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Technical Note

Uncertainty in Widmark calculations: ABV variation in packaged versions of the most popular beers in the UK

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ABSTRACT

Forensic practitioners regularly use the Widmark equation to determine theoretical blood alcohol concentrations for use in cases involving alcohol. It is important with these calculations to determine the uncertainty associated with any result. Previous work has investigated the uncertainty in percent alcohol by volume (%ABV) from beers produced by small independent breweries in the UK but did not study the top selling beers in the UK. The top selling lagers and ales/bitters in the UK were identified by sales volume and the %ABV determined. These data was then used to determine the percent coefficient of variation (%CV) that should be used by forensic practitioners when constructing alcohol technical defence reports for use in forensic cases. These samples, from what may be described as 'big' brewers, were determined to have a smaller root mean square error (RMSE) (± 0.1%*v*/v, $n = 35$), and %CV than those previously reported for beers produced by small, independent breweries in the UK. The results from this study shows that different RMSE's should be used for %ABV when determining the uncertainty of results from Widmark calculations depending if the drinks consumed have been from either 'big' brewers or small, independent breweries.

1. Introduction

Due to the comprehensive understanding of the pharmacology of alcohol in humans the Widmark equation can be used to estimate either the number of drinks a person may have consumed (based on a blood alcohol concentration measurement) or the blood concentration that may be found in an individual (based on the number have drinks they have consumed) [1]. However, as with many equations used in forensics there is uncertainty associated with many of the parameters and the results of the calculations [2–4].

Recently there has been increasing momentum behind calls for greater underpinning of the science, and uncertainty behind methods utilised by the forensic community [5,6]. In addition to this, over 10 years ago Gullberg postulated that for the correct presentation and interpretation of data generated by the Widmark equation, forensic scientists needed to determine the uncertainty in the Widmark calculations, and to include an assessment of this uncertainty in their work [2].

Beer is one of the most widely consumed beverages in the world and was the only alcoholic beverage to appear in the breakdown of the top 10 sales for global beverages (2011–2016) [7]. In the UK 62% of the British population identify as being beer drinkers, in terms of gender this equates to 77% of men and 49% of women, and unusually, is popular amongst nearly all age demographics [8].

In 2018 it was reported that lager accounted for 73% of both the total volume sold and the total value of the alcoholic drinks market [9]. The lager category is made up of standard lager and premium lager [10], and is usually differentiated on price. Market analysis suggests that 47% of adults in the UK drank lager during a monitored six-month period (in the UK), and that the market for this product is predicted to have the capacity for growth in the future as a greater number of smaller, independent, producers ('craft') move into this sector [8]. The popularity of ales is also expected to increase, as both large and small producers try to gain traction in this market segment [8].

A recent study [11] determined the uncertainty of alcohol by volume (ABV) that could be applied for Widmark equation calculations when considering 'craft' beers in small packaging units (bottles and cans). However, unlike in the USA, there is no definition of 'craft' in the UK [12] and this is reflected in a study of consumers which found that only 15% of UK consumers self-identified as having consumed 'craft beer' in the previous six months [8]. Therefore, for forensic purposes it is important to be able to take into consideration the beer that makes up the majority of consumption of beer in the UK.

These beers are often produced by global brewers who usually have

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multiple sites around the world which are often capable of producing the same brands. These breweries will utilise all the technology and skill at their disposal to brew in the most efficient ways possible, producing product with the maximum productivity from the raw materials whilst at the same time creating minimal waste to the environment. One of the techniques at their disposal is High Gravity Brewing (HGB), this brewing practice may utilise the use of adjuncts (additional sources of fermentable sugars) to produce a carbohydrate rich fermentation medium and allows the addition of larger volumes of water at a later stage of the production process, often immediately prior to packaging [13]. The technique was developed to give breweries the capability to increase their production capacity without significant capital expenditure [14]. The addition of water at a late stage of brewing is practiced with great care, as addition of too much water would dilute the beer beyond what was acceptable, risking damage to the brand through consumer perception. These additions are therefore carefully controlled, and, in some cases may be used to the brewers' advantage [15], within the tolerances allowed by packaging legislation in the UK [16,17]. It was postulated that the ABV of these mass-produced beers, of which makes up the majority of beer sales in the UK, would have a smaller standard deviation from what is declared on the packaging when compared with a previous study of craft brewed products [11].

The aim of the current study was to determine the standard deviation (SD) (and percent coefficient of variation (%CV)) in alcoholic content (percent alcohol by volume (% ABV) for the most popular beers in the UK by market share. The top selling lagers, and ales (including bitters and stouts) were identified by sales volume in the UK, some of these beers may not have been brewed in the UK and may have been imported, but all were purchased in the UK and must adhere to UK packaging legislative requirements. These data will be important for reliable determination of the uncertainty of the %ABV of a beer when used in Widmark calculations.

2. Methodology

A total of 38 commercial beer samples were purchased from Scottish retail outlets during April 2018, brands were selected from the Mintel Beer Report 2017 [8]. The labelled alcohol by volume (ABV) of these samples ranged between 3.6 and 7.3%*v*/v. Of the samples selected, 35 products had an ABV ≤ 5.5%*v*/v meaning that EU (and thus, UK legislation [16]) for packaged beer allows for a variation in ABV to be ± 0.5%*v*/v [17], the remaining 3 samples all had a labelled ABV of > 5.5%v/v and therefore are permitted to have an uncertainty of ± 1.0%v/v from the ABV labelled on packaging. Only beers with a labelled ABV of ≤5.5% were included in this study.

The method of analysis was adapted from Maskell et al. [11] and from the American Society of Brewing Chemists [18], in brief, each beer sample upon opening was immediately de-gassed by filtering through grade A filter paper (Whatman, Maidstone UK), into 50 ml centrifuge tubes (Fisher Scientific, Loughborough, UK). Duplicate 20 ml samples were then passed through an Anton-Paar DMA 4500 density meter connected to a Beer ME Alcolyzer unit (Anton-Paar, St Albans, UK) to measure the %ABV. The system is reported to have a repeatability of 0.01%*v*/v by the manufacturer [19]. This analytical method is approved by MEBAK (Central European Commission for Brewing Analysis) for measurement of %ABV [19]. The repeatability of the Anton-Paar was determined by measuring the %ABV of standard solutions of ethanol (0%, 5%, 11.25%, 15% and 20% ABV in triplicate). These analyses were repeated over 3 days. Overall the Anton-Paar was determined to have a mean repeatability of 0.03 ± 0.02% (n = 45).

The root mean square error (RMSE) of the predicted (experimentally determined %ABV) minus observed (labelled %ABV) was calculated using Excel 2016 (Microsoft, Redmond, WA, USA). The normal distribution was determined using histogram analysis (SPSS Statistics v23.0.0.3, IBM, Armock, NY, USA).

The contribution of each variable to the overall uncertainty of measurement for blood alcohol concentration and the %CV for volume of pure ethanol per drink was calculated using GUM Workbench EDU Software v2.4.1.384 (Metrodata GmbH, www.metrodata.de) using the variables from Table 2 and Eq. (1).

$$C_o = \frac{100ZNd}{rM} \tag{1}$$

C_o = the maximum theoretical BAC at the time the ethanol dose was administered (mg/100 ml) assuming complete and instantaneous absorption.

Z = volume of pure ethanol per drink (ml/drink).
N = number of drinks consumed.
d = density of ethanol (g/ml).
r = Volume of distribution of ethanol in the subject (L/kg).
M = mass of the subject (kg).

The %CV for volume of pure ethanol per drink was calculated using eq. 2

$$Z = a \times v \tag{2}$$

a = strength of alcohol beverage (%*v*/v).
v = volume of alcoholic beverage (ml).

3. Results and discussion

In order to determine the uncertainty of the declared alcohol concentration in popular beers in the UK, small pack (bottles or cans) were identified by sales volume in the lager and ale/bitter categories. Three beers were excluded from the study as they had a labelled %ABV that were > 5.5%*v*/v and did not provide a large enough subset for further study as at this %ABV as a different rule applies with packaging declaration.

Packaging legislation in the UK [16] is determined by EU Regulation 1169/2011 [17], which gives an allowable variation between the actual and labelled %ABV. For beers with a %ABV of ≤5.5%*v*/v the legally allowed variation is ± 0.5%v/v. In Fig. 1 it can be observed that the data was normally distributed. Following on from this the mean difference of the measured %ABV minus labelled %ABV was found to be −0.1%*v*/v, and the RSME was determined to be 0.1%v/v, which is easily within the legally allowed limits of the Packaging Regulations and is as expected with data declared during the Molson-Coors tax tribunal [15]. This RMSE was smaller than that previously determined RSME ± 0.4%v/v for 112 different craft beers (n = 112) [11]. These data highlight the differences between beer from small, independent producers and national or global entities, who are likely to have a greater capacity to invest in technology to ensure that the packaged product falls within the legal limits on every occasion.

The simplest way to determine the error associated with a calculation is to use the %CV of the parameter under consideration in the calculation of uncertainty rather than the standard deviation [3]. As the degree of proof in specific trials such as civil (on balance of probabilities) and criminal (beyond reasonable doubt) we have given the %CV for 1σ to 3σ. It is likely that 1σ would be used for civil trials and 2σ or 3σ would be used in criminal trials although the exact σ to be used must be up to the discretion of the forensic practitioner. Fig. 2 and Table 1 illustrate the %CV for 1 - 3σ.

In order to demonstrate the influence of the different %CVs of ABV and the amount of ethanol in an alcoholic beverage (Z) (craft beer, big beer and by way of comparison the value given by Gullberg in his 2007 paper [2]) on alcohol calculations we calculated the C_o for an example individual. The variables for the individual that we used are shown in Table 2. In order to determine the %CV of the amount of ethanol in an alcoholic beverage to compare the results to Gullberg (%CV = 3%) we used the RMSE of %ABV from this study and the work of Maskell et al., [11,20] (ABV and volume). We assumed that the individual had consumed 2 UK pints (568 ml) of 4% ABV beer. As can be seen in Table 2 the %CV for the amount of ethanol in an alcoholic beverage for big beer

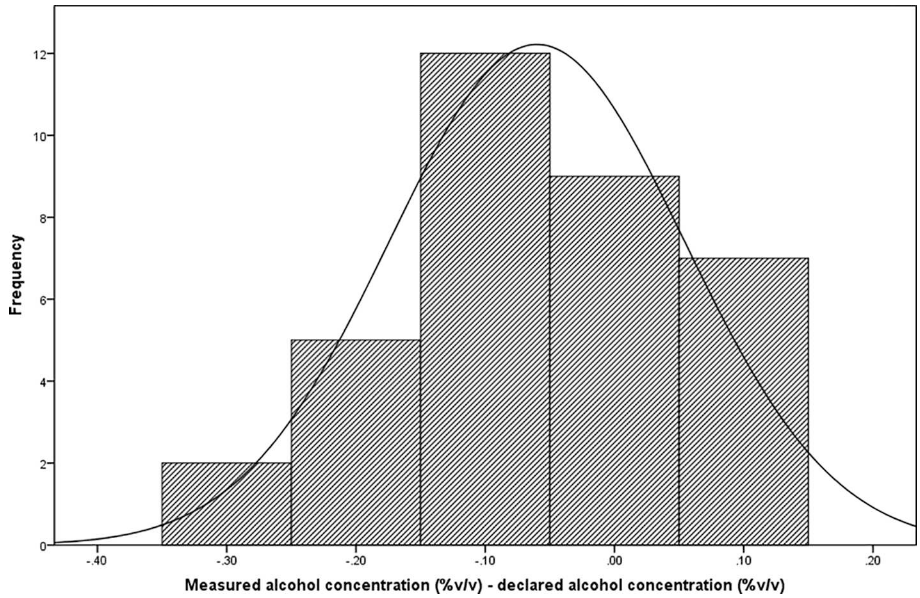

Fig. 1. Histogram of the residuals of the 35 beers with a declared ABV ≤5.5% showing normal distribution.

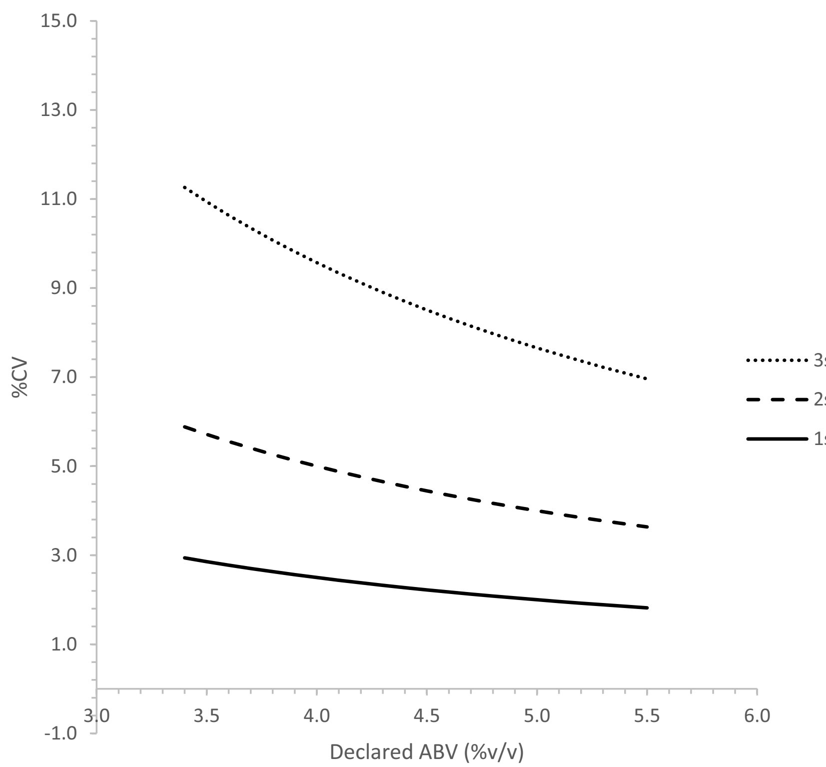

Fig. 2. The %CV that should be utilised for uncertainty calculations when the %ABV of the beer is known. The data is given for 1σ (68% CI), 2σ (95% CI) and 3σ (99.7% CI).

was 1.4% and 5.4% for craft beer. As can be seen from Table 3 the calculated C_o for the individual was 73 mg/100 ml, with a SD of ± 7 mg/100 ml; 9.6%CV (Gullberg); ± 7 mg/100 ml; 9.6%CV (big beer) and ± 8 mg/100 ml; 10.9%CV (craft beer). Table 3 shows that as expected the volume of distribution of ethanol (V_d) has the largest influence on the overall uncertainty of C_o (between 72.1 and 86.8%), followed by the volume of pure ethanol per beverage with a proportion of between 2.2 and 24.5% (big beer having the smallest influence and craft beer having the largest influence).

For the forensic practitioner these data demonstrate the importance of the appropriate confidence intervals for different cases. Although these differences are small, and thus the contribution of ABV error to

Table 1
The %CV that should be utilised for uncertainty calculations when the %ABV of the beer is known. The data is given for 1σ (68% CI), 2σ(95% CI) and 3σ (99.7% CI).

%ABV	%CV		
	1σ	2σ	3σ
3.4	2.9	5.9	11.3
3.5	2.9	5.7	10.9
3.6	2.8	5.6	10.6
3.7	2.7	5.4	10.3
3.8	2.6	5.3	10.1
3.9	2.6	5.1	9.8
4.0	2.5	5.0	9.6
4.1	2.4	4.9	9.3
4.2	2.4	4.8	9.1
4.3	2.3	4.7	8.9
4.4	2.3	4.5	8.7
4.5	2.2	4.4	8.5
4.6	2.2	4.3	8.3
4.7	2.1	4.3	8.1
4.8	2.1	4.2	8.0
4.9	2.0	4.1	7.8
5.0	2.0	4.0	7.7
5.1	2.0	3.9	7.5
5.2	1.9	3.8	7.4
5.3	1.9	3.8	7.2
5.4	1.9	3.7	7.1
5.5	1.8	3.6	7.0

Table 2
Example variable values from a fictitious individual (and associated uncertainties) used to estimate the blood alcohol concentration calculated with the Widmark equation.

Variable		Value	Uncertainty (S.D.)	% CV
Sex		Male		
Weight (kg)		70[a]	1.4	2.0[a]
Vd of ethanol (r; l/kg)		0.7[a]	0.064	9.2[a]
Volume of Drink (v; ml)		568 (1 UK pint)	3.81[b]	0.67[b]
Alcohol Density (d; g/ml)		0.78974[b]	5.9×10^{-4}[b]	0.06[b]
Number of drinks (N)		2	0	0
Strength of Alcohol (%v/v)	Gullberg[a]	4.0	n/a	n/a
	Big Beer[c]	4.0	0.100	2.5
	Craft Beer[d]	4.0	0.432	10.8
Volume of pure ethanol per drink (Z; ml/drink)	Gullberg	22.72	0.68	3.0[a]
	Big Beer	22.72	0.32	1.4[c]
	Craft Beer	22.72	1.22	5.4[d]

Strength of Alcohol (%v/v).
Data From
[a] Gullberg [2].
[b] Maskell et al., 2017 [20]
[c] This study (Table 1).
[d] Maskell et al., 2018 [11].

the total error in Widmark equations is small it should not be considered to be negligible. A different coefficient of variation should be used when it can be confidently determined whether in a case a subject had consumed 'craft' or more 'mainstream' products and take into consideration the %ABV category into which the products would fall. Therefore, this work makes a further contribution to understanding of the discrepancies that may be determined between alcohol consumed and that which is measured and calculated [21].

An important further observation is that if the beer consumed is a product produced by large, global brewing companies it is more likely to be under the declared %ABV but still easily within the legally allowable variance.

Table 3
The proportion (as a percentage) that each variable of the Widmark equation contributes to estimating the uncertainty in C_o (the maximum theoretical BAC at the time the ethanol dose was administered) based on data from Tables 2.

Volume of ethanol per drink %CV	Gullberg (3%)	Big beer (1.4%)	Craft Beer (5.4%)
Volume of pure ethanol per drink (Z; ml/drink)	9.1	2.2	24.5
Alcohol density (d; g/ml)	0.0	0.0	0.0
Volume of distribution of ethanol (r; l/kg)	86.8	93.4	72.1
Weight (kg)	4.1	4.4	3.4
Calculated C_o (mg/100 ml)	73	73	73
SD	7	7	8
%CV	9.6%	9.6%	10.9%

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