Development and Validation of a Model to Predict Breath Alcohol Concentrations: Updating the NHTSA Equation

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Abstract

Objects:

To date, multiple models have been developed to estimate blood or breath alcohol concentration (BAC/BrAC). Several factors have been identified to affect the discrepancy between BACs/BrACs and retrospective estimation (eBAC) with existing equations. To our best knowledge, the model to quantify the effects of factors on the discrepancy between BAC/BrAC and eBAC is still missing. The goal of this work was to develop a model to provide a more accurate retrospective estimation of breath alcohol concentration (eBAC).

Method:

A laboratory study with alcohol consumption and a driving task was conducted with 30 participants (17 male) to explore the factors that may contribute to the discrepancy between BrAC and eBAC obtained with existing models. A new eBAC model was developed to improve the estimation of BrAC by modeling effects of gender, weight, and the delay of BrAC measurement on the discrepancy. The validity of the model was tested with the data from the current experimental study and two published works, and compared with existing eBAC models.

Results:

Results of the model validity examination indicated the developed model had higher R squares and lower root-mean-squared errors (RMSE) in estimating BrAC in three experiments compared with the existing eBAC models, including the NHTSA equation, the Matthew equation, the Lewis equation, the Watson equation, and the Forrest equation.

Conclusion:

The developed eBAC model had a better performance of BrAC estimation compared with existing eBAC models. The validation of the model with the data from three empirical studies indicated its good generalizability in estimating BrAC.

Keywords: Breath alcohol concentration (BrAC); Estimated blood/breath alcohol concentration (eBAC); Forensic back calculation

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INTRODUCTION

Alcohol consumption is associated with falls, injuries, assaults, criminal violations, and automobile crashes (Carpenter & Dobkin, 2015; Keyes et al., 2012; Wechsler et al., 2003). Statistics showed alcohol consumption accounted in part for an estimated 23% of injurious death in the United States (Rehm et al., 2010). Driving under the influence of alcohol (DUI) was a significant contributor to driver risk and vehicle crashes (Shirazi & Rad, 2014; Das et al., 2012). Since blood alcohol concentration (BAC) can be considered as an index of the degree of intoxication, it is crucial to obtain accurate BAC levels to determine the associated risk levels. However, the drawing of a blood sample is only allowed in a few special cases comparing to performing a breathalyzer test. With established conversion between breath alcohol concentration (BrAC) and blood alcohol concentration (BAC), the development of BrAC measurement devices has shown a satisfactory precision and accuracy in measuring BAC levels. The direct measure right after the drinking and driving event is seldom available due to the rapid elimination rate of alcohol. A blood or breath sample for forensic analysis purpose might not be obtained until several hours after an offense was committed. Since mostly there is some time elapsed between BAC or BrAC measurement and DUI offense, the research efforts regarding the accurate retrospective estimation of blood or breath alcohol concentration (eBAC) with a back calculation of blood alcohol concentration are needed (Jones, 2010).

The first eBAC model was developed by Widmark in 1932 (Widmark, 1932). Since then, research efforts were undertaken to modify the original Widmark formula by multiple researchers to achieve a more accurate estimation of BAC or BrAC (e.g., Matthews & Miller, 1979; Watson et al., 1981; Forrest, 1986; Lewis, 1986; National Highway Traffic Safety Administration (NHTSA), 1994; Seidl et al., 2000). Table 1 summarized eBAC models in literature along with parameters describing how well these models fit measured BACs or BrACs (BAC/BrAC).

Empirical studies have found a significant relationship but low to moderate correlations between BAC and eBAC (Larimer et al., 2001; Clapp et al., 2009). Further work is still necessary to improve the fitting of the eBAC models with measured BACs (Clapp et al., 2006). Hustad and Carey (2005) have compared the multiple eBAC equations with measured BrAC in the natural setting. They found the correlation coefficients between BrAC and eBACs were moderate, and even the best fitting model still tended to overestimate BrAC significantly. In their study, several parameters were reported by participants rather than objectively measured. Therefore, the evaluation of the relation between BrAC and eBAC with existing models needs to be further examined in a controlled experiment setting to eliminate the errors brought in by self-reported parameters.

To date, research effort has been undertaken to explore factors contributing to the discrepancy between BAC/BrAC and eBAC. Empirical studies have shown that this discrepancy could be caused by errors in self-report and the effects of individual differences on absorption and metabolism rates. Evidence indicated the number of drinks consumed and the time spent on drinking had significant effects on the discrepancy (Sommers et al., 2000, 2002; Hustad and Carey, 2005). Grant (2012) reported discrepancies between BrAC and eBAC were found as a function of gender. Studies also showed individual's weight contributed to the discrepancy between BrAC and eBAC (Davies and Bowen, 2000; Hustad and Carey, 2005).

To our best knowledge, there has been no model being developed by considering these factors to improve existing eBAC models. The present work will explore the factors contributing to the discrepancy of BrAC and eBAC under an experimental setting with drinking and driving tasks.

Table 1. Summary of eBAC models

Model	Equations	Reported parameter of model fitting	BAC type
NHTSA	BAC = (c*0.806)/(W* r_{NHTSA}) - (β_{60}*t) r_{NHTSA}(male)= 0.58, r_{NHTSA}(female)=0.49	Kraus et al (2005, R^2 =0.22)	BrAC
		Hustad and Carey (2005, r = .54, R^2 = .69 for no-intercept regression)	BrAC
		Carey & Hustad (2002; r = .84)	BrAC
		Sommers et al. (2002, r = 0.43)	BAC
		Sommers et al. (2000, r = 0.26)	BAC
Matthews & Millers	BAC = [(c/2) * (GC/ w)] - (β_{60}*t) GC (male)=7.5 GC (female)=9.0	Silvestri et al. (2013, r = .65)	peakBrAC
		Clapp et al. (2006, r= .35)	BrAC
		Hustad and Carey (2005; r = .54, R^2 = .70 for no-intercept regression)	BrAC
Lewis	BAC = A/(W*r_l) - (β_{60}*t) r_l (male)= 0.76, r_l (female)= 0.68	Hustad and Carey (2005, r= .56, R^2 = .71 for no-intercept regression)	BrAC
Watson	BAC = A/(W*r_w) - (β_{60}*t) r_w(male)=2.447-.09515Y+10.74H+0.3362W r_w(female)= -2.097 + 10.69H + .02466W	Hustad and Carey (2005, r = .55, R^2 = .71 for no-intercept regression)	BrAC
Forrest	BAC = A/(W* r_f) - (β_{60}*t) r_f(male)= 1.0178-0.012127(W/H^2) r_f(female)= 0.8736-0.0124(W/H^2)	Hustad and Carey (2005, r= .54, R^2 = .70 for no-intercept regression)	BrAC
New Model	Inputs: c, W, gender, r_{NHTSA}, β_{60}, t, Delay of BrAC measurement.	Current Experimental Study (r=.80; R^2 = .94 for no-intercept regression)	BrAC
		Marczinski & Fillmore (2009) (r=.92; R^2=.99 for no-intercept regression)	BrAC
		Pavlic, Grubwieser, Libiseller & Rabl (2007; r=.97, R^2 = .99 for no-intercept regression)	BrAC

Note: BrAC = blreath alcohol concentration in g/210L, c = number of standard drinks consumed, W(w) = weight in kg (pounds), β_{60} = the metabolism rate of alcohol per hour (e.g., 0.017 g/dl), t = time in hours since the first sip of alcohol to the time of assessment, A = total volume (in ml) of drinks consumed multiplied by the percent of alcohol of the drink multiplied by the density of alcohol (0.79 g/ ml) divided by 10, H = height in meters, Y = the age of the participant in years.

A mathematical eBAC model will be developed by considering those factors to improve the performance of the eBAC model. The validity of the model will be tested with the data from the current experimental study and two published works, and compared with existing eBAC models. Since the breath alcohol concentration has been used to validate eBAC models in previous studies (Carey & Hustad, 2002; Hustad and Carey, 2005), we adopted the similar approach and used the BrAC data to validate the developed eBAC model.

THE DEVELOPMENT OF A NEW eBAC MODEL

A laboratory study with alcohol consumption and a driving task was conducted to evaluate the relations between measured BrAC and eBAC with existing models in a controlled experiment setting. A discrepancy score was calculated as the absolute value of the difference score (|eBAC-BrAC|). The factors that may contribute to the discrepancy score between BrAC and eBAC were analyzed. To improve the estimation of BrACs, a new eBAC model was developed by modeling factors that significantly contributed to the discrepancy score. Fifty percent (50%) of the data from the current experimental study were randomly selected to train proposed parameters.

Experiment of Blood Alcohol Concentration Estimation and Simulated Driving

Method

Participants

Thirty adults (17 male, 13 female) between the ages of 21 and 36 (mean age= 23.83 years, *SD*=3.40) were recruited by notices posted on university advertisement boards. The racial and ethnic break- down of the sample is as follows: 53.3% White, 6.7% Black or African American, 16.7% Asian, 16.7% Hispanic, and 6.7% other. Potential participants were asked a brief set of screening questions over the phone to determine eligibility. Participants with a self-reported a history of psychiatric disorder, substance abuse disorder, seizures, head trauma, neurosurgery, or other serious medical condition were excluded from the study. Female participants were not eligible if they were pregnant or breastfeeding. Any participants with a Short Michigan Alcoholism Screen Test (SMAST; Seltzer, Vinokur et al., 1975) score of 5 or higher were excluded from the study because of risk for alcohol-dependence. Participants who did not regularly drink alcohol (i.e., fewer than three standard drinks for females or fewer than four standard drinks for males in past three months) were excluded because of ethical concerns. The Social and Behavioral Sciences Institutional Review Board of University at Buffalo approved the study.

Apparatus and Materials

BACs. Alco-Sensor FST instrument (Intoximeters, Inc., St. Louis, MO) was used to measure breath alcohol concentration (BrAC, g/210L) and converts it to BAC in g/dl using a 1:2100 BrAC to BAC partition coefficient.

Demographic questionnaire. This questionnaire included information about participants' demographic background such as age, gender, and racial and ethnic group.

Timeline follow-back (TLFB; Sobell & Sobell, 1992). The TLFB assesses daily patterns of alcohol consumption over the past three months and includes measures of the number of drinks consumed each day over the past three months. Multiple aspects of alcohol consumption over the past three months are recorded including: (a) total number of drinking days in the past, (b) total number of drinks consumed, (c) average number of drinks consumed, (d) maximum number of drinks consumed in one day, and (e) total number of heavy drinking (five or more drinks) days.

Procedure

Participants were asked to attend two sessions in which they received either a placebo dose (0.0 g/kg) or a test dose (0.65 g/kg). The placebo dose consisted of a volume of carbonated mix that matched the total volume of the 0.65 g/kg alcohol drink. Participants were not informed about the order of the dose, which was counterbalanced across participants. Two sessions were separated by a minimum of one day. Before the test session, participants were instructed to fast for four hours and abstain from alcohol for 24 hours. Upon arrival, participants were asked to sign an informed consent document and were informed that they would receive an amount of alcohol that could result in a peak BrAC of 0.08g/210L. Participants were required to show proof of legal drinking age. Urine samples were collected and tested for the presence of drug metabolites (opiates, benzodiazepines, amphetamine, cocaine, and cannabis). All female participants completed urine sample pregnancy tests. Breath samples were collected for recent alcohol use.

At the beginning of the test session participants were weighed to determine the alcohol and mixer amounts for the alcohol session. Participants were asked to fill out a set of questionnaires. Then each participant received a dose of 0.65 g/kg, producing a BrAC of 0.08g/210L that equivalent to a BAC of 0.08g/dl (Van Dyke & Fillmore, 2014). The alcohol dose was administered as absolute alcohol divided equally into three drinks containing one part of alcohol and three parts carbonated mix. Fifteen minutes were allowed for the consumption of the beverages; this would be split into three six-minute intervals to control for consumption rate. From the time of the last sip of alcohol to the first breath sample assessment, 15 minutes elapsed to avoid inaccurate readings resulting from residual mouth alcohol. Participants were asked to finish two driving sessions and were tested twice for their BrAC level after each session: at 60 min and 90 min. After driving sessions, the BrAC was measured every 10 minutes until it fell below 0.02g/dl. Since the BrAC elimination rate is different for each individual, the number of BrAC measurement is different across individuals. The average number of measurement is 11 times, and the total number of values obtained is 338.

Results

Figure 1 plots participant's BrACs under alcohol when breath samples were obtained. The measured BrACs ranged from 0.01 to 0.17 g/210L with a mean value of 0.06 g/210L. The measured peak BrACs ranged from 0.08 to 0.17 g/210L with a mean value of 0.11 g/210L. The relationship between BrAC and eBAC obtained with five existing eBAC equations was evaluated.

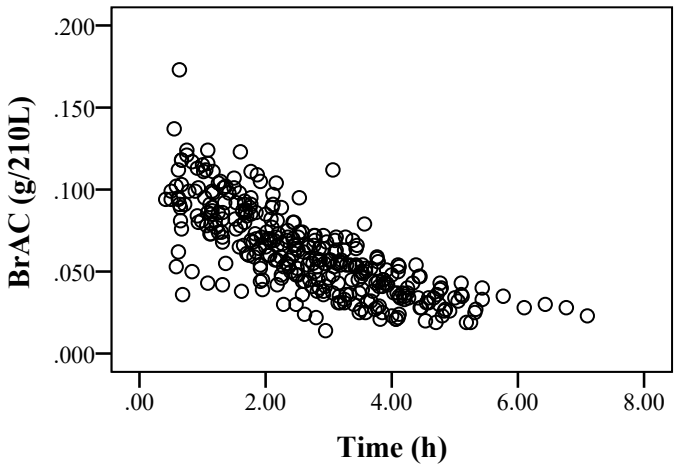

Figure 1. Breath alcohol concentrations (BrACs) as a function of time since last sip of drinking.

As shown in Table 2, the Pearson's correlation coefficients of eBACs with BrACs ranged from 0.73 to 0.79. The means and standard deviations of the eBACs calculated with five existing eBAC equations were shown and compared with the mean and standard deviation of the measured BrAC values obtained from the data. The NHTSA equation was selected for the following discrepancy analysis since it had the highest correlation with BrAC and the smallest mean difference from BrAC.

Table 2. Intercorrelation between Measured BrAC and eBAC Calculated by Five Equations

Measurement	Mean (SD)	1	2	3	4	5	6
NHTSA	0.065(0.023)	-					
Matthew	0.091(0.024)	.99**	-				
Lewis	0.039(0.023)	.99**	.97**	-			
Watson	0.047(0.024)	.98**	.99**	.96**	-		

Forrest	0.043(0.025)	.97**	.98**	.94**	.99**	-	
Measured BrAC	0.061(0.027)	.77**	.75**	.75**	.75**	.73	-

Note: ** p <.01. N=324.

As it shown in Table 3, a linear regression model was firstly constructed to explore significant predictors of BrAC. The model accounted for 68.0% of variance (Adjusted R^2=.68, F (8, 315)=83.83, p<.001). Due to potential correlations among significant predictors reported in Table 3, a more restrained model was further obtained by backward stepwise regression with a cutoff of p value less than 0.1 to eliminate correlated predictors. Significant predictors (with p<.05) of BrAC included the number of standard drinks, drink frequency, the average number of drinks consumed in past three months, and the delay of BrAC measurement (i.e. the time elapse between the last sip of drinks and the breath test). This model accounted for similar amounts of variance (68.0%) to those found in the previous regression model (F (6, 317)= 112.39, p < .001).

Table 3. Results of regression analysis for variables predicting BrAC

Predictors	*Beta*	*SE*	*t*
No. of standard drinks	0.37	0.009	3.55***
Gender	0.02	0.003	0.42
Age (years)	-0.05	0.00	-1.52
Weight (kg)	-0.17	0.00	-1.74
Drinking frequency[a]	-0.14	0.00	-3.59***
Average no. of drinks[a]	-0.16	0.001	-3.81***
Maximum no. of drinks per day [a]	0.00	0.00	-0.01
Time spent on drinking (h)	-0.79	0.00	-24.14***
Delay of BrAC measurement (h)	-0.79	0.00	-24.17***

Note: *p<.05, ** p <.01, *** p <.001; [a] measured in three months.

An eBAC Model Development

In order to develop the new eBAC model, it is necessary to explore variables that have a significant impact on the discrepancy of BrAC and eBAC of most commonly used existing equations (e.g. NHTSA formula). The discrepancy score was calculated by subtracting eBAC from BrAC: Discrepancy= |eBAC – BrAC| (Hustad and Carey, 2002; 2005). Variables were entered into separate linear regression models to test if they were significant predictors of the discrepancy. The factors of age (β =-.009, p=.88) and the maximum number of drinks per day (β =-.02, p=.69) were not significant predictors of the discrepancy. The significant predictors were then entered together into the regression model with a backward elimination procedure to reduce insignificant explanatory variables. The explanatory factor that was excluded from the regression model was 'time spent on drinking' (β =0.006, p=.30). The final model was shown in Table 4. The model accounted for 99.2% of the variance of the discrepancy (F(7, 316)=5473.426, p<.001).

Table 4. Results of regression analysis for variables predicting discrepancy of BrAC and eBAC

Predictor variables	*Beta*	*SE*	*t*
No. of standard drinks received	-1.07	0.00	-64.63***
Gender	-0.53	0.00	-76.90***
Weight (kg)	0.73	0.00	48.24***
Drinking frequency	-0.02	0.00	-4.42***
Average no. of drinks[a]	-0.01	0.00	-2.38**
Delay of BrAC measurement (h)	1.28	0.00	146.51***

Note: *p<.05, ** p <.01, *** p <.001; [a] measured in three months.

A new eBAC model was developed based on the relationship between significant predictors and the discrepancy summarized in Table 4. A nonlinear model was constructed since both the discrepancy analysis and the literature indicated the nonlinear relations between the parameters and the BAC (Yang et al., 2009).

Consistent with a previous study (Grant, 2012), the discrepancy analysis indicated existing eBAC equation had a less accurate estimation of BrAC for males than for females (F(1, 322)=53.14, p<.001). In the new BrAC model, a weighted parameter regarding the gender was introduced to improve BrAC estimation.

$$r_{NHTSA}(Gender) = \begin{cases} r_{NHTSA}(Female), & For\ female \\ b_1 \times r_{NHTSA}(Male), & For\ male \end{cases} \quad (1)$$

where b_1 accounted for the effects of drinker gender on discrepancy scores.

The results of the discrepancy analysis indicated that participant's weight was significantly related to the discrepancy score (F(1, 322)=23.11, p<.001), which would be improved in the model by adding a parameter of weight regarding the absorption rate of alcohol. The discrepancy between eBAC and BrAC also increased as the number of standard drinks received (F(27, 296)=19.6, p<.001). However, this trend could be the joint effect of gender and weight since the number of standard drinks was calculated for each participant to get a BrAC reaching 0.08 g/210L based on their gender and weight (Hustad and Carey, 2002). Therefore, the absorption rate of alcohol was then modeled by adding a parameter of weight to eliminate the discrepancy:

$$\text{Absorption rate} = \frac{0.806 \times c}{r_{NHTSA}(Gender) \times (b_2 W)} \quad (2)$$

where the coefficient b_2 accounted for the effects of weight on discrepancy scores.

The discrepancy score increased as the time of BrAC measurement increased (F(1, 322)=5.35, p<.05). In particular, as the delay of BrAC measurement increased, the eBAC tended to underestimate BrAC. The estimation of BrAC along with time was then modeled by adding a weighted delay of BrAC measurement:

$$BrAC = \frac{0.806 \times c}{r_{NHTSA}(Gender) \times (b_2 W)} - \beta_{60} \times (t + (b_3 D) \quad (3)$$

$$\text{with } r_{NHTSA}(Gender) = \begin{cases} r_{NHTSA}(Female), & For\ female \\ b_1 \times r_{NHTSA}(Male), & For\ male \end{cases}$$

where $BrAC$ = breath alcohol concentration in g/210L, c = number of standard drinks consumed, β_{60} = the metabolism rate of alcohol per hour (e.g., 0.017 g/dl), t = time in hours since the first sip of alcohol to the time of assessment. The coefficients b_1, b_2, and b_3 were defined to measure the effects of different gender ($r_{NHTSA}(Gender)$), weight (W), and the delay of BrAC measurement (D, in hours) on the discrepancy score, respectively.

The initial values for each of the parameters were set according to the linear proportionality suggested by NHTSA formula. Fifty percent (50%) of the collected data in the current experimental study were randomly selected to train proposed parameters. Initial values and trained values of each parameter were presented in Table 5.

Table 5. The results of parameter estimations for the developed model (with 50% of data)

Parameter	Initial Value	Estimated Mean	*SE*	95% CI	
				Lower Limit	Upper Limit
b_1	1.00	0.9	0.85	0.94	0.90
b_2	1.00	1.10	1.03	1.16	1.10
b_3	0	0.03	-0.09	0.14	0.03

It is now possible to formulate the new eBAC equation:

$$BrAC = \frac{0.806 \times c}{r_{NHTSA}(Gender) \times (1.1 \times W)} - \beta_{60} \times (t + (0.03 \times D) \quad (4)$$

$$\text{with } r_{NHTSA}(Gender) = \begin{cases} 0.49, & For\ female \\ 0.9 \times 0.58, & For\ male \end{cases}$$

where BrAC = breath alcohol concentration in g/210L,
c = number of standard drinks consumed,
W= weight in kg
β_{60} = the metabolism rate of alcohol per hour (e.g., 0.017 g/dl),
t = time in hours since the first sip of alcohol to the time of assessment.
D= delay of BrAC measurement in hours

THE VALIDATION OF THE DEVELOPED eBAC MODEL

In order to validate the developed eBAC model, the following section compared the new eBAC model and existing eBAC models with data from three experimental studies. The new model was firstly validated with the 50% of the rest data from the current experimental study, and the modeling performance was compared with five existing equations. To test the generalizability of the developed eBAC model, the model was then validated with two published work in literature to test its performance in estimating BrAC levels and compared with five existing equations. The comparability of the model predictions (eBAC) and experimental results (BrAC) was quantified by R-square (R^2) and the root-mean-squared error (RMSE). These parameters examined how well a model fitted observed data.

Published Drinking Experiments

A literature review was conducted to identify available published drinking experiments that could be used to validate the developed eBAC model. Only two published works were found to meet the criteria that reporting the details of participant demographics and alcohol administration procedures to estimate BAC/BrAC levels, and reported details of measured magnitude and time-course of BAC/BrAC levels to validate BAC/BrAC levels.

The first published work studied the elimination rates of BrAC over time under social drinking conditions (Pavlic et al., 2007). Fifty-nine participants ranged from 20 to 40 years were recruited with an average age of 29.1 years (*SD* = 5.2). The performance of the developed model was compared with that of the other five models. The second published work studied the effect of drinker type on drunk driving behavior and measured the BrAC over time (Marczinski & Fillmore, 2009). Twenty-eight participants ranged from 21-28 were recruited an average age of 22.6 years (*SD* = 2.3). Since the height information of participants was not reported in this work, the model was compared with the other three equations except Watson and Forrest equations.

Experiment One (Data from current experimental study)

The validity of the new eBAC model was first examined with the data from the current experimental study. As 50% of the data from the current experimental study was randomly selected to train the parameters, the rest 50% of the data was used to compare with the prediction of the new models. The values of parameters were the same as the trained values shown in Table 5. As it shown in Figure 2, the prediction of the new model fitted the tested data over time.

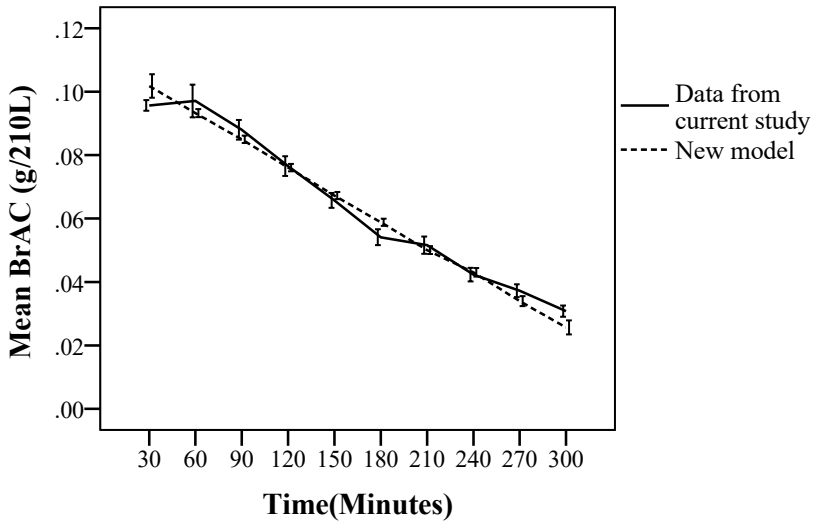

Figure 2. The prediction of BrAC with proposed new eBAC model compared with the data from current experiment (Error Bar: +/-1SD).

As shown in Table 6, results of model predictions of data from the current experimental study indicated the new eBAC model had a better modeling performance of BrAC compared with the other five models. The model prediction resulted in the highest R^2 of 0.64 with a lower value of RMSE (0.016).

Table 6. Comparison of the Developed Model with Existing eBAC Models (Data from Current Experimental Study)

Data Source	Model	Pearson correlation	R^2	R^2 for no-intercept regression	*RMSE*
Current Experimental Study	NHTSA	0.75	0.57	0.93	0.02
	Matthew	0.73	0.54	0.93	0.03
	Lewis	0.78	0.61	0.91	0.03
	Watson	0.75	0.56	0.91	0.02
	Forrest	0.73	0.55	0.90	0.02
	New Model	0.80	0.64	0.94	0.02

Comparing with reported parameters of model fit in literature for other models, shown in Table 1, the Pearson correlation coefficients of the developed eBAC model and BrAC was the highest (r=0.80). The new eBAC model and other existing models were then compared with no-intercept linear regressions suggested by literature (Hustard and Carrey, 2005). R^2 for no-intercept regression of the new eBAC model was higher (0.94) compared with those reported in the literature and those of the other models in the current experimental study.

Experiment Two (Pavlic et al., 2007)

To examine the generalization of the new eBAC model, the model validity was examined in a published work of Pavlic et al. (2007). Fifty-nine participants were recruited to drink alcohol under a social drinking condition. The BrAC were measured after a two-hour drinking session, and average 30 minutes after that. The parameters of the new model were the same as that of the current experimental study shown in Table 5. As it shown in Figure 3, the prediction of the new model well fitted the trend of BAC over time.

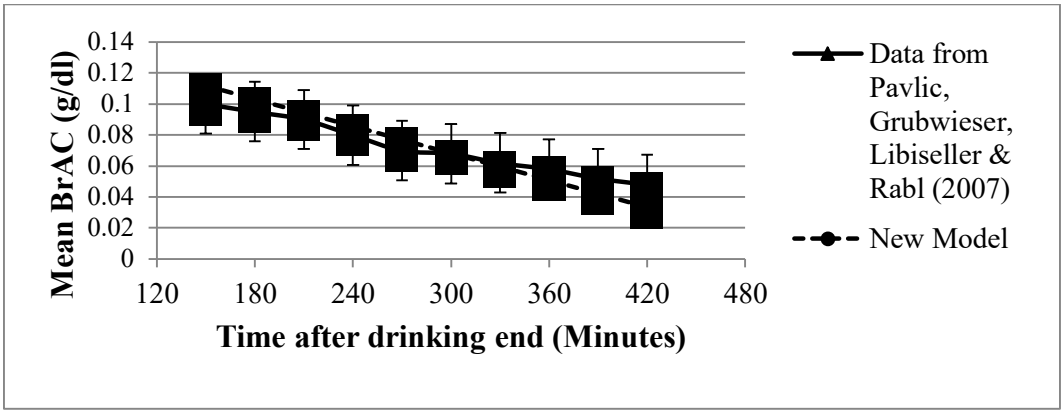

Figure 3. The prediction of BrAC with proposed new eBAC model compared with the data from Pavlic, Grubwieser, Libiseller & Rabl (2007) (Error Bar: +/-1SD).

The results of model predictions also indicated the new model had a better modeling performance of BrAC compared with that of the other five eBAC models (see Table 7). In particular, the model prediction of BrAC resulted in the highest R^2 of 0.94. R^2 value for non-intercept linear regression model of the new eBAC model was also the higher (0.99) compared the other models in the current study. Compared with previous literature's reported model fitting parameters, as shown in Table 1, the new eBAC model had a higher Pearson correlation coefficient with the BrAC than those reported in the literature (r=0.97).

Table 7. Comparison of the Developed Model with Existing eBAC Models (Data from the work of Pavlic et al., 2007)

Data Source	Model	Pearson correlation coefficients	R^2	R^2 for no-intercept regression	*RMSE*
Pavlic, Grubwieser, Libiseller & Rabl (2007)	NHTSA	0.86	0.75	0.97	0.0003
	Matthew	0.87	0.75	0.97	0.0003
	Lewis	0.86	0.75	0.97	0.0003
	Walson	0.96	0.92	0.95	0.0003
	Forrest	0.96	0.93	0.98	0.0002
	New Model	0.97	0.94	0.99	0.0003

Experiment Three (Marczinski & Fillmore, 2009)

To generalize the application of the new eBAC model, the model validity was further examined in another published work of Marczinski & Fillmore (2009). Twenty-eight participants were recruited to perform a driving task during which they received a moderate dose of alcohol (0.65 g/kg) or a placebo. The BrAC were measured over time before, between and after the driving task. The settings of the parameters of the new model were the same as that of the current experimental study shown in Table 5. As it shown in Figure 4, the estimation of the new model well fitted the descending limb of BrAC over time.

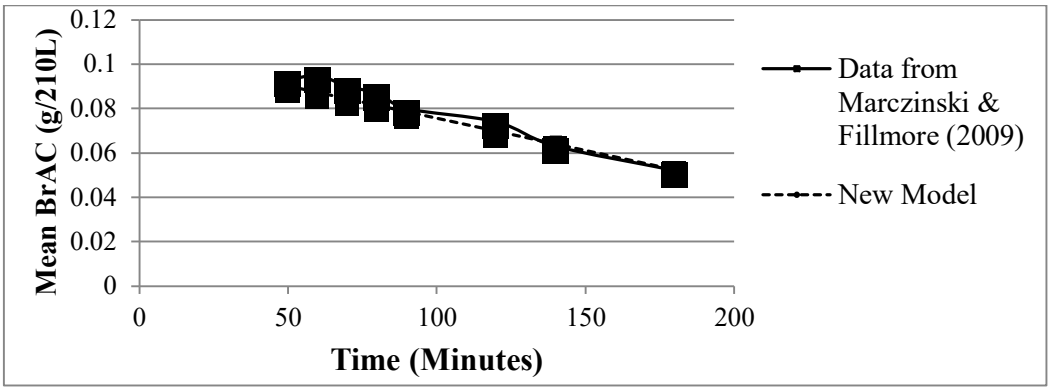

Figure 4. The prediction of BrAC with new eBAC model compared with the data from Marczinski & Fillmore (2009) (Error Bar: +/-1SD).

The results of model predictions also indicated the new model had a better modeling performance of BrAC compared with the other three models (see Table 8). In particular, the model prediction of BrAC resulted in the highest R^2 of 0.85 with a lower value of RMSE (0.01) compared with that of the NHTSA equation, the Matthew equation, and the Lewis equation. R^2 value for non-intercept linear regression model of the new eBAC model was higher (0.99) compared with other models in predicting the BrAC levels measured in the work of Marczinski & Fillmore (2009) and those reported in the literature. Comparing with the reported model fitting parameters in the literature for other models as shown in Table 1, the Pearson correlation coefficients of the new eBAC model and the BrAC obtained from the published work was the highest (r=0.92).

Table 8. Comparison of the Developed Model with Existing eBAC Models (Data from the work of Marczinski & Fillmore, 2009)

Data Source	Model	Pearson correlation coefficients	R^2	R^2 for no-intercept regression	*RMSE*
Marczinski & Fillmore (2009)	NHTSA	0.85	0.74	0.98	0.01
	Matthew	0.72	0.52	0.98	0.02
	Lewis	0.80	0.64	0.98	0.01
	New Model	0.92	0.85	0.99	0.01

Summary of the Validation of the New eBAC Model

The validity of the model was examined with data from the current experimental study and two published work. Table 9 summarized the performance of the new eBAC model and existing models in estimating BrAC data from three empirical studies. Results from all three studies indicated the new model had a better performance of BrAC estimation compared with existing eBAC models, including the NHTSA equation, the Matthew equation, the Lewis equation, the Watson equation, and the Forrest equation.

As is shown in Table 9, predictions of the new model had higher R^2 values compared with existing eBAC models across three studies. In terms of the value of *RMSE*, predictions of the new model had lower to equal RMSE in estimating BrACs compared with existing models across three studies with only one exception. The RMSE of the new model was slightly higher than the Forrest equation in modeling BrAC from the work of Pavlic et al. (2007). However, the

higher R^2 of the new model compared to the Forrest equation still indicated its better performance of the data fitting. The examination of the model validity with three sources indicated its good generalizability in estimate BrAC.

Table 9. Summary of the Comparison of New Model and Existing eBAC Models Based on Data from Three Empirical Studies

Data Sources	Model Assessment Parameters	New Model	Existing Models				
			NHTSA	Matthew	Lewis	Watson	Forrest
Pavlic, Grubwieser, Libiseller & Rabl (2007)	R^2	0.94	0.75	0.75	0.75	0.92	0.93
	RMSE	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002
Marczinski & Fillmore (2009)	R^2	0.85	0.74	0.52	0.64	NA	NA
	RMSE	0.01	0.01	0.02	0.01	NA	NA
Current Experimental Study	R^2	0.64	0.57	0.54	0.61	0.56	0.55
	RMSE	0.02	0.02	0.03	0.03	0.02	0.02

DISCUSSION

Driving under the influence of alcohol is a national problem in the United States. The present work developed a new eBAC model to provide a better tool for BrAC estimation. A discrepancy analysis that was conducted in the current experimental study explored the factors to be improved in the eBAC model. The effects of gender, weight, and the delay of BrAC measurement on the discrepancy score were modeled based on the discrepancy analysis results. Fifty percent of the data from the current experimental study was randomly selected to train proposed coefficients of the new eBAC model.

The goodness of fit of the model was examined with remained 50% data from the current experimental study and compared with the predictions of other five exiting models. The generalizability of the model was examined by testing the validity of the new eBAC model with two published work and comparing it with the other five existing models. Results of the model validity from all three studies indicated the new model had a better performance of BrAC estimation compared with existing eBAC models. The new model developed in this work also showed a better performance in estimating BrAC compared with the reported parameters of model fitting in literature, as shown in Table 1. The Pearson correlation coefficients of the new model with the data from three empirical studies were generally higher than those reported in the literature. The only exception was the Pearson correlation coefficients of the new model (r=0.80) with the data from the current experimental study was slightly lower than that of the NHTSA equation (r=0.84) in modeling BrAC from the work of Carey & Hustad (2002). However, the Pearson correlation coefficients reported for NHTSA equation in literature had a large variation ranging from 0.26-0.84. The Pearson correlation coefficient of the new eBAC model was relatively stable with a range of 0.80-0.97 compared with the NHTSA equation.

This work is one of a few mathematical models in the field of BrAC/BAC modeling that considers the discrepancy between the BrAC and eBAC. The discrepancy raised concern about utilizing eBAC models to estimate BAC/BrAC over time. Previous research resulted in conflicting conclusions about the effect of gender on the discrepancy (Sommers et al., 2000, 2002; Hustad and Carey, 2005). The results of discrepancy analysis in the current experimental

study showed the estimation of BrAC for males were less accurate than for females, which were consistent with the effect of gender reported in previous studies (Hustad & Carey 2005; Grant et al., 2012). The new eBAC model added a coefficient of the male gender to eliminate discrepancy of eBAC and BrAC brought by gender difference. The discrepancy analysis also indicated individual's weight significantly contributed to the discrepancy score, which was consistent with the literature (Davies and Bowen, 2000; Hustad and Carey, 2005). To improve the estimation of BrACs/BACs, the new eBAC model added a coefficient of weight to model effect of weight on the discrepancy. In addition, the results of discrepancy analysis showed the delay of BrAC measurement significantly contributed to the discrepancy. By adding a weighted delay of the BrAC measurement, the new eBAC model reduced the underestimation of eBACs.

The discrepancy analysis in the current study indicated age was a non-significant predictor of the discrepancy. However, this non-significance may be due to the young limited range of the age of the selected sample. Existing findings in the literature suggested the eBACs of elderly people might have been underestimated (Bielefeld, Auwärter, Pollak, & Thierauf-Emberger, 2015). Therefore, the application of the eBAC model for elderly population needed to be tested across different age groups in order to implement the model to a general population. Meanwhile, the maximum number of drinks per day does not significantly predict the discrepancy, nor it is a significant predictor of BrAC. Comparing with the other two variables regarding the drinking history, the maximum number of drinks per day might not be a sensitive variable to predict the change of BrAC levels. Besides, the time spent on drinking was excluded from a restrained model of the discrepancy using a backward stepwise regression procedure. Since the current experimental study was conducted in a controlled setting, the time spent on drinking might have a smaller variation comparing with that in a natural setting. Therefore, the time spent on drinking is needed to be further tested with a larger range to simulate the natural drinking episodes in order to implement the model in a general setting.

Although the developed eBAC model showed a better performance in predicting BrAC comparing to existing eBAC models, the development and validation of the new eBAC model would be interpreted in the light of its limitations. Firstly, the sample recruited in the current experimental study was limited to young adults. In order to investigate the validity of the model comparison in the above validation section, we compared the mean age and age range of the sample in the current experimental study and other empirical studies. As it shown in the appendix, other empirical studies listed in Table 9 that used to validate the new eBAC model and those listed in Table 1 that reported fitting parameters of existing eBAC models covered a similar age group (M=23.29, SD=3.91) as the current study (M=23.83, SD=3.40). Despite the limited age range of the sample recruited, the validation results did suggest that the developed eBAC model have a better performance of BrAC estimation compared with existing models for young adults. Therefore, studies regarding the validation of our newly developed eBAC model across different age groups are critical to help improve the generalizability and implementation of the eBAC model. Meanwhile, due to the small sample size, it is difficult to examine the validity of the new eBAC model across different racial and ethnic groups. Therefore, future research efforts could address this question by comparing the goodness of fit of the new eBAC model for different racial and ethnic groups with a large sample.

Secondly, the effect of food consumption and pattern of drinking on the estimation of BrAC was not modeled in the current work since this variable was controlled in the laboratory settings for current experimental study and the published works. The food intake was found to be a source of variability of BrAC in the natural setting and could be modeled in the future. On the

other hand, the food consumption and patterns of drinking would only be obtained depending on reports of the driver or witnesses in reality, which may introduce the noise in the retrospective estimation of the BrAC level.

Thirdly, the model was validated with the BrAC levels under 0.20 g/210L. Further work is needed to examine the validity of the model in predicting higher BrAC levels that over 0.20 g/210L. In addition, the validity of the developed model to construct blood alcohol concentration has to be further tested. Since it is very difficult to obtain the blood sample, the current study validated the eBAC model with the breath alcohol concentration. A similar approach was adopted to validate eBAC models with measured BrAC in previous studies (Carey & Hustad, 2002; Hustad and Carey, 2005).

Most of the necessary data for the application of the new model was collected in the standard DUI procedure. The measurement delay was the only new data needed to be collected to implement the new eBAC model, which could be easily estimated or measured based on the public surveillance videos. Although the drinking frequency and the average number of drinks were reported to have significant impacts on the discrepancy, these two variables were not included in the new model during its development stage due to the concern of the practical implementation. The main reason for exclusion of these variables was that the corresponding data was usually collected based on self-reports rather than objective measurement, which might make it difficult for police officers to obtain the accurate information in DUI enforcement and procedures.

The present work developed a new eBAC model to estimate individuals BrACs with backward reconstructions to provide more accurate evidence for DUI offenses. Since the blood or breath sample may often be obtained several hours after the offenses, the eBAC models will provide the back calculation of BrAC or BAC at some earlier time, such as the time of driving under the influence. This study takes the first step to improving the eBAC modeling with a discrepancy analysis of the measure BrACs and eBAC. The validation of this model with data from three empirical studies indicated its good generalizability and a better ability in estimating BrAC comparing with existing eBAC models.

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