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Influence from breathing pattern on alcohol and tracer gas expirograms—Implications for alcolock use

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ABSTRACT

Measurement of breath alcohol concentration is strongly influenced by timing and the breathing pattern. In particular, shallow expiration and hyperventilation leads to underestimation of the breath alcohol concentration. In the present study, expirograms of alcohol, water and carbon dioxide were recorded in 30 healthy individuals at various breathing manoeuvres (tidal volume, slow maximum and vital capacity expiration, breath holding, and hyperventilation). Estimation of the end expiratory alcohol concentration with the use of simultaneously measured carbon dioxide was shown to reverse the tendency of underestimation at shallow expiration and hyperventilation. These findings indicate that breath alcohol estimations can be performed at shorter expiration time and reduced expired volume compared to existing alcolocks. This is believed to improve their usability and to prevent a possible route for manipulation.

1. Introduction

The use of alcolocks for the prevention of drunk driving and for quality assurance of transport services has increased rapidly in recent years. The majority of the drivers (more than 99.8%) are sober [1], and for an acceptance and use of alcolocks, focus should be directed to this majority of drivers and the ease of use of the device and the breath test procedure. State of the art alcolocks require a prolonged and often forced breath test, and the reason for this requirement is the slow but steady increase of ethanol concentration in expired air with an increase in expired volume/expiration time, see Fig. 1. For the frequent users, and persons with small lung capacity or obstructive pulmonary disease, the allowance of a more shallow expiration to be performed and the elimination of the requirement of a mouthpiece should result in a considerably increased usability, with respect to handling and effort. Contact free measurement of the BrAC is found to be possible by simultaneous measurement of a tracer gas in the expired breath: CO_2 [2,3], O_2 [4] and water [5] have been suggested as possible tracer gases. Simultaneous measurement of the expired PCO_2 has also been found likely to enable early and reliable determination of the BrAC [3].

Earlier studies in both the field of medicine and forensic science have shown that breathing manoeuvres such as hyperventilation, breath holding, re-breathing procedure or expirations of different volumes will result both in changed BrAC and PCO_2 in the expired air compared to the values measured after a vital capacity breath test [6–14]. Unlike evidential breath alcohol testing, alcolocks are used by drivers without any external supervision. The risk of a deliberately manipulative breath test using small expirations and/or provocative breathing is therefore evident. This implies that the tracer gas measurement method must be valid regardless of the breath test manoeuvre performed by the user, and for validity two prerequisites must be fulfilled: small intra- and inter-individual variations in the end expiratory concentration of the tracer gas and, similarities in the expirograms of ethanol and the tracer gas, regardless of the type of breath test performed.

The purpose of this study was to investigate the validity of the measurement method, with respect to the performance of provocative breathing manoeuvres. Based on our previous results, the hypothesis is that the concentrations of ethanol and CO_2 are affected in a similar way, and that simultaneous measurement of CO_2 can be used to reduce the time and effort of breath sampling and decrease the effect of manipulative breathing.

2. Materials and methods

2.1. Subjects

Thirty adults (13 females and 17 men) were enrolled in the study, their age ranged from 18 to 69 years with a mean of 45 years, and a mean body mass index of

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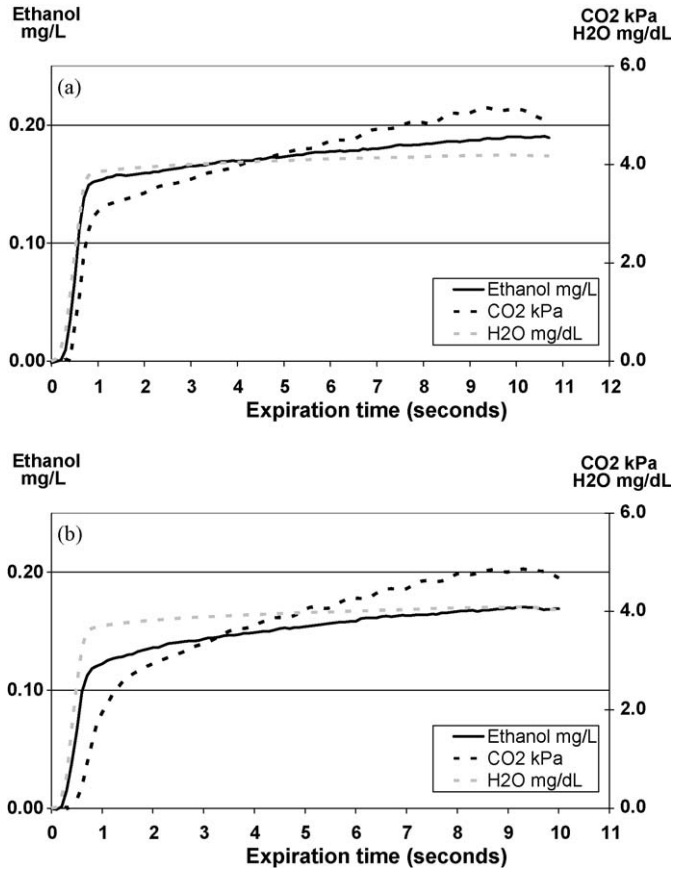

Fig. 1. The differences in characteristics of the expirograms for a vital capacity breath test (a) and a breath test performed after hyperventilation (b). The breath tests were performed by the same subject shortly after each other and the expired volumes were comparable. *Note*: The decrease in ethanol and CO_2 concentration and the earlier onset of the final phase of the CO_2 expirogram in (b) as compared to (a).

24.3 (standard deviation = 2.1). The subjects were recruited as to achieve a group of healthy subjects with a large range in age and lung capacity. Ten of the subjects were smokers, of varying degree.

The study was approved by the Regional Ethical Review Board in Uppsala, Sweden. All subjects were accustomed to consuming alcohol and were informed and gave their written consent before the test procedure began. The subjects were not asked to fast before the measurement and were allowed to drink non-alcoholic beverage and eat smaller amount of food after consumption of the alcoholic beverage.

2.2. Measurement of alcohol, CO_2 and H_2O concentration in exhaled air

The breath tests were performed with an evidential breath analyser equipped with a mouthpiece (Evidenzer, Nanopuls AB, Uppsala, Sweden). The instrument's measurement principle is based on infrared transmission spectroscopy, and a combination of two optical filters (3.47 μm and 3.80 μm) allowed determination of the breath ethanol concentration [15]. With the chosen wavelengths for ethanol detection, interference from other endogenous breath substances becomes insignificant [16]. The instrument was modified with additional optical filters at 2.57 μm and 2.77 μm, for enabling determination of the H_2O concentration and the PCO_2, respectively. The concentration of water vapour was used for calculation of the end expiratory temperature of the breath test, assuming complete saturation. Water condensation was avoided by having the mouthpiece attached to the heated inlet tube during the measurement.

During a breath test, the breath analyser continuously recorded the concentration of ethanol, CO_2, and H_2O, with a sampling rate of 10 Hz. The estimated total error for the H_2O concentrations was $\pm 0.6\ mg\ l^{-1}$, less than 3% for CO_2, and for ethanol it was the largest of $\pm 0.01\ mg\ l^{-1}$ or ±3%.

2.3. Experimental procedure

The subjects performed two breath tests to get acquainted with the procedure of the breath analyser before consuming any alcohol. Then they consumed 0.3 g alcohol per kilo body mass within 10 min, in the form of white or red wine, or spirits. The reason for the relative small amount of alcohol consumed was the interest in studying the effect from provocative breathing in subjects with a level of intoxication corresponding to the legal limit of drunk driving in Sweden; $0.1\ mg\ l^{-1}$. Alcohol absorption was allowed for 30 min before the breath tests began.

In order to study how different breathing manoeuvres affected the expired concentrations of ethanol and CO_2, four different provocative breathing manoeuvres were performed in addition to the recommended vital capacity breath test, Table 1. The first breath test performed by the subjects was a prolonged tidal volume breath test during which the subjects were asked to exhale a volume of approximately 0.5–1.0 l after a normal inspiration. As a second test the subjects were asked not to inhale but just to exhale from resting lung level (functional residual capacity, FRC) to residual volume (RV). This breath test manoeuvre, called slow maximum expiration, mimics a very short period of breath holding. Thereafter a vital capacity (VC) breath test was performed. The last two breath tests were controlled hyperventilation, and 30 s of breath holding, both with expiration to RV. In order to standardise the hyperventilation manoeuvre the test leader set the pace (approximately 4 s per inspiration–expiration) and gave instruction for four maximum inspiratory/expiratory ("vital capacity") manoeuvres and a final fifth inspiration to TLC before expiration to RV into the breath analyser. The breath tests were performed in rapid succession but with a minimum of 2 min between each test. All subjects sat while they performed the breath tests, and the measurements were carried out with the same test leader (author: AKA).

2.4. Data analysis

The characteristics of the expirograms were analysed with respect to the onset of the final phase, which is characterised by a plateau or a slow, steady increase of gas concentration [7,12]. The time for the onset of the final phase was defined as the point where the value of the time derivative is half of its maximum value. The time is calculated from the start of the expiration, detected by a pressure sensor in the instrument. From the expirograms recorded with the breath analyser the measured concentration at 2 s, and at the end of expiration were extracted. These two values together with the mean concentration during the last second of expiration were used for further analysis. The choice of 2 s is to ensure that the onset of the final phase has occurred, based on previous studies [3].

Since a vital capacity breath test is the recommended procedure for the reference breath analyser instrument used in this study, each subjects' vital capacity breath test served as reference in the intra-individual analyses of different breath manoeuvres and enabled paired *t*-test analysis. The strength of the significance was indicated as (NS $p > 0.05$; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$). For analysis of the strength of correlation between measured values, the Pearson's regression coefficient was calculated. Henceforth, the term breath alcohol concentration (BrAC) is used for end expiratory concentrations after a vital capacity breath test. The measured BrAC is termed reference BrAC, whereas the estimated value of the end expiratory BrAC with the use of a tracer gas is termed estimated BrAC.

Estimation of the end expiratory BrAC was performed with the use of the ethanol and tracer gas concentrations measured simultaneously in expired air. The equation used for the estimation is:

$$\mathrm{BrAC_{Est}} = \frac{\mathrm{EtOH_{2\,s}}}{\mathrm{Tracer_{2\,s}}} \cdot \mathrm{Tracer_{ref}} \quad (1)$$

where $\mathrm{BrAC_{Est}}$ is the estimated end expiratory BrAC, $\mathrm{Tracer_{Ref}}$ is the end expiratory reference concentration of the tracer gas, $\mathrm{Tracer_{2\,s}}$, $\mathrm{EtOH_{2\,s}}$ is the measured concentration of tracer gas and ethanol respectively in the breath sample after 2 s of expiration.

In the case of a non-diluted breath sample, the ratio $\mathrm{Tracer_{Ref}/Tracer_{2\,s}}$ represents the expired volume fraction of the total lung volume, whereas in the case of contact free measurement [18–20] the ratio represents the breath sample dilution. For evaluation of the measurement method, with respect to small expirations and provocative breath manoeuvres, the ethanol concentration and the concentration of the tracer gases (CO_2 and H_2O) were measured after 2 s of expiration and the estimated BrAC was calculated with Eq. (1). The mean value of the subject's end expiratory concentration of respective tracer gases at the vital capacity breath test were used as reference concentration, $\mathrm{Tracer_{ref}}$. The measurement method and the assumptions it encloses have been discussed in detail earlier [2,3].

3. Results

3.1. Characteristics of the test subjects and the breath tests

All recorded breath tests were included in the analysis except one (a slow maximum expiration breath test), where the subject did not perform according to the instructions.

The large range in volume expired during the vital capacity breath test (1.97–7.47 l) indicated a large difference in lung capacity between the test subjects, Table 2. For 3 of the 30 test subjects the exhaled volume at the vital capacity breath test was

Table 1
Description of the five types of breath manoeuvres.

Breath test	Type of inspiration	Type of expiration
Tidal volume	Normal inspiration (~0.5 l)	Slow expiration of 0.5–1.0 l
Slow maximum expiration	No inspiration	Slow expiration from functional residual capacity to residual volume
Vital capacity	Inspiration to total lung capacity	Forced expiration to residual volume
Hyperventilation	Five times to total lung capacity	Four times expiration to functional residual capacity, 5th expiration to residual volume
Breath holding	Inspiration to total lung capacity	Slow expiration to residual volume, after 30 s of breath holding

less than 75% of the normal value, but all three had values above 60% of the normal value [17,18]. The exhaled volumes at the different types of breath tests were all significantly different from the volume exhaled during the vital capacity breath test (paired *t*-tests), Table 2. The duration of the tidal volume ($p < 0.001$) and slow maximum expiration ($p < 0.001$) breath tests were significantly shorter than the vital capacity breath test. The temperature at the end of the tidal volume ($p < 0.001$) and hyperventilation ($p < 0.001$) breath test was significantly lower than the temperature at the end of the vital capacity breath test, whereas the temperature after 30 s of breath holding was significantly higher ($p < 0.001$).

3.2. The characteristics of the expirogram

Fig. 1a and b visualises the difference in characteristics and concentrations in the expired air during a vital capacity breath test and a breath test performed after extensive hyperventilation.

The order in which the onset of the final phase of the expirograms for the three gases occurred was the same regardless of breathing manoeuvre. However, the mean time of onset for each gas differed between the types of breath test, Table 3. The time of onset for the final phase for water and ethanol was stable regardless of breathing manoeuvre, whereas, for CO_2, the onset for a tidal volume breath test occurred significantly later as compared to the vital capacity breath test ($p < 0.001$). After hyperventilation ($p < 0.01$) and breath holding ($p < 0.001$) the onset for CO_2 occurred earlier, and thus closer in time to the onset for H_2O and ethanol, as compared to the vital capacity breath test.

Table 2
The expired volumes, durations, and end expiratory air temperatures for the different breath tests. Mean value and standard deviation are given together with a percentage value showing the relative change with respect to the corresponding vital capacity breath test. The significance of the changes is indicated.

Breath test	Exhaled volume (l)	Duration (s)	Mean expiratory air temperature last second (°C)
Vital capacity (VC)			
Mean	3.9	8.7	35.2
SD	1.2	4.2	0.5
Minimum	1.97	2.8	34.6
Maximum	7.47	24.1	36.2
Tidal volume			
Mean	0.8	2.6	34.3
SD	0.1	0.4	0.7
% change with respect to VC	−79%	−70%	−3%
Significant difference	***	***	***
Slow maximum expiration			
Mean	1.9	5.4	35.2
SD	0.8	2.8	0.6
% change with respect to VC	−51%	−37%	−0%
Significant difference	***	***	NS
Hyperventilation			
Mean	3.4	8.3	34.9
SD	1.3	3.0	0.8
% change with respect to VC	−13%	−3%	−1%
Significant difference	***	NS	***
Breath holding			
Mean	3.3	8.0	35.9
SD	1.3	3.7	0.4
% change with respect to VC	−15%	−7%	+2%
Significant difference	***	NS	***

3.3. Changes in concentrations by provocative breathing manoeuvres

The provocative breath tests changed the H_2O vapour concentration to a minor extent compared to the change in ethanol concentration and PCO_2, Table 4.

Fig. 2a shows how the provocative breath tests influence the end expiratory ethanol concentration in relation to the reference BrAC for each subject. The general location under the identity line for the tidal volume and the hyperventilation breath tests show that the expired ethanol concentration can be deliberately decreased with breathing manoeuvres with these manipulative procedures. However, a small expiration of only 2 s in addition to a deliberately provocative breathing manoeuvre will further decrease the ethanol concentration, cf. Fig. 2b. The average discrepancy in ethanol concentration between a vital capacity breath test and the provocative breath tests after full expiration and after only 2 s of expiration are expressed through the equation of the regression lines and summarised in Table 5. The negative slope of the plot of the tidal volume breath tests in Fig. 2a and all breath tests manoeuvres except for the breath holding breath test in Fig. 2b indicate that the manipulative effect from small expiration increases with increased BrAC.

3.4. Estimation of the end expiratory breath alcohol concentration with the use of a tracer gas

The breathing manoeuvres affected the expired concentrations and the ratio between the ethanol concentration and the PCO_2 ($EtOH/CO_2$), and the H_2O concentration ($EtOH/H_2O$), respectively. The ethanol concentration and the PCO_2 measured

Table 3
The time of onset for the final phase of the three gas expirograms. Significant differences in time of onset between the provocative breath test and the corresponding vital capacity breath test are indicated. *Note*: The time of onset for water (H_2O) and ethanol occurs within a relatively small interval for the different breath tests, whereas the time of onset for CO_2 is more affected by the breathing manoeuvre.

Breath test	Time of onset of the final phase (s)		
	H_2O	Ethanol	CO_2
Vital capacity	0.76 ± 0.08	0.80 ± 0.08	1.07 ± 0.25
Tidal volume	0.82 ± 0.07 **	0.84 ± 0.18 NS	1.25 ± 0.21 ***
Slow maximum expiration	0.79 ± 0.07 NS	0.81 ± 0.08 NS	1.18 ± 0.29 NS
Hyperventilation	0.75 ± 0.06 NS	0.78 ± 0.07 NS	0.98 ± 0.16 **
Breath holding	0.73 ± 0.07 NS	0.75 ± 0.06 **	0.85 ± 0.11 ***

Table 4
The measured ethanol, CO_2 and H_2O concentrations for the five different breath tests, both at 2 s and the mean concentration during the last second of expiration. The mean concentration and standard deviations are given together with the relative change in concentration as compared to the mean concentration measured during the last second of the vital capacity breath test. The significance of the change is indicated with significance stars, and analysed with paired *t*-test. Note: Expirations of 2 s and hyperventilation before breath testing decrease the measured ethanol concentration, whereas breath holding increase the end ethanol concentration. Provocative breath test and expirations of 2 s affect the H_2O concentration less as compared to the ethanol and CO_2 concentration.

Breath test	Ethanol conc. (mg l^{-1})		PCO_2 (kPa)		H_2O conc. (mg l^{-1})	
	2 s	Last second	2 s	Last second	2 s	Last second
Vital capacity	0.114 ± 0.05 84 ± 6% ***	0.137 ± 0.06 100%	3.11 ± 0.35 74 ± 10% ***	4.28 ± 0.63 100%	38.0 ± 1.3 95 ± 2% ***	40.1 ± 1.06 100%
Tidal volume	0.119 ± 0.05 86 ± 11% ***	0.120 ± 0.05 87 ± 10% ***	3.80 ± 0.58 90 ± 13% ***	3.84 ± 0.66 91 ± 14% ***	38.1 ± 1.4 95 ± 3% ***	38.2 ± 1.5 95 ± 3% ***
Slow maximum expiration	0.126 ± 0.05 92 ± 9% ***	0.136 ± 0.06 99 ± 6% NS	4.23 ± 0.57 100 ± 15% NS	4.82 ± 0.63 113 ± 9% ***	39.0 ± 1.5 97 ± 3% ***	40.1 ± 1.4 100 ± 2% NS
Hyperventilation	0.109 ± 0.04 80 ± 8% ***	0.129 ± 0.05 94 ± 6% ***	2.84 ± 0.48 67 ± 12% ***	3.88 ± 0.65 91 ± 9% ***	37.6 ± 1.7 94 ± 4% ***	39.5 ± 1.6 98 ± 3% *
Breath holding	0.137 ± 0.06 102 ± 8% NS	0.147 ± 0.06 109 ± 8% ***	5.21 ± 0.61 123 ± 16% ***	5.40 ± 0.63 127 ± 13% ***	40.2 ± 0.1 100 ± 3% NS	41.5 ± 1.0 103 ± 2% ***

Table 5
The average discrepancy in concentration between the provocative breath test and the reference BrAC is expressed with the equation of the regression line for each of the measurement series represented in Fig. 2a and b. Pearson's correlation coefficient and the random error indicated with the residual standard deviation are listed for each breath test.

	The end ethanol conc. and in relation to the reference BrAC			The 2 s ethanol conc. in relation to the reference BrAC		
	Equation regression line	Corr. coeff. (*R* value)	Residual standard deviation (mg l^{-1})	Equation regression line	Corr. coeff. (*R* value)	Residual standard deviation (mg l^{-1})
Tidal volume	$y = -0.081x - 0.003$	0.37	0.0021	$y = -0.11x - 0.002$	0.47	0.0024
Slow maximum expiration	$y = 0.0027x + 0.0005$	0.02	0.00021	$y = -0.080x + 0.0009$	0.37	0.0021
Vital capacity	–	–	–	$y = -0.17x + 0.001$	0.70	0.0018
Hyperventilation	$y = -0.068x + 0.002$	0.52	0.0012	$y = -0.25x + 0.006$	0.77	0.00014
Breath holding	$y = 0.096x + 0.008$	0.06	0.0015	$y = -0.062x + 0.008$	0.29	0.0022

at 2 s of expiration, for the different breath tests, were used in Eq. (1) to estimate the end expiratory vital capacity BrAC. As end expiratory reference value for PCO_2 the subject's mean concentration measured at the end of the vital capacity breath test was used (4.26 kPa). The result of the corresponding estimation with H_2O as tracer gas was calculated with use of the subject's vital capacity mean value of 40.1 mg l^{-1}, as end expiratory reference concentration.

The average discrepancy in ethanol concentration expressed with the equation of the regression line between the reference BrAC and the estimated BrAC with use of CO_2 and H_2O is presented in Table 6. No significant offset exists for any of the breath manoeuvres after compensation with CO_2 or H_2O as tracer gas. In addition to the general deviation expressed with the equation of the regression line, a maximal random error of approximately 0.005 mg l^{-1} can be added to the BrAC estimated with use of CO_2 or H_2O as tracer gas.

Fig. 3 presents the percentage difference and the significance of the difference between the reference BrAC and the measured ethanol concentration after 2 s and the estimated BrAC with both tracer gases, respectively. Use of H_2O as tracer gas did not have much effect on the BrAC. Determination of the alcohol concentration after 2 s of expiration and estimation of the end expiratory BrAC from the 2 s concentration with use H_2O, caused underestimation. Breath manipulation with shallow expiration and hyperventilation prior to breath alcohol testing decrease the alcohol concentration the most, but with CO_2 as tracer gas an overestimation instead of an underestimation of the end expiratory BrAC was done, whereas, a breath holding procedure cause a larger underestimation of the BrAC.

Table 6
The average discrepancy in the ethanol concentration expressed with the equation of the regression line between the estimated BrAC with use of CO_2 and H_2O, and the reference BrAC. The random error is indicated with the residual standard deviation. *Note*: None of the equations show a significant offset.

	The difference between estimated PCO_2 and reference BrAC			The difference between estimated H_2O BrAC and reference BrAC		
	Equation regression line	Corr. coeff. (*R* value)	Residual standard deviation (mg l^{-1})	Equation regression line	Corr. coeff. (*R* value)	Residual standard deviation (mg l^{-1})
Tidal volume	$y = -0.083 + 0.009$	0.20	0.0042	$y = -0.065x - 0.003$	0.33	0.0019
Slow maximum expiration	$y = -0.10 + 0.005$	0.30	0.0042	$y = -0.051x + 0.0003$	0.29	0.0018
Vital capacity	$y = 0.15x + 0.0008$	0.41	0.0035	$y = -0.14x + 0.002$	0.68	0.0015
Hyperventilation	$y = 0.18x + 0.005$	0.38	0.0047	$y = -0.21x + 0.007$	0.77	0.0018
Breath holding	$y = -0.21x + 0.006$	0.60	0.0042	$y = -0.054x + 0.0073$	0.29	0.0046

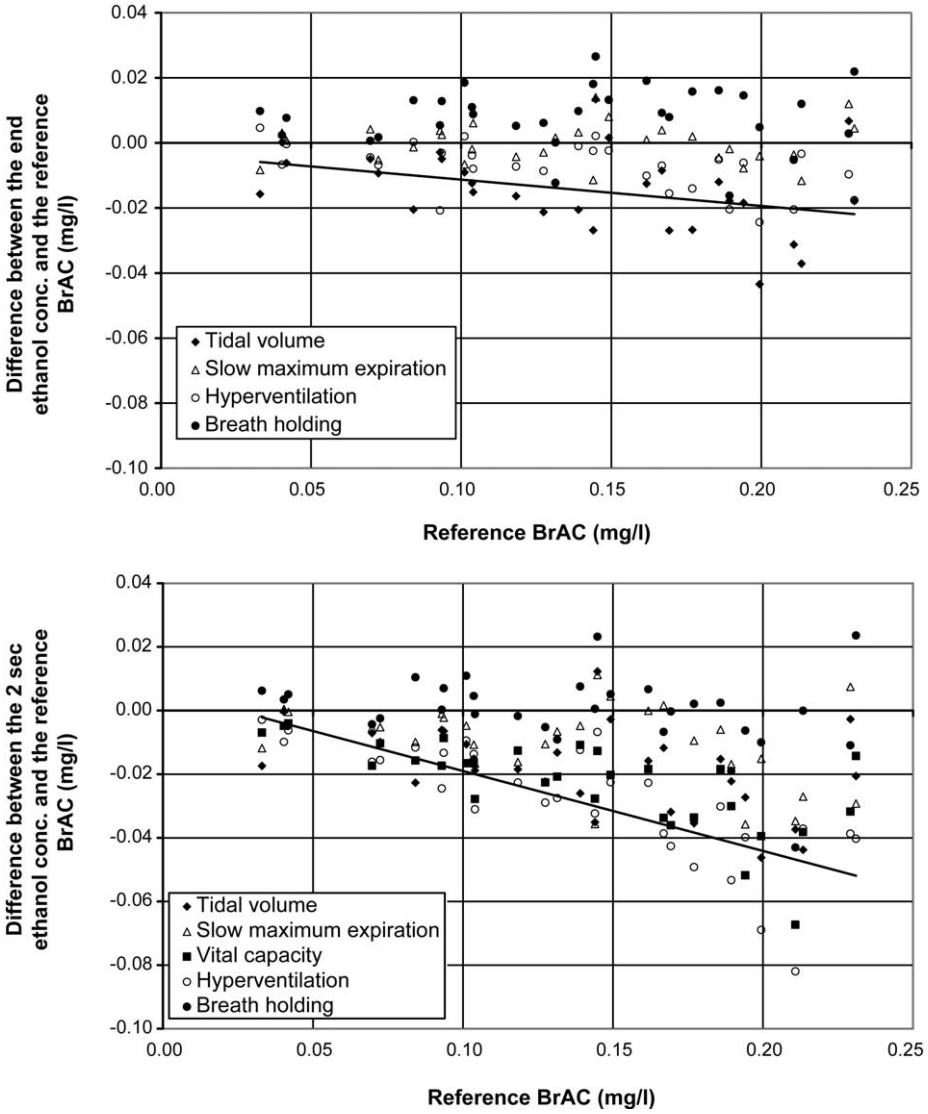

Fig. 2. The effect on measured ethanol concentration from provocative breathing manoeuvres. (a) The difference between the ethanol concentration measured at the end of the provocative breath test and the ethanol concentration measured at the end of the vital capacity breath test (reference BrAC), in relation to the reference BrAC. (b) The difference between the ethanol concentration measured after 2 s of expiration and the reference BrAC, in relation to reference BrAC. The regression line for the tidal volume breath test and the hyperventilation breath tests is inset to illustrate the decreasing effect of the measured BrAC, in (a) and (b), respectively.

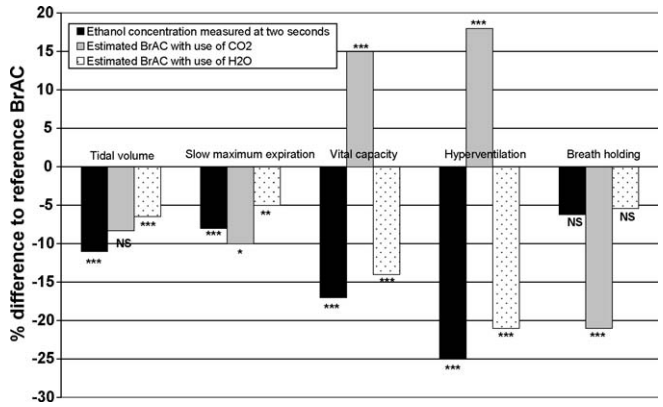

Fig. 3. The difference, expressed in percentage, between the reference BrAC and the ethanol concentration measured after 2 s of expiration, and the BrAC estimated with use of CO_2 and H_2O, respectively. The statistical significance of the difference, tested with paired *t*-test, is indicated with stars of significance.

4. Discussion

In agreement with previous work [3,6–10,14] this study shows that measurement of breath alcohol concentration is strongly influenced by its timing, and the breathing pattern at, or immediately prior to, the actual breath test. In particular, we find that measurement results may be underestimated by measuring too early in the expiratory phase, and by shallow expiration or hyperventilation (Fig. 2).

The mild hyperventilation manoeuvre performed in the present study decreased the reference BrAC by 6% on average. After more extensive hyperventilation, subjects have been observed to decrease their ethanol concentration by as much as 20% compared to the reference BrAC, with comparable size of the expired volume. Another observation is that after hyperventilation in chilly ambient air of +1 °C, the measured BrAC, may decrease additionally (−25%) [Kaisdotter Andersson, unpublished material].

During hyperventilation heat and water is eliminated via the respiratory tract, and the temperature of the mucous layer of the airway surfaces is additionally decreased [19]. This implies that the solubility of ethanol in the mucous membrane is increased and

more ethanol will be distributed to the air during inspiration, thus a larger re-absorption will occur during expiration [9,20]. Inspiration of cold air further depletes the mucous membrane of ethanol during inspiration, which results in lower BrAC in expired air [20].

After 30 s of breath holding the subjects increased on average their BrAC by 8%, compared to the reference BrAC, which gives a maximum increase in the same range as in earlier observations of breath holding (12–16%) [9,13]. Breath holding allows gas diffusion from the mucous membrane to the inspired air for a longer time, which enables recovery with respect to temperature and humidity, and replenishment of ethanol from the capillaries [9,14]. Thus, in contrast to hyperventilation, no extensive re-absorption of ethanol to the mucous membrane will occur during expiration.

The time of onset for CO_2 on the expiratory curve is related to the mixing of dead-space air and alveolar air. Hyperventilation leads to mixing of air due to repetitive breathing, whereas breath holding implies increased time for gas mixing which leads to the presence of CO_2 higher up in the respiratory tract.

The rationale of the present study is that the use of CO_2 as a tracer gas will prevent underestimation of BrAC due to early measurement, shallow expiration, or hyperventilation. Since expired CO_2 emanates from deeper airways than expired ethanol [7,12,14,21] the ethanol/CO_2 concentration ratio will always decrease with time during expiration. Experimental evidence that this is indeed the case is provided in Table 6 and Fig. 3.

Analysis of the time of onset of the final phase for both the ethanol and the CO_2 expirograms indicates that measurement after 2 s of expiration should guarantee that the final phases of the expirograms have been reached regardless of the breathing manoeuvre, results that agree with our previous study [3].

Water is another candidate tracer gas, exhibiting the advantage of smaller variability compared to CO_2 [3,5]. However, the results of Table 6 and Fig. 3 indicate that underestimation will still prevail in shallow expiration and hyperventilation. This is related to the fact that water is abundant in the entire airways.

The basic requirements of alcolocks for general preventive use are threefold: first, the device should effectively disable driving when a certain alcohol concentration limit – normally coinciding with the legal limit – is exceeded. Second, the alcolock should constitute a minimum obstacle to the completely sober driver. Third, attempts at circumvention or manipulation should be counteracted. The results of the present study will have important implications for the second and third requirements, without negative influence on the first.

The implication of the present study on the second requirement is to motivate a measurement procedure which will be easier and faster to the vast majority of sober drivers. A first BrAC estimation based on the ethanol/CO_2 ratio can be delivered within 2 s. If this first estimation is safely lower than the concentration limit, the device may immediately unlock. Commercially available alcolocks often require 5 s of forced expiration, and an expired volume of 0.7–1.2 l.

The use of CO_2 as tracer gas will, when implemented in an alcolock, shut down one possible route of manipulation, namely the possibility of reducing BrAC readings by shallow expiration or hyperventilation. Such manipulative attempts will in fact be "punished", since CO_2 will be more strongly affected by these manoeuvres than ethanol.

5. Conclusion

The study indicates that the use of CO_2 as tracer gas may reduce the time and effort required in the vast majority of alcolock usages. It would also eliminate the route of manipulation by shallow expiration or hyperventilation.

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