
13 Intoxicated subjects (defined as above the quoted legal US limit of 100 mg/100 ml)
14 14% actually over reported, compared to none of the non-intoxicated patients (above
15 10 mg/100ml but below 100 mg/100ml) only 7 patients (5 drivers and 2 passengers)
16 from a sample of 181 denied alcohol consumption but tested positive (>10mg/100ml)
17 [49]. Although it is not possible to determine the drinks consumed this study illustrates
18 again differences between declared drinking and actual alcohol consumed. The mean
19 BAC difference between EBAC and BAC was -75.71 mg/100 ml (SD 115.82 mg/100
20 ml) n=107) with drivers -98.47 mg/100 ml (SD 106.19) n = 78. Only 60% of patients
21 would give information suitable for calculation of EBAC. Overall respondents would
22 admit to drinking alcohol but would be “unable or unwilling to describe the exact
23 quantity and frequency of alcohol consumption” [49]. In the second study [48] the
24 mean difference in EBAC and BAC was -79.27 mg/100 ml (SD 108.27 mg/100 ml)
25 n=128) with drivers -113.18 mg/100 ml (SD 96.78) n = 68 [48] there was a similar
26 refusal rate of 58% when compared to the other study (60%) [49] and that of Perrine
27 and colleagues [47]. These studies show that in short term recall (24 - 48hr) of drink
28 consumption, drinkers of >8 drinks tend to underestimate the number of drinks they
29 have consumed by around on average of 0.3 – 0.7 drinks. There is a greater
30 divergence between actual number of drinks consumed and reported amount of drinks
31 consumed with >8 drinks where the drinkers reported a mean of around 1.65 – 2.00
32 less drinks reported than actually consumed. This can go up to an underreporting of
33 ~4.8 drinks when 15 drinks have been consumed. Below 8 drinks there is a tendency
34 of a slight over estimation of the amount of alcohol consumed but only by around 0.1
35 - 0.2 drinks. The ability to recall the number of drinks, as expected due to memory,
36 was reduced when longer time periods were involved (27 days). Other research has
37 shown that men are more likely to underestimate than women and drivers are more
38 likely, as expected due to the legal implications, more likely to underestimate the
39 number of drinks consumed [48, 49]. Further studies that focus on the forensic
40 variation in alcohol self-reporting, reporting of drink consumption of others by
41 witnesses and also in a variety of cases would be useful to allow more accurate
42 estimations in future work.

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21

5.2 What is the size of a “drink” in a pub/bar?

Evidence clearly shows an underreporting of consumption of the number of “drinks” reportedly consumed compared to actual consumption after both 1 - 2 days and 27 days in personal recall studies. In all of these studies they did not investigate the size of the “standard” drink or what people’s perception of a “drink” is. The size of a standard drink varies between countries with a range of 8 – 20 g of pure ethanol in a “standard measure” [53]. In the UK drinks are measured in “UK Units” (8 g pure ethanol) with the “standard” drink in the USA being 14 g of pure ethanol [54]. It is important to understand what people consider to be a standard “drink” as in the UK 51 % of sales of alcoholic beverages are “off” sales [55], with around 76 % of sales in the USA being off sales [56] . In the UK it is easier for people to recall the number of drinks they have consumed if they are purchasing from a bar or shop as these will come pre-packaged or will be a set size (with some variation of course). In the USA for bars, due to there being no federal legislation controlling the size of a drink measure when in draught or poured, and at home in both the UK and USA, where consumers can define their own “drink” size it is important to have knowledge of these sizes in order to be as accurate as possible in Widmark calculations. The size of a drink in a USA bar is covered in section 4.1.

5.3 What is the size of a self-poured “standard” drink?

In countries that serve set measures of alcoholic beverages in bars/pubs it is possible to give a good estimate of the volume of a beverage consumed assuming the drinker has a good memory for the number of drink they have consumed. The estimation of the size of a “standard” drink for off sales is however more complicated as people can have any volume of beverage that they choose without any legal restrictions on the size. Thus each drinker will have their own definition of the size of a “drink”. The best way to determine the volume of drink that has been consumed would be to obtain the glass that has been used for drinking and ask for the volume (or level) to be indicated by the drinker. The volume of a “standard” drink is important for the determination of the average alcohol consumption of people around the world. This has led to studies looking at the average (mean) “standard” drink that people pour themselves. As can be seen in table 6 the “standard self-pour measure” of wine, beer and spirits either study the number of units or the volume of the drink poured. The size of an average drink has been shown to be affected by the drink (beer, wine, spirits) the glass that it is poured into and also the gender of the person pouring the drink. The data from Wilkinson and colleagues [57] and Kerr and colleagues [58] (Table 6B) illustrates that the number of units in a standard drink increases with the alcohol concentration, this will partially be because of the increased amount of alcohol per ml of the drinks. Based

1 on the philosophy of being in the motorists favour the estimates of uncertainty that are
 2 most suitable are those of Kerr and colleagues [58]. As these results are in UK units
 3 they would need to be converted to ml for use in Widmark calculations. It is also
 4 important to note that studies have shown the glass type used has an effect on the
 5 size of drink that is poured, such that when asked to pour the same volume (44.3ml)
 6 of a beverage into a short-wide glass and a tall thin glass of equal volume the subjects
 7 poured significantly more (54.6 ml and 46.4 ml respectively) into the tall thin glass
 8 compared to the short-wide glass (17.8% more) [59]. The size of the container also
 9 has an effect with larger amount of liquid being poured into larger containers with the
 10 larger the glass size the larger the discrepancy [60, 61]. In a study into hand poured
 11 measures of spirits the subjects were asked to pour a “single” pub measure (25 ml)
 12 and a “double” pub measure (50ml) into three types of glasses (straight sided half pint
 13 glass, whisky tumbler and wine glass). The mean for each glass for a single measure
 14 was 27.2 ± 10.0 ml, 30.1 ± 10.3 ml, 26.3 ± 8.7 ml respectively. For a double measure
 15 51.3 ± 17.7 ml, 54.7 ± 17.9 ml, 46.7 ± 14.7 ml. Showing that overall the greatest
 16 deviation from the expected volume was when pouring into “whisky type tumblers”
 17 [62].

18

19 **6. Estimated uncertainty of the amount of ethanol (A)**

20 It is possible to calculate the uncertainty of the amount of ethanol (A) by either using
 21 the method of general error propagation (GEP) [63, 64] used by Searle [7] and
 22 Gullberg [6] in their calculations of uncertainty of Widmark calculations or that of the
 23 Monte Carlo simulation method [65-67] as used by Zuba and Piekoszewski [8].

24

25 **6.1 General Error Propagation**

26

27 Based on the data that has been discussed above it is possible to give estimations of
 28 the uncertainty of volume (v), alcoholic strength (z), density of alcohol (d) and the
 29 number of drinks (or volume of beverage) consumed. Using the standard deviations
 30 that are known for the values v (volume), z (concentration), d (density) and common
 31 general error propagation (GEP) methodology it is possible to determine the standard
 32 deviation of the amount of pure alcohol consumed (A) using equation 8. It has been
 33 assumed that F (bioavailability) = 1 and is thus not included in the calculations.

34

$$35 \quad \frac{\Delta A}{A} = \sqrt{\frac{\Delta v}{v} + \frac{\Delta z}{z} + \frac{\Delta d}{d}} \quad (8)$$

36

37 It can be simpler to use the coefficient of variance (the standard deviation of each
 38 variable divided by its mean) with A being a function of 3 variables

39

1 $A = f(v, z, d)$

2

3 This gives equation 9.

4

5
$$e_A = \sqrt{e_v^2 + e_z^2 + e_d^2} \quad (9)$$

6

7 e_A = coefficient of variance of amount of alcohol consumed

8 e_v = coefficient of variance of volume of drink consumed

9 e_d = coefficient of variance of the density of ethanol

10 e_z = coefficient of variance of the alcoholic strength of the drink (ABV)

11

12

13 **6.2 Monte Carlo Simulation**

14

15 Monte Carlo simulations are a method that uses inferential statistics, where a random
 16 sample tends to exhibit the same properties as the population from which it is drawn,
 17 to estimate the value of an unknown quantity. Simply we use randomly generated
 18 numbers for all of the input parameters to the model (in this case the Widmark
 19 equation) where each of the input parameters (such as weight, elimination rate
 20 constant etc.) of the model have a predetermined probability distribution, such as a
 21 normal distribution, rectangular distribution and triangular distribution). The
 22 predetermined probability distributions can be based (as in this study) on experimental
 23 data. As expected the approximation of the unknown quantity becomes better with an
 24 increase in the number of iterations (n) that are completed. [66]). Further detail on the
 25 theory and use of Monte Carlo simulations can be found in the following references
 26 [66, 68].

27

28 The uncertainty of amount of alcohol consumed (A) when using the Monte Carlo
 29 method was calculated using GUM Workbench EDU Software Version 2.4.1.384
 30 (Metrodata GmbH, www.metrodata.de) using 2,000,000 iterations. The modelling
 31 assumed a rectangular distribution (as the data for each input parameter was equally
 32 likely to fall between the ranges given) for each input parameter. The standard
 33 deviation for the input parameter was entered as 1σ (68 %). For the legal range of
 34 ABV allowable (either 0.5 % or 1.5 %, depending on the state concentration) was
 35 assumed to be at 3σ (99.7 %) and was divided by 3 to give 1σ (68 %) for use in the
 36 modelling.

37

38 **6.3 Revised estimation of the uncertainty of the alcohol content in** 39 **beverages.**

40

41 In order to determine if the revised information in this study gave a reduced variation
 42 in the calculated alcohol concentration quoted by Gullberg [6] and Zuba [8] we used the

1 GEP method using equation 9 (detailed in section 6.1) and the Monte Carlo method
 2 using equation 2 (detailed in section 6.2) to calculate the coefficient of variance (CV)
 3 of alcohol. We utilised the values of the drinks given in the Gullberg study (Beer, 12 fl
 4 oz (us), 4% ABV [6]) and the Zuba study (Spirit, 250ml, 40% ABV [8]) but using the
 5 country specific variation volume and ABV from this study (USA for Gullberg, UK for
 6 Zuba). For Gullberg the volume was converted from fl oz (USA) to ml. It was assumed
 7 that the alcohol was bottled and the ABV was given on the label. For the Zuba data it
 8 is assumed that the drink was a single measure bottle. The value of uncertainty (SD)
 9 for ABV was obtained from Table 1 and volume from Table 5. The values used to
 10 calculate the precision (%CV) of the ethanol result and the calculated results are given
 11 in table 7A and 7B. As expected due to the improved uncertainty estimates from this
 12 paper compared to the publications by Gullberg [6] and Zuba [8] the %CV of the
 13 alcohol estimate was reduced. The Monte Carlo Method gave a lower calculated
 14 uncertainty (Table 7B) the GEP method (Table 7B) for both of the calculations of Beer
 15 (2.69 %CV for GEP compared to 1.69 %CV for Monte Carlo) and Spirits (1.85 %CV
 16 for GEP compared to 1.29 %CV for Monte Carlo). These results suggest that the
 17 Monte Carlo Method of determination of the uncertainty, at least for calculation of the
 18 amount of alcohol, is the preferred method of calculation over the standard GEP
 19 methodology.

20

21

22

23 **6.4 Proportion of the contribution of the Improved Ethanol Volume, Strength** 24 **and Density Estimates to Widmark Calculations**

25 In order to determine the proportional contribution of each of the seven variables to
 26 the total uncertainty in the Widmark equation ($v, z, d, r, W, \beta, t, f$, when calculating blood
 27 alcohol concentration); and the variables C_{max} , β , t , r , W , d and z , when calculating
 28 the number of drinks consumed). We used the revised uncertainty determine in this
 29 study for v, z and d the remaining variables were based on the data provided by
 30 Gullberg [6]. The relevant equation (equation 1 for blood alcohol concentration and
 31 equation 10 for number of drinks consumed) was entered in to GUM Workbench EDU
 32 (Version 2.4.1.384). As before we used type B errors that were assumed to exhibit a
 33 rectangular distribution. There were 2,000,000 iterations. The variables were all
 34 assumed uncorrelated except r and β where the correlation was -0.135 (based on the
 35 study by Gullberg and Jones [69]). As can be seen from the data in table 8A there was
 36 a reduction in the total error contribution of the volume (v), the density (d) and the ABV
 37 (z) to the overall calculation when the revised uncertainties were used, as expected.
 38 The total error contribution was 19.7% (based on the %CV provided by Gullberg)
 39 compared to 8% (based on the %CV from this study). The largest reduction in
 40 contribution to the total uncertainty observed was with the volume (14.1% to 3.6%).
 41 This led to an overall reduction in the uncertainty of the calculation of C_{max} of 0.5 %
 42 (from 12.5% to 12%) and a reduction of the SD of the mean C_{max} calculated (114
 43 mg/100ml) of 1 mg/100ml (from 14.5 mg/100ml to 13.5 mg/100ml). This of course is

1 only a reduction in the precision of the result it does not look at the accuracy of the
2 result.

3 It is also possible to look at the influence the improvement in the uncertainty has on
4 the use of the Widmark equation has for the calculation of the volume of ethanol that
5 has been consumed when the BAC is known. Again the data has been taken from
6 Gulberg [6] the transformed equation is:-

$$7 \quad v = (Ct + \beta t) \frac{rM}{100zd} \quad (10)$$

8

9 The variables used in the determination of the proportional uncertainty for density (d)
10 and ABV (z) are detailed in table 8B. There is a slight reduction in the overall
11 proportional uncertainty of 1.9 % (6.4 % to 4.5 %) with no change in the calculated SD
12 of ± 255 ml or the overall %CV of 14%. This is to be expected as they are only two
13 variables compared to three variables above. The volume was the variable of the three
14 with the largest contribution to the total uncertainty.

15

16 **Conclusions**

17 The results in this study allow forensic practitioners to both calculate and use reference
18 variables in order to improve their calculations of uncertainty when using the Widmark
19 equation. Although they are small improvements in uncertainty further improvement of
20 the reliability of Widmark calculations could be obtained with further work to determine
21 variance of the other parameters in the Widmark equation.

22

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2

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33

34

1 **Table 1: Allowable variations in alcohol content from labelled content in the EU**
 2 **and USA**

Country	Alcohol Type	Alcohol ABV	Allowable Variation	Reference
EU	Beer	Not Exceeding 5.5 %	± 0.5 %	EC Directive (87/250/EEC)
	Beer	> 5.5 %	± 1.0 %	
	Beverages containing macerated fruit or parts of plants	-	± 1.5 %	
	All others	-	± 0.3 %	
USA	Beer	-	± 0.3 %	27 CFR 7.71 (c)
	Distilled Spirits (50 or 100 ml bottles / products containing solids in excess of 600 mg per 100ml)	-	± 0.25 %	27 CFR 19.356 (c)
	All other distilled spirits	-	± 0.15 %	
	Wine	7 – 14 %	± 1.5 %	27 CFR 4.36 (b)

3

Table 2: Results of TTB Alcohol Beverage Sampling Program (ABSP) data from <https://www.ttb.gov/sampling/> (accessed 21/04/2017)

Year	Beverage	Raw Numbers					Percentages				Average	
		Number sampled	Number over filled	Number under filled	ABV: Number under	ABV: Number over	Overfill	Underfill	ABV:under	ABV:over	ABV:under	ABV:over
2011	Spirits	337	0	5	9	60	0.0	1.5	2.7	17.8		
	Beer	204	6	8	13	8	2.9	3.9	6.4	3.9		
	Wine	117	0	0	1	2	0.0	0.0	0.9	1.7		
2012	Spirits	246	1	1	12	60	0.4	0.4	4.9	24.4		
	Beer	206	0	0	19	10	0.0	0.0	9.2	4.9		
	Wine	196	0	1	0	1	0.0	0.5	0.0	0.5		
2013	Spirits	275	0	2	15	50	0.0	0.7	5.5	18.2		
	Beer	239	0	0	23	30	0.0	0.0	9.6	12.6		
	Wine	154	0	0	3	1	0.0	0.0	1.9	0.6		
2014	Spirits	190	0	0	14	42	0.0	0.0	7.4	22.1	0.72%	0.34%
	Beer	155	0	0	18	16	0.0	0.0	11.6	10.3		
	Wine	105	0	0	1	0	0.0	0.0	1.0	0.0		
2015	Spirits	154	0	0	8	40	0.0	0.0	5.2	26.0	0.95%	0.58%
	Beer	158	0	0	10	28	0.0	0.0	6.3	17.7	0.86%	0.69%
	Wine	138	0	0	1	1	0.0	0.0	0.7	0.7	2.70%	2.00%
2016	Spirits	175	0	0	14	36	0.0	0.0	8.0	20.6	0.66%	0.28%
	Beer	157	0	0	10	19	0.0	0.0	6.4	12.1	0.71%	0.94%
	Wine	118	0	0	2	0	0.0	0.0	1.7	0	1.7%	-

Table 3: Average Alcoholic Beverage Concentrations (ABV) in the UK Based on Data from Tesco.com and LWC-drinks.co.uk

Alcoholic Beverage	Mean ABV	Mode ABV	SD	Range (max)	Range (min)	n
Alcopops	4.0	4.0	0.0	4.0	4.0	10
Premix Spirits	5.2	5.0	0.4	4.0	6.4	29
Alcoholic Sorbets	4.7	4.7	0.0	4.7	4.7	9
Craft & Specialist Beer	5.7	5.6	1.1	4.1	9.2	35
Stout & Porter	4.0	#N/A	1.3	2.0	6.0	8
Lager	4.6	5.0	1.0	2.0	8.0	43
Draught Lager (All)	4.5	5.0	0.5	3.6	5.0	25
Draught Lager (Standard)	4.1	4.0	0.4	3.6	4.9	12
Draught Lager (Premium)	4.8	5.0	0.3	4.1	5.0	13
Ale & Bitter	4.8	5.0	0.9	2.0	7.3	90
Cider (All)	5.5	4.5	1.4	4.0	8.4	33
Cider (Bottled Fruit)	4.1	4.0	0.2	4.0	5.0	29
Cider (craft)	6.0	4.5	1.4	4.0	8.2	18
Cider (canned)	5.0	4.5	1.2	3.5	8.4	13
Cider (Pear)	4.5	4.5	0.0	4.5	4.5	3
Wine (White)	12.0	12.5	1.4	5.5	14.0	166
Wine (Red)	13.1	13.5	1.0	8.0	14.5	195
Wine (Rose)	10.5	12.0	1.8	5.5	13.0	38
Champagne	12.2	12.5	0.3	11.5	12.5	27
Prosecco	11.1	11.0	0.3	10.5	11.5	10
Sherry	17.1	17.5	1.4	15.0	19.0	28
Port	19.8	20.0	0.4	19.0	20.0	18
Vodka (All)	39.0	40.0	1.3	37.5	40.0	24
Vodka (Normal)	39.0	40.0	1.3	37.5	40.0	13
Vodka (Flavoured)	38.9	40.0	1.3	37.5	40.0	11
Rum (All)	38.5	40.0	6.6	21.0	63.0	25
Rum (White)	43.1	37.5	11.2	37.5	63.0	5
Rum (Golden)	39.6	40.0	0.9	37.5	40.0	7
Rum (Dark)	39.0	40.0	1.4	37.5	40.0	5
Rum (Spiced)	36.1	35.0	3.5	30.0	40.0	7
Gin (All)	38.2	37.5	4.6	26.0	43.1	22
Gin (standard)	38.9	37.5	2.0	37.5	43.0	12
Gin (premium)	41.2	40.0	1.4	40.0	43.1	7
Gin (Sloe)	28.0	29.0	1.7	26.0	29.0	3
Brandy	34.8	36.0	6.0	22.0	40.0	17
Cognac	40.0	40.0	0.0	40.0	40.0	9
All Whisk(e)y	40.2	40.0	3.7	20.0	50.0	83
Scotch Whisky	40.7	40.0	2.5	28.0	46.0	59
Bourbon	39.9	40.0	4.5	35.0	50.0	15
Irish Whiskey	40.0	40.0	0.0	40.0	40.0	3
Other Whiskey	36.0	43.0	8.6	20.0	43.0	6

Table 4: Mean, Standard deviation and %CV of the alcohol concentration (ABV) of various beer types found at the 2016 Great British Beer Festival (www.gbbf.org/beer)

	Golden Ale	Bitter	IPA	Mild	Porter	Stout	Speciality	Overall
ABV (Mean)	4.2	4.3	5.1	4.0	4.9	5.0	4.4	4.4
ABV (Mode)	4.0	4.0	5.0	3.8	4.7	5.0	4.0	4.0
Standard Deviation	0.4	0.5	1.0	0.6	0.7	1.0	0.4	0.7
%CV	8.5	11.9	20.1	15.5	14.8	19.4	8.6	15.8
ABV Range (min)	3.6	3.5	3.5	3.0	4.0	3.7	3.8	3.0
ABV Range (max)	5.5	6.6	7.5	6.0	6.5	7.5	5.2	7.5
n=	140	108	43	36	12	24	23	386

Table 5: Allowable variations in beverage volume in the EU and USA

Country	Alcohol Type	Draft/bottle	Allowable Variation	Reference
EU	All (Serving) Line	Draft <200 ml	± 5 %	Annex MI-008
EU	All (Serving) Brim	Draft <200 ml	0 - 10 %	
EU	All (Serving) Line	Draft >200 ml	± 5 % + 2.5 %	
EU	All (Serving) Brim	Draft >200 ml	0 - 10 ml +5 %	
EU	All (transfer) - Line	Draft <100 ml	± 2 ml	
EU	All (transfer) - Brim	Draft <100 ml	0 - 4 ml	
EU	All (transfer) - Line	Draft >100 ml	± 3 %	
EU	All (transfer) - Brim	Draft >100 ml	0 - 6 %	
US	Pre-packaged	Bottle (<100ml)	± 4.5 %	27 CFR 19.356
US		Bottle (101 - 375ml)	± 3.0 %	
US		Bottle (376-999 ml)	± 2.0 %	
US		Bottle (>1000ml)	± 1.5 %	
Country	Alcohol Type	Draft/bottle	Tolerable negative error (TNE)	Reference
EU	Pre-packaged	Bottle (5 - 50 ml)	9%	Annex MI-008
EU		Bottle (50- 100 ml)	4.5 ml	
EU		Bottle (100 - 200 ml)	4.50%	
EU		Bottle (200 - 300 ml)	9 ml	
EU		Bottle (300 - 500 ml)	3%	
EU		Bottle (500 - 1000 ml)	15 ml	

Table 6: Experimental determination of self-pour measures of alcoholic beverages. A) and B) in UK units. C) Volume (ml)**A)**

Study	Spirits				Wine			
	Mean (units)	SD	95% CI	n	Mean (units)	SD	95% CI	n
Wilson [70]	1.44	0.72		?				
Gill & Donaghy [71]	2.13		2.16 - 2.41	238	1.92		1.86 - 1.97	238
Gill et al [72]	2.24		1.8 - 2.7	19	1.98		1.7 - 2.2	19
Boniface et al [73]	1.93	0.78		201	1.90	0.8		264

B)

Study	Spirits				Wine				Beer			
	Female		Male		Female		Male		Female		Male	
	Mean (units)	SD	Mean	SD	Mean (units)	SD	Mean	SD	Mean (units)	SD	Mean	SD
Wilkinson et al. [57]	1.56	3.51	1.98	3.40	1.48	0.22	1.73	0.94	0.99	1.75	1.44	1.13
Kerr et al. [58]	2.48	1.81	2.66	1.55	2.01	1.33	1.87	1.00	1.75	1.16	1.60	0.36

C)

Study	Spirits				Wine			
	Female		Male		Female		Male	
	Volume (ml)	SD	Volume (ml)	SD	Volume (ml)	SD	Volume (ml)	SD
Wilson [70]	36	18	Only mean no sex given					
Lemmens [74]	48	30	44	16	106.00	33	112	33
Gill & Donaghy [71]	57.1	24	Only mean no sex given					

Where the data was not shown as SD (SE) it was converted to SD.

Table 7A: The revised uncertainties volume, ABV and amount of alcohol from Gulberg and Zuba based on the uncertainties found in this paper (GEP method).

Publication	Volume (ml)	Volume %CV	Density (g/cm³)	Density %CV	ABV (%v/v)	ABV %CV	Calculated Alcohol Amount (g)	Calculated Alcohol Amount %CV
Gullberg [6]	354.88	1	0.78974	0.07	4	2.5	11.21	2.69
Zuba [8]	250	1.67	0.78974	0.07	40	0.8	78.97	1.85

Table 7B: The revised uncertainties volume, ABV and amount of alcohol from Gulberg and Zuba based on the uncertainties found in this paper (Monte Carlo Method).

Publication	Volume (ml)	Volume %CV	Density (g/cm³)	Density %CV	ABV (%v/v)	ABV %CV	Calculated Alcohol Amount (g)	Calculated Alcohol Amount %CV
Gullberg [6]	354.88	1	0.78974	0.07	4	2.5	11.2	1.69
Zuba [8]	250	1.67	0.78974	0.07	40	0.8	79.0	1.26

Table 8: The proportion that each variable in the Widmark equation contributes to estimating A) the blood alcohol concentration (Ct) or B) the volume of drink (v) consumed based on data from Gullberg and this Study

A)

Gullberg Data				Data from this study		
Variable	Value	SD	Percentage of Total Uncertainty	Variable	SD	Percentage of Total Uncertainty
v	3550 ml	103 ml	14.10%	3550.0 ml	48.4 ml	3.60%
z	0.040000 %v/v	693x10 ⁻⁶ %v/v	5.00%	0.040000 %v/v	577x10 ⁻⁶ %v/v	4.00%
d	0.78900 g/ml	4.56 x10 ⁻³ g/ml	0.60%	0.78974 g/ml	3.41x10 ⁻³ g/ml	0.40%
r	0.7300 L/Kg	0.0388 L/Kg	41.70%	0.7300 L/Kg	0.0388 L/Kg	47.80%
W	81.640 Kg	0.943 Kg	2.20%	81.640 Kg	0.943 Kg	2.60%
β	14.80 mg/100ml/h	1.88 mg/100ml/h	36.00%	14.80 mg/100ml/h	1.88 mg/100ml/h	41.20%
t	5.0000 h	0.0577 h	0.30%	5.0 h	0.0577 h	0.40%
Total (v,z,d)			19.70%	Total (v,z,d)		8.00%

B)

Gullberg Data				Data from this study		
Variable	Value	SD	Percentage of Total Uncertainty	Variable	SD	Percentage of Total Uncertainty
Cmax	114.00 mg/100ml	1.91 mg/100ml	2.00%	114.00 mg/100ml	1.91 mg/100ml	2.00%
β	14.80 mg/100ml/h	1.88 mg/100ml/h	41.20%	14.80 mg/100ml/h	1.88 mg/100ml/h	42.10%
t	5.0000 h	0.0577 h	0.40%	5.0000 h	0.0577 h	0.40%
r	0.7300 L/Kg	0.0388 L/Kg	47.40%	0.7300 L/Kg	0.0388 L/Kg	48.40%
W	81.640 Kg	0.943 Kg	2.60%	81.640 Kg	0.943 Kg	2.60%
d	0.78900 g/ml	4.56x10 ⁻³ g/ml	0.60%	0.78974 g/ml	3.41x10 ⁻³ g/ml	0.40%
z	0.040000 %v/v	693x10 ⁻⁶ %v/v	5.80%	0.040000 %v/v	577 x10 ⁻⁶ %v/v	4.10%
Total (z,d)			6.40%	Total (z,d)		4.50%