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Clinical paper

Is the occurrence of reversed airflow in manual ventilation during cardiopulmonary resuscitation associated with reduced net tidal volumes?

Maxim Vanwulpen[a,b,*], *Ruben Cornelis*[b], *Arthur Bouillon*[b], *Saïd Hachimi-Idrissi*[a,b,c]

Abstract

Background: During cardiopulmonary resuscitation, following advanced airway placement, chest compressions and ventilations are performed simultaneously. During inspiration, chest compressions and positive pressure ventilation exert opposite forces on the respiratory system, frequently resulting in reversed airflow.

Methods: Following endotracheal intubation, a flow sensor was connected to the respiratory circuit of intubated, adult out-of-hospital cardiac arrest patients receiving manual chest compressions and manual ventilations. Chest compression parameters were measured using an accelerometer. Inspiratory and expiratory volumes during the inspiratory phase of positive pressure ventilations were quantified. Duration of the inspiratory and expiratory phases was calculated.

Results: In this study, 25 patients were included, 682 ventilations were analyzed. Reversed airflow was observed in 23 patients, occurring 389 times during 270 ventilations. Median volume of reversed airflow was 2 mL (IQR 1.4–7 mL). There was no difference between net tidal volumes of ventilations during which reversed airflow did (median 420 mL, IQR 315–549) or did not occur (median 406 mL, IQR 308–530). When reversed airflow occurred, the duration of the inspiratory phase was longer (median 1.2 sec, IQR 0.9–1.4) compared to ventilations without reversed airflow (median 0.9 sec, IQR 0.9–1.4). Univariate analysis showed a weak correlation between chest compression depth and volume of reversed airflow.

Conclusion: Reversed airflow frequently occurs during cardiopulmonary resuscitation. Volumes of reversed airflow were small, showing a weak correlation with chest compression depth. The occurrence of reversed airflow was not associated with reduced net tidal volumes.

Keywords: Cardiac arrest, Cardiopulmonary resuscitation, Ventilation, Advanced life support, Reversed airflow, Chest compressions

Introduction

Early, high-quality cardiopulmonary resuscitation is crucial to increase the chance of survival following cardiac arrest.[1] Current guidelines emphasize minimally interrupted, high-quality chest compressions. Following advanced airway placement, chest compressions and ventilations are performed simultaneously.[1,2] Continuous chest compressions limit no-flow time, leading to increased coronary and cerebral perfusion, possibly resulting in improved outcomes.[3] Ventilations producing visible chest rise, lasting approximately 1 second, at a rate of 10 per minute are recommended.[2] In anesthetized adults, visible chest rise has been reported to occur at a mean tidal volume of 384 mL (95% CI 362–406).[4]

During the inspiratory phase of ventilation, chest compressions and positive pressure ventilation exert opposite forces on the thorax. The positive pressure generated by chest compressions has been observed to variably limit ventilation, in some cases resulting in reversed airflow.[5] It is unclear if reversed airflow is associated with reduced tidal volumes.[3]

The only human study on reversed airflow during simultaneous manual ventilations and manual chest compressions found a mean volume of reversed airflow of 96 mL per episode, occurring in 21/25 patients, in 65% of all studied ventilations. Tracheal pressure measurements were used to quantify flow during prehospital cardiopulmonary resuscitation, possibly limiting accuracy. The association between reversed airflow and delivered ventilation was not studied.[5]

More recently, two cadaver studies using mechanical chest compressions and mechanical ventilation also reported the occurrence of reversed airflow. In the first, the median volume of reversed airflow was 71.8 mL (IQR 26.4–172), no data on the proportion of ventilations showing reversed airflow was provided.[6] In the second, median

* Corresponding author.
E-mail address: maxim.vanwulpen@ugent.be (M. Vanwulpen).

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volume of reversed airflow was 0.05 mL/kg predicted body weight (range 0–0.7), the highest recorded volume was 45.6 mL, occurring median 1 time (range 0–2) during inspiration.[3]

Primary goals of this study were to quantify reversed airflow during the inspiratory phase of ventilation, determining whether the occurrence of reversed airflow is associated with reduced net tidal volumes. Additionally, we aimed to explore whether reversed airflow is associated with differences in duration of the inspiratory phase of the current and expiratory phase of the preceding ventilation, with differences in duration of the preceding ventilation; and if the volume of reversed airflow is correlated with chest compression depth, chest compression rate and already delivered tidal volume.

Methods

This was a single center, observational study. Recruitment took place over a total period of 30 months (February–April 2016, October–December 2017, October–December 2018, March 2022–November 2023). A convenience sample of adult, out-of-hospital cardiac arrest patients, treated by the prehospital medical team (consisting of a physician, nurse, and emergency medical technician) of the Ghent University Hospital, were eligible for inclusion. If the prehospital medical team reported any problems with the respiratory circuit during resuscitation (on the medical report), the patient was excluded from analysis. The statistical analysis plan was finalized after data collection.

Patients were treated according to then current European Resuscitation Council guidelines.[7,8] Manual chest compressions were performed by different members of the prehospital medical team, with real-time CPR feedback available. Immediately following endotracheal intubation, a flow sensor was connected to the endotracheal tube. Ventilations were performed manually by the treating physician. No real-time ventilation feedback was used.

Ethical approval for this study was obtained from the Ghent University Hospital institutional review board (reference EC/2008/025/AM02). Deferred consent was requested if the patient survived. Materials used in this study were partly funded by a Zoll Foundation research grant (reference number KW/2191/NKU/001/013).

Materials

A Sensirion SFM3200 bidirectional flow sensor for medical applications, controlled by a Microsoft Surface Go 2 tablet via a Sensirion SEK-SFM3XXX evaluation kit, was used. Full scale flow range of the sensor was −100–250 slm, manufacturer reported typical accuracy was 2% of the measured value, typical offset was 0.034 slm. The sensor was calibrated for use with oxygen. The update time of the sensor was 0.5 ms, the sample rate of the recording software was set to 5 ms.

A disposable filter separated the flow sensor from the endotracheal tube. An adult 1600 mL self-inflating bag was used to perform ventilations, the bag was inflated with 100% oxygen. Flow measurements started automatically after connecting the sensor. A Zoll X-series monitor-defibrillator was used, an accelerometer placed on the patient's chest provided chest compression data.

Analysis

In each patient, the first and last minute of flow measured following endotracheal intubation were analyzed. Net tidal volumes were defined as the integral of flow occurring during the inspiratory phase of ventilation. Inspiratory flow rates during cardiopulmonary resuscitation have been reported to range between 23 and 124 L/min.[5] Flow generated by chest compressions is typically limited.[9] The beginning of the inspiratory phase was defined as a positive flow exceeding 20 L/min. The beginning of the expiratory phase was defined as a flow less than −20 L/min.

Reversed airflow was defined as a negative flow occurring during the inspiratory phase of ventilation. Integral calculation was used to determine the volume of reversed airflow and the tidal volume delivered prior the occurrence of reversed airflow. Volumes exceeding 1 mL were reported, smaller volumes were below the resolution threshold of the sensor and were unlikely to be clinically relevant. The durations of the ventilatory cycle, inspiratory and expiratory phases were calculated. Results were reported as median and interquartile range.

Net tidal volume, proportion of ventilations with reversed airflow, duration of the ventilatory cycle, duration of the inspiratory and expiratory phase were compared between the first and last minute of flow measured. Net tidal volume, duration of the inspiratory phase of the current ventilation, duration of the previous ventilatory cycle and duration of the expiratory phase of the previous ventilation were compared between ventilations during which reversed airflow did and did not occur. A Chi-square test was used to compare proportions, the Chi-square statistic (X^2) was reported. To compare non-normal data, Mann-Whitney U-tests were used, the Z-statistic (Z) was reported.

Spearman correlation analysis was used to assess the relationship between chest compression parameters and the volume of reversed airflow, as well as between tidal volume delivered prior to reversed airflow and the volume of reversed airflow; the Spearman's correlation coefficient (r_s) was reported. A p-value less than 0.05 was considered statistically significant.

Demographic and treatment data were collected from the medical report.

Results

In this study, 25 patients were included, 20 were male. No patients were excluded from analysis. Median age was 64 years (IQR 57–75). Bystander CPR was performed in 14 patients. The initial rhythm was asystole in 9 patients, ventricular fibrillation in 9 patients and pulseless electrical activity in 7 patients. Median duration of CPR was 24 minutes (IQR 16–30). Median time between start of CPR and endotracheal intubation was 13 minutes (IQR 10–15). Return-of-spontaneous circulation was achieved in 6 patients (Table 1).

Median net tidal volume was 411 mL (IQR 309–537). Median duration of the ventilatory cycle was 3.3 sec (IQR 2.3–4.7). Median maximal inspiratory flow was 45 L/min (IQR 37–59), median maximal flow of reversed airflow was 4 L/min (IQR 3–6). Median chest compression depth was 5.6 cm (IQR 5.2–6), median chest compression rate was 120 compressions per minute (IQR 115–125).

A total of 682 ventilations were analyzed, the median number of ventilations analyzed per patient was 27 (IQR 20–34). Reversed air-

Table 1 – Summary of patient and treatment characteristics. Mean and standard deviation (SD) are reported for continuous data following a normal distribution, median and interquartile range (IQR) for non-normal continuous data, proportions for categorical data.

Age	63 years (SD = 14)
Duration of CPR	23 min (SD = 8)
Time between start of CPR and endotracheal intubation	13 min (IQR 10–15)
Witnessed arrest	12/25
Bystander CPR	14/25
ROSC	6/25
First monitored rhythm	
Asystole	9/25
Ventricular fibrillation	9/25
Pulseless electrical activity	7/25
Pathogenesis	
Medical	23/25
Drug overdose	2/25
Sex	
Male	20/25
Female	5/25

flow was observed in 23 patients, occurring 389 times during 270 ventilations (Fig. 1). In these patients, the median number of ventilations with reversed airflow was 10 (IQR 3–13), ranging from 1 to 36. During these ventilations, a median of 1 episode (IQR 1–2) of reversed airflow was observed, ranging from 1 to 4 episodes.

Median interval between the two periods of analysis was 7 minutes (IQR 4–10). Observed net tidal volume, volume of reversed airflow and duration of the different phases of the ventilatory cycle did not follow a normal distribution.

There was no statistically significant difference between net tidal volumes observed during the first (median 425 mL, IQR 318–520) and the second analyzed minute (median 404 mL, IQR 296–563), between the proportion of ventilations with reversed airflow during the first (142/367) and the second analyzed minute (128/315; $X^2 = 0.268$, $p = 0.605$) or between the duration of the ventilatory cycle during the first (median 3.2 seconds, IQR 2.4–4.4) and the second analyzed minute (median 3.4 seconds, IQR 2.5–5; $Z = -1.554$, $p = 0.120$).

In the first minute of analysis, the expiratory phase was significantly shorter (median 2.15 sec, IQR 1.4–3.1) compared to the second minute of analysis (median 2.3 sec, IQR 1.5–3.8, $Z = -2.283$, $p = 0.022$). No statistically significant difference between the duration of the inspiratory phase in the first (median 1 sec, IQR 0.8–1.3) and second minute of analysis (median 1 sec, IQR 0.8–1.3) was observed ($Z = -0.341$, $p = 0.733$).

Median volume of reversed airflow was 2 mL (IQR 1.4–7), ranging from 1 to 129 mL (Fig. 2). When reversed airflow occurred multiple times during a single ventilation, median cumulative volume of reversed airflow was 16.2 mL (IQR 5.6–37.5 mL). The net tidal volume of ventilations during which reversed airflow occurred (median 420 mL, IQR 315–549) was not significantly smaller than the net tidal volume of ventilations during which reversed airflow did not occur (median 406 mL, IQR 308–530; $Z = -0.627$, $p = 0.531$). Visualization of a single ventilatory cycle is provided in Fig. 3.

When reversed airflow occurred, duration of the inspiratory phase was significantly longer (median 1.2 sec, IQR 0.9–1.4), compared to when reversed airflow did not occur (median 0.9 sec, IQR 0.7–1.2; $Z = -7.468$, $p < 0.001$). There was no statistically significant difference in the duration of the expiratory phase of the preceding ventilation when reversed airflow did (median 2.1 sec, IQR 1.4–3.1) or did not occur (median 2.2 sec, IQR 1.4–3.5; $Z = -1.409$, $p = 0.159$) or in the duration of the preceding ventilatory cycle when reversed airflow did (median 3.4 sec, IQR 2.4–4.7) or did not occur (median 3.1, IQR 2.4–4.7; $Z = -0.853$, $p = 0.394$).

Univariate analysis showed a statistically significant, weak correlation between chest compression depth and volume of reversed airflow ($r_s(387) = 0.190$, $p < 0.001$). No statistically significant correlation between chest compression rate and volume of reversed airflow.

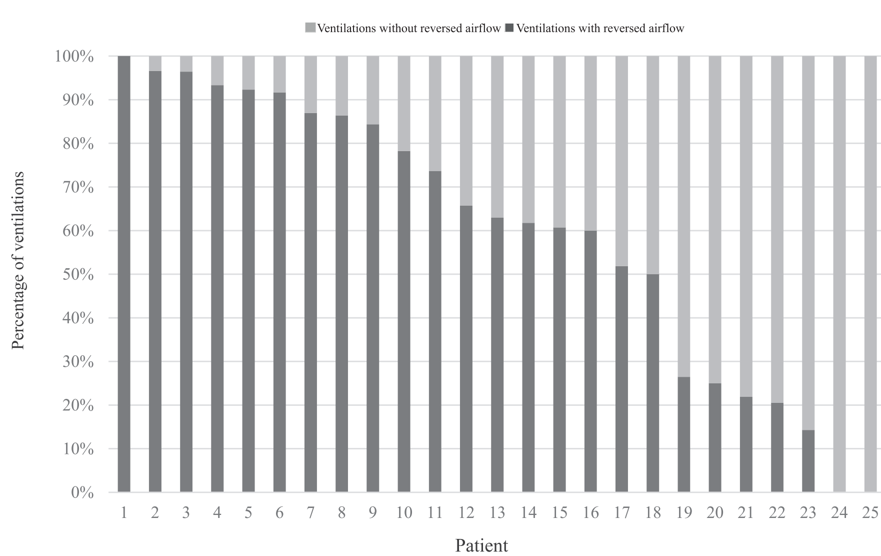

Fig. 1 – Stacked bar chart visualizing the proportion of ventilations during which reversed airflow occurred per patient.

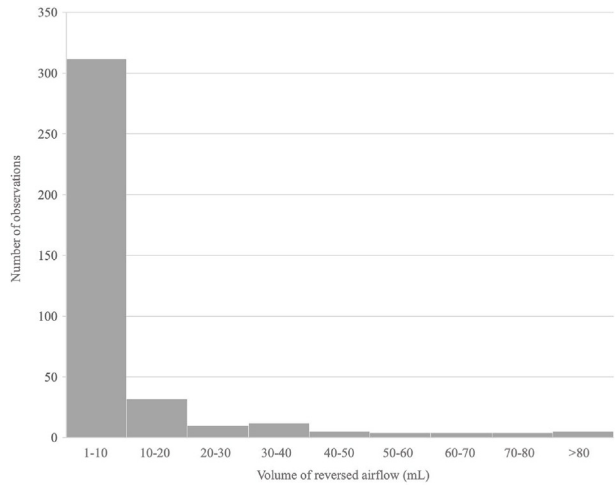

Fig. 2 – Histogram – observed volumes of reversed airflow.

($r_s(387) = -0.071$, $p = 0.159$) or between reversed airflow and already delivered tidal volume was found ($r_s(387) = -0.034$, $p = 0.500$).

Discussion

This study confirms reversed airflow to frequently occur during cardiopulmonary resuscitation. Compared to a previous study performed during prehospital treatment of out-of-hospital cardiac arrest, volumes of reversed airflow were smaller and showed less variation, which could be due to using a more accurate method of measuring flow in the current study.

Both studies showed a weak linear relation between chest compression depth and the volume of reversed airflow.[5] In the current study, no correlation between chest compression rate or the already delivered tidal volume and the volume of reversed airflow was found.

Observed volumes of reversed airflow were smaller than observations made in two previous cadaver studies.[3,6] In both studies, mechanical chest compressions and mechanical ventilations were used. Mechanical chest compressions have been suggested to exert a more forceful pressure on the thorax.[10] The effect of mechanical chest compressions and mechanical ventilation on reversed airflow needs further study.

Our results confirm previous findings of frequent hyperventilation during cardiopulmonary resuscitation, predominantly caused by excessive respiratory rates.[11] In the first minute following intubation, duration of the expiratory phase of ventilation was slightly shorter compared to the last minute of measurements. No difference in duration of the total ventilatory cycle, duration of the inspiratory phase or net tidal volumes was found between the two analyzed minutes. The use of ventilation feedback could aid in preventing excessive respiratory rates during manual ventilation.[12].

It was previously unclear if reversed airflow was associated with reduced net tidal volumes.[3] In the current study, there was no difference in net tidal volumes when reversed airflow did or did not occur. When reversed airflow occurred, the duration of the inspiratory phase was longer. Reversed airflow appears more likely to occur when inspiratory flow is delivered over a longer period.

Despite not being associated with smaller net tidal volumes, reversed airflow could affect the effectiveness of ventilation in other ways. When reversed airflow occurs, dead space ventilation is increased.[5] Volumes of reversed airflow were typically small, indicating the clinical relevance of this process is likely limited. Additionally, rapidly changing pulmonary pressures might promote small airway closure.[13] These pathophysiological processes were not evaluated in this study.

Other limitations existed in this study. The sensor used increased total airway resistance, possibly limiting airflow. During the design of the research device, care was taken to minimize added resistance. A convenience sample was used, patients were included at the physician's discretion, possibly introducing sampling bias. Measurements were performed following endotracheal intubation, in a relatively late stage following cardiac arrest. No formal assessment of possible

Fig. 3 – Single ventilatory cycle with one episode of reversed airflow. Volumes of inspiration and reversed airflow in bold.

leaks in the respiratory circuit was made. Due to the prehospital setting of this study, we were unable to analyze blood gases during cardiopulmonary resuscitation, which could have provided information on the effectiveness of ventilation.

Conclusion

Reversed airflow frequently occurs during cardiopulmonary resuscitation. Volumes of reversed airflow were small, showing a weak correlation with chest compression depth. The occurrence of reversed airflow was not associated with reduced net tidal volumes.

CRediT authorship contribution statement

Maxim Vanwulpen: Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation. **Ruben Cornelis:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Arthur Bouillon:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Saïd Hachimi-Idrissi:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author details

[a]*Department of Emergency Medicine, Ghent University Hospital, Corneel Heymanslaan 10, Ghent, Belgium* [b]*Faculty of Medicine and Health Sciences, Ghent University, Sint-Pietersnieuwstraat 25, Ghent, Belgium* [c]*Faculty of Medicine and Pharmacy, Vrije Universiteit Brussel, 1090 Brussels, Belgium*

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