

Relationship Between EtCO₂ and Quality-Parameters During Cardiopulmonary Resuscitation

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Abstract

Monitoring end-tidal carbon dioxide (EtCO₂) is suggested as an indicator of cardiopulmonary resuscitation (CPR) quality since it reflects blood flow to the lungs. However, the relationship between EtCO₂ and CPR quality parameters is poorly understood. In this study, we analyzed the EtCO₂ linear relation with chest compression depth, chest compression rate, and ventilation rate.

Six resuscitation episodes with the capnogram and the compression depth signal were selected to identify intervals with a stable EtCO₂ value. The corresponding ventilation rate, compression depth and compression rate were annotated. Multiple linear regression was used to correlate EtCO₂ changes with variations of CPR parameters, intra and inter-patient.

Median (P_{25} , P_{75}) coefficient of determination R^2 per patient was 0.86 (0.78, 0.89), decreasing to 0.64 when values were considered jointly. An increase of 1 ventilation per minute caused a decrease of 1.1 mmHg in EtCO₂. An increase of 1 mm in depth caused an increase of 0.26 mmHg. Compression rate did not significantly influence the results.

EtCO₂ reflected CPR quality during resuscitation attempts, although the relationship between EtCO₂ and CPR quality parameters varied between patients. The main explanatory variable was ventilation rate.

1. Introduction

During cardiac arrest, the quality of cardiopulmonary resuscitation (CPR) is a key determinant of outcomes. Compressions depth and rate, as well as ventilation rate are main CPR quality parameters. Current resuscitation guidelines recommend a compression depth between 5 and 6 cm, at a rate between 100 and 120 compressions per minute, and a ventilation rate of 12 ventilations per minute for intubated patients [1]. These target values have been established on the basis of observational studies relating CPR

parameters with survival [2]. Anatomic and physiological differences among patients suggest that CPR should be adjusted to optimize the hemodynamic response of each patient. Consequently, research on non-invasive indicators of blood flow during chest compressions is required. This would provide a real measurement of the CPR influence on the patient's hemodynamic response.

Capnography signal monitors end-tidal carbon dioxide concentration (EtCO₂) during respiration. EtCO₂ is a non-invasive indicator of cardiac output and pulmonary circulation [3,4], and can provide a surrogate physiological measurement of the cardiac output at low flow states. Monitoring of EtCO₂ during CPR was firstly proposed by Kalenda in 1978 [5]. Currently, resuscitation guidelines recommend the use of capnography by the advanced life support with intubated patients, as an indicator of CPR quality [6]. Unfortunately, quantitative relations between EtCO₂ and CPR quality parameters are not yet well-established, and clinical studies on this topic are scarce. Two very recent observational studies have evaluated this association through the analysis of time-synchronized intervals of out-of-hospital cardiac arrest resuscitation episodes [7,8].

In this study we proposed a simple EtCO₂ generation model to analyze this relationship. Our hypothesis was that this model could allow establishing useful and reliable relations between EtCO₂ levels and CPR quality parameters during resuscitation attempts.

2. Materials and methods

2.1. Model for carbon dioxide concentration in the pulmonary cavity

Figure 1 depicts the model we proposed for the analysis of variations of carbon dioxide concentration in the pulmonary cavity. Generation of carbon dioxide in the pulmonary cavity relies on the alveolar exchange of oxygen and carbon dioxide which is proportional to pulmonary circulation. Consequently, it depends directly on the depth

and rate of chest compressions. Ventilation is the only factor determining carbon dioxide extraction from the pulmonary cavity. Assuming equal exchanged air volume in each ventilation, extraction is exclusively governed by ventilation rate.

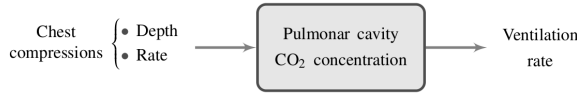


Figure 1. Proposed model for CO₂ concentration during CPR.

A more complex model should include additional factors as previous pathologies or drugs administration during the resuscitation intervention. One key factor is that the capnogram (and therefore the EtCO₂ values) is not a stationary signal. In fact, the capnogram has a noticeable inertial response to changes in the regulating parameters of the model. This behavior can be observed in Figure 2 which shows the effect of an abrupt change in compression depth on the EtCO₂ level. In this example, compression depth suddenly increases from an average of 25 mm to 55 mm (at instant 980 s, approximately), while the EtCO₂ starts increasing, taking more than 1 min to reach an equilibrium level of 20 mmHg. This dynamic behavior of the EtCO₂ level introduces a significant confusion factor that, if not properly considered, may bias the correlation results.

This study paid special attention to a careful selection of intervals during which the EtCO₂ value was stationary, i.e. the value remained constant along the entire interval. Figure 3 shows an example. In this interval EtCO₂ level and the rest of the parameters of the model can be considered constant.

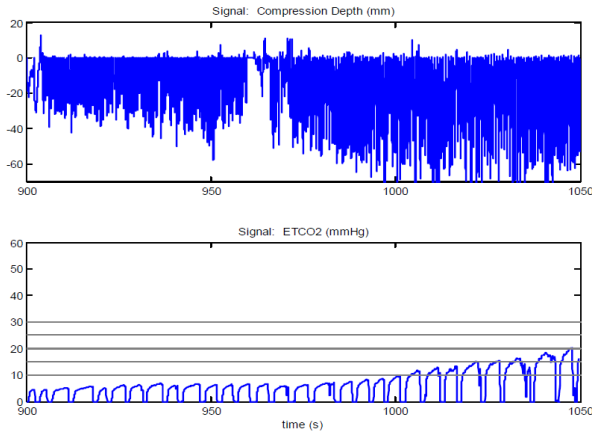


Figure 2. Example of EtCO₂ increasing trend (bottom) after an abrupt change in compression depth (top).

2.2. Data collection

We extracted thirty episodes (one per patient) from a large out-of-hospital cardiac arrest database, compiled by the Tualatin Valley Fire & Rescue (Tigard, OR, USA) between 2006 and 2010. Episodes were recorded by MRx monitor-defibrillators (Philips, USA). Signals of interest for our study were the capnography signal (endotracheal airway) and the compression depth signal (calculated from a chest pad, QCPR, Philips, USA). Each episode contained at least 1000 compressions. Data were provided anonymously. Capnography and compression depth signals were stored with a sampling frequency of 40 and 250 samples/s, respectively.

2.3. Methods

We visually reviewed the entire episodes to select those with more than eight intervals in which the EtCO₂ level could be considered stationary. This selection criterion reduced our dataset drastically to six episodes. Each interval was characterized by four parameters: the EtCO₂ value (mmHg), the ventilation rate (f_v , in ventilations per minute, vpm), both measured in the capnogram; the average compression rate (f_c , in compressions per minute, cpm), and the average compression depth (d_c , in mm), measured in the compression depth signal.

Figure 3 shows one of the selected intervals. Depth and rate of consecutive compressions were identified in the t_1 - t_2 interval marked in the compression depth signal (top). Average depth and rate was 44 mm and 89.5 cpm, respectively. Ventilation rate was calculated in the t_3 - t_4 interval as the number of ventilations (3) divided by the interval duration (0.575 min). EtCO₂ value was the constant value in the same interval, 15 mmHg.

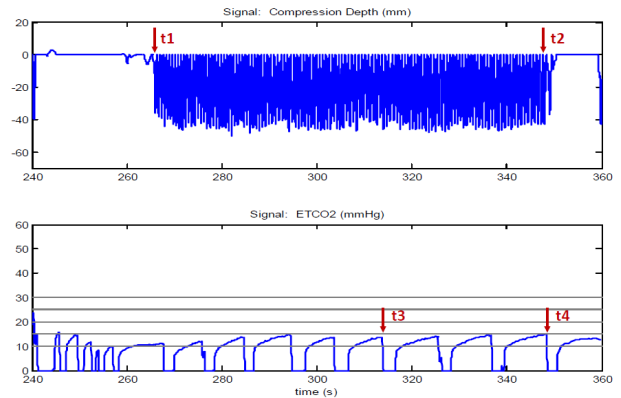


Figure 3. Stationary behavior of EtCO₂ level during resuscitation. Interval in the compression depth signal (top) to obtain compression depth and rate, and in the capnogram (bottom) to obtain ventilation rate and EtCO₂.

2.4. Statistical Analysis

Multiple linear regression was used to model the variation in EtCO₂ (ΔEtCO_2) between consecutive intervals with respect to variations in the model parameters: Δf_v , Δd_c , and Δf_c . The coefficient of determination R^2 was used to assess the model goodness of fit. R^2 values were provided as median (P_{25} , P_{75}), where P_{25} and P_{75} were the 25th and the 75th percentiles, respectively. The statistical analysis was performed both per patient and for all patients jointly.

3. Results

We selected a total of 63 intervals from the six episodes. A median of eleven intervals were selected per episode. Mean (SD) values per patient were 22 (8) mmHg, 40 (4) mm, 111 (14) cpm, and 8 (2) vpm, for EtCO₂ level, compression depth, compression rate, and ventilation rate, respectively.

Figure 4 shows a 3D scatter plot depicting EtCO₂ variations (colored dots) with respect to variations in the model parameters for all data points.

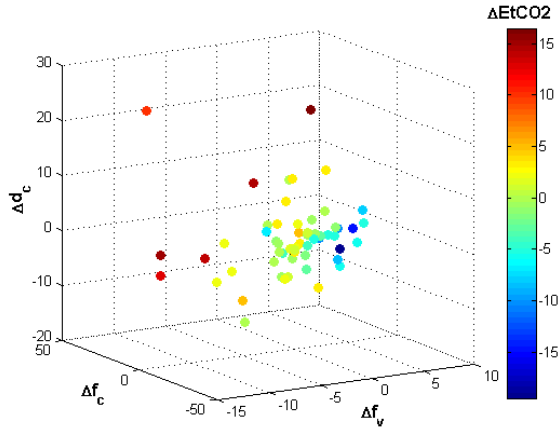


Figure 4. 3D scatter plot depicting ΔEtCO_2 (colored dots) with respect to Δf_v , Δd_c , and Δf_c .

Median value for R^2 was 0.86 (0.78, 0.89) in the analysis per patient, but this value decreased to 0.64 when all values were considered jointly. In both types of analysis, the main explanatory variable was f_v .

Considering the whole dataset, the regression equation was:

$$\Delta\text{EtCO}_2 = -1.09\Delta f_v + 0.26\Delta d_c - 0.02\Delta f_c \quad (1)$$

From the equation, it can be derived that an increase of one ventilation per minute caused a decrease of 1.1 mmHg in the EtCO₂ value. An increase of 1 mm in d_c caused an

increase of 0.26 mmHg. Parameter f_c was least important, a decrease of 1 cpm caused a decrease of 0.02 mmHg. Excluding f_c from the model did not change R^2 .

Figure 5 depicts a scatter plot showing the influence of Δf_v in EtCO₂ variations considering those intervals with $\Delta d_c < 3.5$ mm. Similarly, Figure 6 shows the influence of Δd_c in EtCO₂ variations (for intervals with $\Delta f_v < 2.5$ vpm).

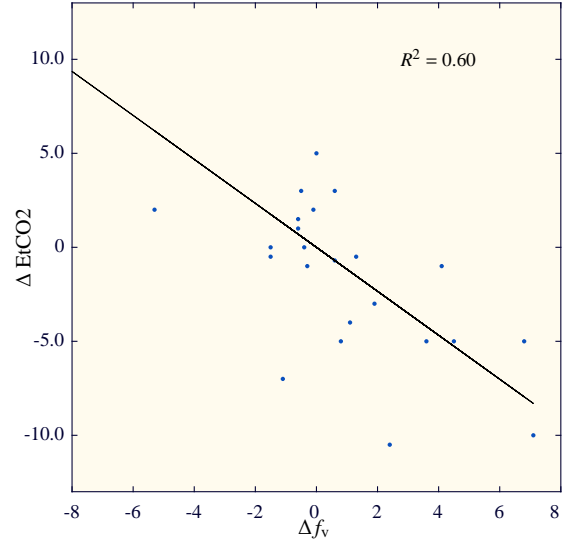


Figure 5. EtCO₂ correlation with ventilation rate variations ($\Delta d_c < 3.5$ mm).

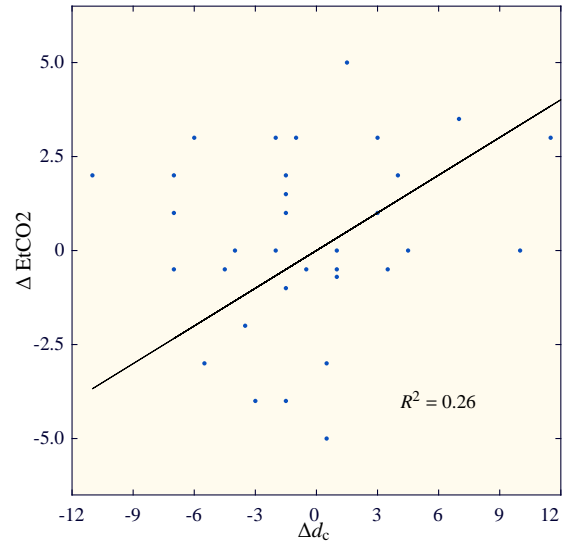


Figure 6. EtCO₂ correlation with compression depth variations ($\Delta f_v < 2.5$ vpm).

4. Discussion

Chest compressions and ventilations during CPR contribute to artificially maintain a minimal flow of oxygenated blood to the vital organs. During advanced life support interventions, non-invasive capnography is proposed as a good indicator of blood flow and CPR quality.

Despite many factors influencing EtCO₂ we proposed a simple model for carbon dioxide exchange being governed by three quality parameters: compression depth, compression rate, and ventilation rate. The selection of stationary EtCO₂ intervals allowed the analysis of the EtCO₂ equilibrium level reached after changes in the model factors, avoiding bias due to EtCO₂ dynamics.

Our results showed a noticeable correlation between EtCO₂ and quality parameters ($R^2 = 0.64$), which increased when patients were analyzed separately ($R^2 = 0.86$). The main explanatory variable was ventilation rate, which showed an inverse correlation with EtCO₂ level. Compression depth showed a much lower but direct correlation, and compression rate barely influenced EtCO₂ variations.

These observed trends were aligned with two recent studies with a similar objective [7, 8]. Ventilation rate was the main factor in all studies: an increase of 10 ventilations per minute caused a decrease in EtCO₂ of 3.0 mmHg [7], of 16.8% [8], and of 11.0 mmHg in our study. Compression depth was a significant predictor of increased EtCO₂: an increase of 10 mm in depth caused an increase of 1.4 mmHg [7], of 4.0% [8], and of 2.6 mmHg in our study.

Differences could be explained by the selection of the time-synchronized intervals. Duration was 15 s in [7] 1 min in [8], and variable in our study. The slow response of EtCO₂ level to variations in its determining factors could introduce a confusion factor in the analysis if non-stationary EtCO₂ intervals are included. We think separated analysis of stationary and non-stationary behavior of EtCO₂ could provide valuable information to better understand and explain its relation with CPR quality parameters. Nevertheless, we should conduct studies with larger databases to ensure generalization of the results.

5. Conclusion

In our study, variations in EtCO₂ correlated with variations in ventilation rate and in compression depth during CPR, although this relationship varied between patients. The main explanatory variable was ventilation rate. Our results were aligned with those reported in larger observational studies, although dynamics of EtCO₂ should be considered carefully in order to assess this relationship.

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References

- [1] Kleinman ME, Brennan EE, Goldberger ZD, Swor RA, Terry M, Bobrow BJ, Gazmuri RJ, Travers AH, Rea T. Part 5: Adult basic life support and cardiopulmonary resuscitation quality 2015 american heart association guidelines update for cardiopulmonary resuscitation and emergency cardiovascular care. *Circulation* 2015;132(18 suppl 2):S414–S435.
- [2] Travers AH, Perkins GD, Berg RA, Castren M, Considine J, Escalante R, Gazmuri RJ, Koster RW, Lim SH, Nation KJ, et al. Part 3: Adult basic life support and automated external defibrillation 2015 international consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations. *Circulation* 2015; 132(16 suppl 1):S51–S83.
- [3] Jin X, Weil MH, Tang W, Povoas H, Pernat A, Xie J, Bisera J. End-tidal carbon dioxide as a noninvasive indicator of cardiac index during circulatory shock. *Critical care medicine* 2000;28(7):2415–2419.
- [4] Isserles SA, Breen PH. Can changes in end-tidal pco2 measure changes in cardiac output?. *Anesthesia Analgesia* 1991; 73(6):808–814.
- [5] Kalenda Z. The capnogram as a guide to the efficacy of cardiac massage. *Resuscitation* 1978;6(4):259–263.
- [6] Link MS, Berkow LC, Kudenchuk PJ, Halperin HR, Hess EP, Moitra VK, Neumar RW, O'Neil BJ, Paxton JH, Silvers SM, et al. Part 7: adult advanced cardiovascular life support 2015 american heart association guidelines update for cardiopulmonary resuscitation and emergency cardiovascular care. *Circulation* 2015;132(18 suppl 2):S444–S464.
- [7] Sheak KR, Wiebe DJ, Leary M, Babaeizadeh S, Yuen TC, Zive D, Owens PC, Edelson DP, Daya MR, Idris AH, et al. Quantitative relationship between end-tidal carbon dioxide and cpr quality during both in-hospital and out-of-hospital cardiac arrest. *Resuscitation* 2015;89:149–154.
- [8] Murphy RA, Bobrow BJ, Spaite DW, Hu C, McDannold R, Vadeboncoeur TF. Association between prehospital cpr quality and end-tidal carbon dioxide levels in out-of-hospital cardiac arrest. *Prehospital Emergency Care* 2016;20(3):369–377.

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