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Allan R. Gainsford,[1] *Ph.D.; Dinusha M. Fernando,*[2] *M.Sc. (Hons); Rodney A. Lea,*[1] *Ph.D.; and Allan R. Stowell,*[1] *Ph.D.*

A Large-Scale Study of the Relationship Between Blood and Breath Alcohol Concentrations in New Zealand Drinking Drivers*

ABSTRACT: Blood alcohol concentrations (BAC) and corresponding breath alcohol concentrations (BrAC) were determined for 21,582 drivers apprehended by New Zealand police. BAC was measured using headspace gas chromatography, and BrAC was determined with Intoxilyzer 5000 or Seres Ethylometre infrared analysers. The delay (DEL) between breath testing and blood sampling ranged from 0.03 to 5.4 h. BAC/BrAC ratios were calculated before and after BAC values were corrected for DEL using 19 mg/dL/h as an estimate of the blood alcohol clearance rate. Calculations were performed for single and duplicate breath samples obtained using the Intoxilyzer (groups I-1 and I-2) and Seres devices (groups S-1 and S-2). Before correction for DEL, BAC/BrAC ratios for groups I-1, I-2, S-1, and S-2 were (mean ± SD) 2320 ± 260, 2180 ± 242, 2330 ± 276, and 2250 ± 259, respectively. After BAC values were adjusted for DEL, BAC/BrAC ratios for these groups were (mean ± SD) 2510 ± 256, 2370 ± 240, 2520 ± 280, and 2440 ± 260, respectively. Our results indicate that in New Zealand the mean BAC/BrAC ratio is 19–26% higher than the ratio of the respective legal limits (2000).

KEYWORDS: forensic science, alcohol, blood analysis, breath analysis, Intoxilyzer 5000, Seres Ethylometre 679T, Seres Ethylometre 679ENZ, blood/breath alcohol ratio, variability, drunk drivers

The relationship between blood and breath alcohol concentrations (BAC and BrAC) has been the subject of many laboratory-based studies (1–6). In particular, the BAC/BrAC ratio has been studied by those interested in BrAC as a surrogate measure of the BAC, in the context of law enforcement. Some of these studies have been carried out on drinking drivers in the field (7–9). However, as mentioned by Jones and Andersson (9), very few large-scale studies of the BAC/BrAC ratio in drinking drivers have been published in peer-reviewed journals. Furthermore, those studies that have been published have involved the use of just one type of breath testing instrument (7–9). In this paper, we present a large-scale study of the BAC/BrAC ratio in New Zealand (NZ) drinking drivers, involving the use of evidential breath testing instruments from two different manufacturers. All measurements were made on samples taken in the field for normal land transport law enforcement purposes. Therefore, there was a variable delay (DEL) between the time of BrAC measurement and the time of blood sampling for BAC measurement. We describe the relationships between BAC and BrAC under NZ field conditions, with and without allowance for DEL, and consider their forensic implications.

[1] Environmental Science and Research Limited, PO Box 50-348, Porirua, New Zealand.
[2] Environmental Science and Research Limited, Private Bag 92-021, Auckland, New Zealand.

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Materials and Methods

Breath Alcohol Analysis

Over a 15 year and 5 month period ending 17 June 2004, BrAC results were obtained for a total of 21,582 NZ drinking drivers who subsequently underwent blood sampling for alcohol analysis. Breath alcohol analyses were performed by police officers operating a total of 96 Intoxilyzer 5000 VA instruments (CMI Inc., Owensboro, KY) and 100 Seres Ethylometre 679T or 679ENZ instruments (Seres, Aix-en-Provence, France). The Intoxilyzer 5000 VA has an infrared detector, employing two analytical wavelengths (3.48 and 3.39 μm) and a 3.80 μm reference wavelength. The Seres Ethylometre instruments also have infrared detectors, but a single analytical wavelength of 9.5 μm is employed. Therefore, the two types of instrument have different specificities and are subject to different potential interferences (10–12). The analytical functions of these instruments are the same as those used in Europe and the United States. However, they differ in minor aspects of their software relating mainly to presentation of results on the result cards.

All instruments were calibrated at the Institute of Environmental Science and Research Limited (ESR) using standard alcohol vapors produced using Smith & Wesson Mark IIA (Smith & Wesson, Springfield, MA) or Alcotest CU34 (Draeger Safety Inc., Durango, CO) breath alcohol simulators. Standards of 400 μg/L were used to calibrate the Intoxilyzers, and standards of 480 μg/L were used to calibrate the Seres instruments. Accuracy and precision were considered acceptable for all instruments only if the mean of 10 analyses was within ± 2.5% of the target concentration and the standard deviation was ≤6.5 μg/L. Linearity of all instruments was checked using a 1200 μg/L standard. No calibration checks were performed in the field, but

all instruments were serviced and recalibrated at ESR at least annually.

Both the Intoxilyzer and Seres instruments used in NZ are programmed to allow the driver reasonable opportunity to give duplicate breath samples, suitable for analysis, within the space of about 7 min. Blank tests and internal standard checks are also performed within this time. Results are displayed and printed in units of μg/L, and the lower of the duplicate results, or in some circumstances, a single result, is used for evidential purposes. However, in this study, each BrAC value represents either the mean of duplicate results or the result of a single analysis.

The main legal BrAC limit for NZ drivers 20 or more years of age is 400 μg/L (0.084 g/210 L). The corresponding BAC limit is 80 mg/dL (0.08% w/v). To allow for analytical uncertainty at the main legal BrAC limit, Intoxilyzer 5000 and Seres Ethylometre instruments used in NZ are programmed to display a result of 400 μg/L for any result from 400 to 439 μg/L inclusive. For this reason, no result of 400 μg/L was included in this study, and there is an unavoidable discontinuity in the data set.

Prior to 29 December 2001, drivers in NZ were denied the right to a blood test if (a) their BrAC was above 600 μg/L, (b) results for duplicate breath samples were obtained, and (c) the higher of the two results was not more that 15% greater than the lower result. For drivers with a BrAC of 600 μg/L or less, not only did the 15% criterion not apply, but a single result could also be used for evidential purposes in the event of an inadequate second sample. However, the latter group of drivers also had the right to a blood test, and most of them were able to provide duplicate breath samples that met the 15% agreement criterion. A law change on 29 December 2001 ensured that all NZ drivers exceeding a legal BrAC limit had the right to a blood test. As a consequence of the timing of data collection relative to this law change, the nature of the standard breath test procedure, the main legal limit, the allowance for analytical uncertainty mentioned above, and the fact that evidential tests are performed only if drivers fail a breath screening test, a high proportion (64.7%) of the BrAC values in this study are in the range of 440–600 μg/L, only a small proportion of the duplicate results (4.1%) do not meet the 15% criterion, and a small proportion of the BrAC results (7.8%) relate to single analyses.

In NZ there is no requirement for a 15–20 min observation period prior to evidential breath testing. The 15% agreement criterion effectively means that duplicate results are not accepted unless they are within $\pm 7.5\%$ of the mean. Therefore, mouth alcohol effects (13), if present, would either have a very small impact on the final result or would completely invalidate the result and lead to further breath testing or a blood test.

Blood Alcohol Analysis

Samples of venous blood were taken by a syringe and placed in 15 mL screw-capped glass bottles containing potassium oxalate as anticoagulant and sufficient sodium fluoride as preservative to give a final concentration of 2% in the blood. The bottles were then sealed and sent to ESR where they were stored at $5 \pm 4^{\circ}C$ until they were analysed for alcohol. Analyses were performed by headspace gas chromatography (14). Perkin-Elmer F40, F42, and F45 instruments were used from 1988 to 1991. Since 1991, Tekmar 7050 headspace autosamplers have been used, interfaced with Hewlett-Packard 5890 Series II gas chromatographs. In spite of the change in hardware, the analytical method has remained essentially unchanged, involving duplicate sixfold dilutions of blood with aqueous internal standard containing *n*-propanol (0.02% w/v) and sodium azide (2.3% w/v) and use of a 1.2 m, 2 mm I.D. stainless steel column packed with 10% Carbowax 600 on Chromosorb W 60/80 mesh. All results were confirmed by re-analysis using a sixfold dilution of blood with *t*-butanol as internal standard and a second packed column (Porapak Q or 0.2% Carbowax 1500 on Graphpac GC 80/100 mesh). The coefficient of variation (CV) for the method is less than 1% over the range of BAC values reported in this paper.

No systematic bias was seen up to a BAC of 100 mg/dL. A small positive systematic bias begins to be seen at BAC values above 100 mg/dL, increasing to a maximum of +2% at a BAC of 450 mg/dL. Analytical uncertainty in BAC results is allowed for in NZ by subtracting 6 mg/dL from the actual result before reporting. This is a very generous deduction, which has had the practical effect of minimizing legal challenges to BAC results. However, all BAC results used in this study are actual results.

Statistical Analysis

Descriptive statistical analyses were carried out for the variables BrAC (μg/L), BAC (mg/dL) and DEL (hours) by instrument type and by number of breath tests (single or duplicate).

The relationship between BrAC and BAC was modelled using linear regression analyses. Instrument group comparisons were performed using unpaired (independent) samples *t*-tests. All statistical analyses were carried out using Statistical Analysis Software (SAS) System version 8.2. A *p*-value of ≤ 0.05 was taken to be statistically significant.

Sample Groups

The data were divided into four groups depending on which breath-testing instrument was used and whether single or duplicate breath test results were obtained for each driver. Two groups (Intoxilyzer: $n = 1010$, Seres: $n = 665$) making up a total of 1675 drivers failed to provide more than one satisfactory breath sample. These groups are called I-1 and S-1, respectively. The other two groups (Intoxilyzer: $n = 14{,}101$, Seres: $n = 5806$) comprised 19,907 drivers who provided duplicate breath samples. These groups are called I-2 and S-2, respectively.

Calculation of Individual BAC/BrAC Ratios

BAC/BrAC ratios were calculated *with* and *without* adjustment for DEL. Adjustment for DEL was performed by increasing each BAC value by a factor of 19 mg/dL/h multiplied by DEL, as used by Jones (9). The adjusted BAC was then divided by the single available BrAC value (groups I-1 and S-1), or by the mean BrAC value (groups I-2 and S-2). This adjustment yielded estimates of the BAC values that would have been obtained had they been measured at the time of the breath tests. The figure of 19 mg/dL/h is an estimate of the mean blood alcohol clearance rate obtained in a study of Swedish drinking drivers (15) and was used in the absence of corresponding data for NZ drivers. As BrAC units used in NZ are a factor of 10^4 lower than the BAC units, all calculated BAC/BrAC ratios were multiplied by this factor before reporting.

Results

Descriptive Statistics

For each of the four study groups, descriptive statistics for the variables BAC, BrAC, and DEL are given in Table 1. The relationship between BAC and BrAC data in each of the four groups is

TABLE 1—*Descriptive statistics for variables BrAC, BAC, and DEL.*

Instrument	Sample Group	Variable	Mean	Range	Standard Deviation	Sample Size
Intoxilyzer	I-1	BrAC (μg/L)	813	69–1963	239	
	(single analyses)	BAC (mg/dL)	189	12–438	58	1010
		DEL (h)	0.73*	0.1–2.8		
Intoxilyzer	I-2	BrAC (μg/L)	550	171–1771	152	
	(duplicate analyses)	BAC (mg/dL)	121	13–407	38	14,101
		DEL (h)	0.68*	0.03–5.4		
Seres	S-1	BrAC (μg/L)	703	175–1466	222	
	(single analyses)	BAC (mg/dL)	164	38–348	53	665
		DEL (h)	0.71*	0.15–2.55		
Seres	S-2	BrAC (μg/L)	549	172–1666	162	
	(duplicate analyses)	BAC (mg/dL)	125	19–350	41	5806
		DEL (h)	0.69*	0.03–3.2		

*The DEL values are not normally distributed. Medians are 0.667, 0.642, 0.650, and 0.658, for I-1, I-2, S-1, and S-2, respectively.
All BAC and BrAC values are rounded to the nearest whole number.
BrAC, breath alcohol concentrations; BAC, blood alcohol concentrations; DEL, delay.

also presented graphically in Fig. 1. The distribution of measurement agreements between the duplicate breath test results is illustrated in Fig. 2 for both the Intoxilyzer and Seres instruments. For 96% of the duplicates, the higher of the two results was no more than 15% greater than the lower value.

Relationship Between BAC and BrAC

The relationship between BAC and BrAC for the four different groups of data is best described by the linear regression equations in Table 2. All statistical assumptions for linear regression were met. Statistically significant relationships between BAC and BrAC ($p < 0.001$) were observed for groups I-1, I-2, S-1, and S-2. In all cases BrAC was a strong predictor of BAC, accounting for 88%, 89%, 88%, and 90% of BAC variation, respectively.

Individual Blood/Breath Ratios

Table 3 gives mean values for individual BAC/BrAC ratio data for all four groups, with and without the adjustment of BAC for DEL described in the methods section. There was no significant difference between groups I-1 and S-1 before or after adjustment

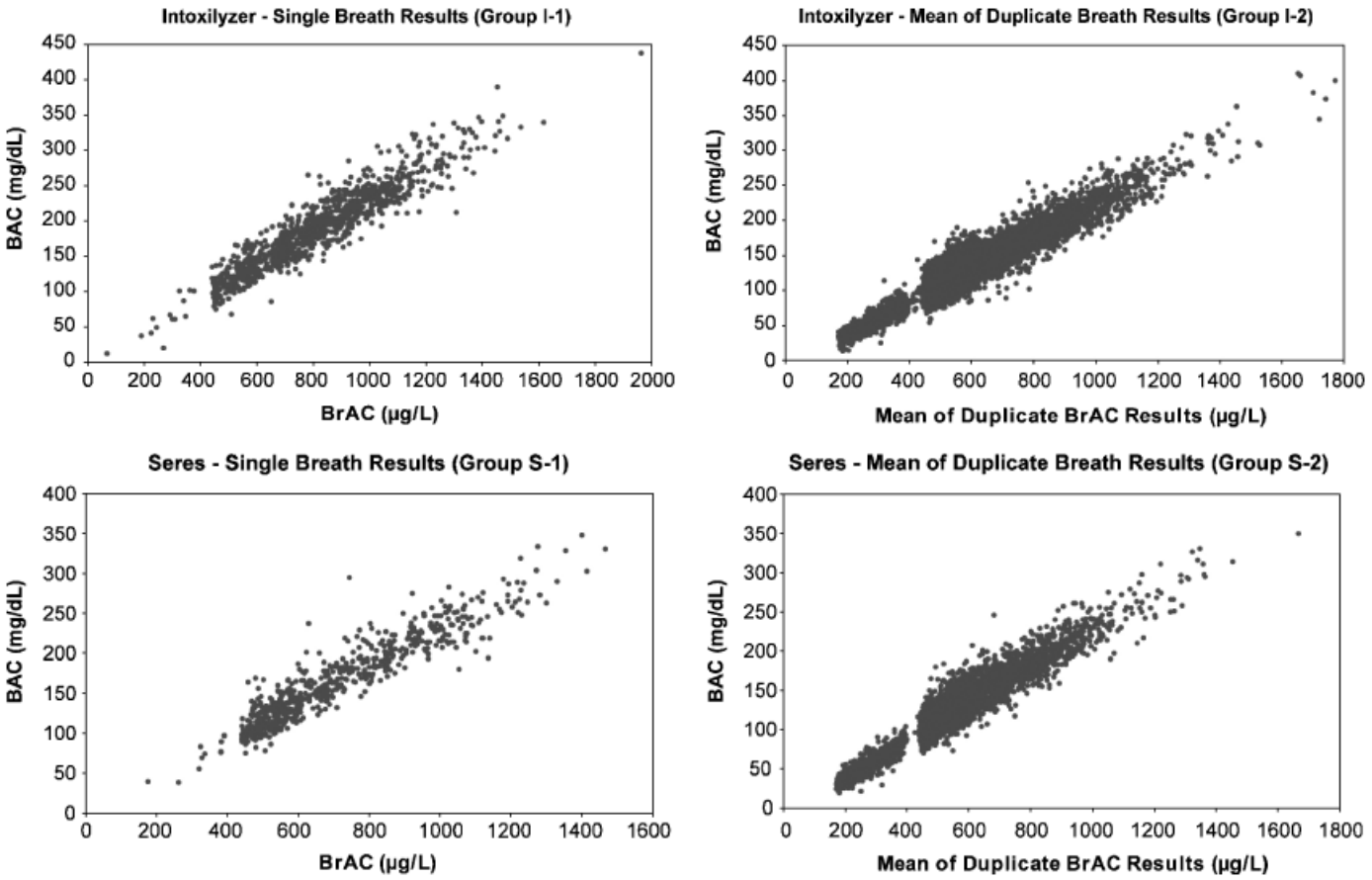

FIG. 1—*Blood-breath scatter plots for a sample of 21,582 New Zealand drinking drivers. Blood alcohol concentrations values are not adjusted for delay.*

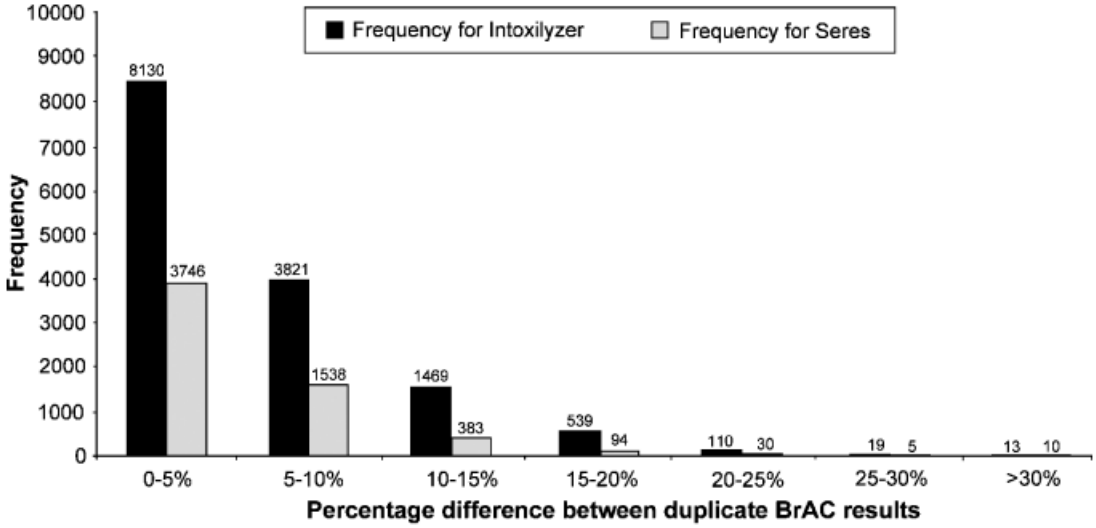

FIG. 2—*Frequency distribution of the differences between duplicate breath test results. Differences between duplicate results are expressed as a percentage of the lower result.*

for DEL ($p > 0.05$). However, there were clearly significant differences between groups I-2 and S-2 both before and after adjustment for DEL ($p < 0.0001$). The same was true when group I-1 was compared with group I-2 and when group S-1 was compared with group S-2.

Discussion

It is obvious from the data in Table 1 and Fig. 1 that there are only small differences between the largest two groups (I-2 and S-2) with respect to the distributions of BrAC and BAC values. However, group I-1 has significantly higher mean BrAC and BAC values compared with group S-1. It must be stressed that the distributions of BrAC and BAC values reported in this study are not representative of the whole population of NZ drinking drivers. Fewer than 10% of drivers returning a positive breath test result would later be blood tested and for reasons given in "Materials and Methods," the data in this study have a strong bias towards BrAC results within the range of 440–600 μg/L. Therefore, the mean BAC values for groups I-2 and S-2 are considerably lower than the population mean, which is likely to be closer to those obtained for groups I-1 and S-1 for which there is much less selection bias. It could also be argued that compared with the total population of NZ breath test results, a higher proportion of the breath test results in this study were obtained under nonideal conditions and may therefore be subject to analytical bias. For example, in the case of duplicate BrAC results, 4% of them (821) were available for this study only because they did not meet the 15% agreement criterion for duplicate samples and a subsequent blood sample became mandatory. Most of the remaining BrAC–BAC pairs were available for study because the driver refused to accept the BrAC result. However, in the absence of any evidence to the contrary, we assumed that a driver's decision to proceed with a blood test instead of accepting the breath test result is usually based more on the hope of a more favorable blood test result than any justifiable reason for doubting the validity of the breath test. Furthermore, deleting the results that did not meet the 15% agreement criterion resulted in negligible changes to the parameters we have reported. This was expected in view of the small number of duplicates failing to meet the 15% agreement criterion and the even smaller number of very poor agreements between duplicate breath results (see Fig. 2).

In the case of groups I-1 and S-1 where only single BrAC results were obtained, failure to obtain valid duplicates may have been because of difficulties in providing samples of deep lung air. The same might be said of the set of single BrAC results presented by Jones and Andersson (9). As a result, compared with the results obtained for groups I-2 and S-2, it is possible that the results for

TABLE 2—*Relationship between BAC and BrAC for the different instruments and groups of data.*

Instrument	Group	Regression Equation	Adjusted R^2	SE of Estimate
Intoxilyzer	I-1	BAC = 3.29+0.228BrAC	0.88	19.8
Intoxilyzer	I-2	BAC = −7.15+0.232BrAC	0.89	12.6
Seres	S-1	BAC = 5.04+0.225BrAC	0.88	18.3
Seres	S-2	BAC = −5.76+0.237BrAC	0.90	13.1

All coefficients are highly statistically significant ($p < 0.001$).
BrAC, breath alcohol concentrations; BAC, blood alcohol concentrations.

TABLE 3—*Mean of individual BAC/BrAC ratios with standard deviations, ranges, and significance of differences between the two breath-testing instruments.*

	Intoxilyzer 5000 Mean BAC/BrAC Ratio (± SD) [Range]	Seres Ethylometer Mean BAC/BrAC Ratio (± SD) [Range]	Significance of Difference*, p
Values with no adjustment for DEL			
Single BrAC values	2320 (± 260) [743–3390]	2330 (± 276) [1450–3970]	0.5776
Duplicate BrAC values	2180 (± 242) [688–3580]	2250 (± 259) [837–3650]	<0.0001
Values after adjustment for DEL according to Jones and Andersson (9)			
Single BrAC values	2510 (± 256) [933–3580]	2520 (± 280) [1640–4160]	0.5780
Duplicate BrAC values	2370 (± 240) [878–3770]	2440 (± 260) [1030–3840]	<0.0001

*p-values derived from unpaired (independent) samples t-tests.
The sample sizes for all groups are as shown in Table 1.
BrAC, breath alcohol concentrations; BAC, blood alcohol concentrations; DEL, delay.

groups I-1 and S-1 may be less representative of the BAC/BrAC ratio expected under ideal sampling conditions. For this reason and the fact that the distribution of data in groups I-1 and S-1 is completely different from that in groups I-2 and S-2, we decided to perform separate analyses of the data in each group.

In adjusting the measured BAC for DEL, the assumption that all drivers were in the elimination phase of the blood alcohol curve was made. Although this assumption is unlikely to be correct in all cases, there is strong evidence to suggest that it is a reasonable approximation for a very high proportion of drivers (16–18). Therefore, we believe that the DEL-adjusted BAC values give a much more accurate picture of the BAC/BrAC ratio than the non-adjusted values.

Using 19 mg/dL/h to adjust for DEL, the mean BAC/BrAC ratios for groups I-1 and I-2 were, respectively, 4.3% higher and 1.5% lower than Jones and Andersson's mean value of 2407 (SD = 214) for 793 BAC/BrAC ratios calculated from Intoxilyzer 5000-derived single BrAC values and their corresponding DEL-adjusted BAC values. These differences are surprisingly small for two completely independent studies. The distributions of values about the mean in each study were also similar. Our results are also similar to those of Harding et al. (8), who also used an Intoxilyzer 5000 for their BrAC measurements.

Although the mean BAC/BrAC ratios obtained using single BrAC results were higher than those obtained using means of duplicate BrAC results, the differences were relatively small (5.9% for the Intoxilyzer and 3.3% for the Seres instruments). However, these data may be of interest to those operating breath testing regimes where only single test results are required. One possible explanation for these differences is that a relatively high proportion of the single results might have been obtained from drivers who had some difficulty meeting the sample acceptance criteria for the respective instruments, thereby creating a small bias towards low BrAC results.

The significant differences between the instruments are unlikely to result from differences in specificity, because the method used for blood alcohol analysis is capable of detecting common industrial solvents and inhalants that could potentially interfere with the breath alcohol analysis. Examples of such compounds are methanol, toluene, xylene, methyl ethyl ketone, and isopropanol (10–12). No such solvents were detected in any of the blood samples involved in this study. However, solvent interference in breath analysis cannot be absolutely ruled out because some of the less water-soluble solvents such as toluene and aliphatic hydrocarbons rapidly dissipate from the breath after exposure ceases (19,20). Therefore, a spuriously high breath alcohol result obtained soon after solvent exposure might be followed less than an hour later by a blood alcohol analysis showing negligible concentrations of the interfering substance. This type of interference would result in a lowering of the apparent BAC/BrAC ratio and the Intoxilyzer 5000VA would almost certainly be more susceptible to it than either the Seres 679T or Seres 679ENZ, which do not respond to hydrocarbons.

Laws defining separate legal BAC and BrAC limits exist in many countries, including NZ. Therefore, the BAC/BrAC ratio is often irrelevant for law enforcement purposes. However, it is still relevant where only BrAC values are available and estimates of BAC are required. These may be needed for a variety of forensic purposes, e.g., estimating the dose of alcohol based on the existing body burden of alcohol (21). If BrAC values are used for such purposes without an appreciation of the variation of the BAC/BrAC ratio under field-sampling conditions, the estimates made may give the impression of greater accuracy and precision than is actually obtainable. The results described in this study will assist in the estimation of the uncertainty associated with a BAC value calculated from a BrAC result. They may also assist legislators who may consider changing breath alcohol limits to make them more consistent with blood alcohol limits.

It has been noted (9) that use of the BAC/BrAC ratio of 2100, implicit in jurisdictions expressing BrAC in terms of g/210 L (8), gives drivers an approximately "10% advantage" over drivers who give blood samples. In NZ this advantage is even greater. The ratio of the respective legal limits for blood and breath alcohol in NZ is 2000. Our data suggest that the average BAC/BrAC ratio measured in the field is 19–26% higher than this. Furthermore, in actual law enforcement practice the ratio of the legal limits is further reduced to 1977 because allowances for measurement uncertainty ensure that the main legal limits for blood and breath alcohol are not exceeded until results of at least 87 mg/dL and 440 μg/L, respectively, are returned. This means that for NZ drivers who are well in excess of the main legal breath alcohol limit, there must be an excessively long DEL between the breath test and a subsequent blood test before they will gain any advantage by demanding a blood test.

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Additional information and reprint requests:
Allan Stowell, Ph.D.
Environmental Science and Research Limited
PO Box 50-348
Porirua
New Zealand
E-mail: Allan.Stowell@esr.cri.nz