Bedside lung ultrasound for monitoring the effectiveness of prehospital treatment with continuous positive airway pressure in acute decompensated heart failure

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Objective The aim of this pilot study was to determine the usefulness of prehospital lung ultrasound in monitoring the effectiveness of treatment with continuous positive airway pressure (CPAP) versus standard therapy in patients with acute decompensated heart failure (ADHF).

Materials and methods Twenty patients with ADHF were enrolled in this prospective, observational study. They were allocated randomly to a CPAP group (CPAP and standard therapy) or a control group (standard therapy only). Lung ultrasound was performed in each group and B-lines were counted and compared before and after treatment.

Results There were statistically significant differences before and after treatment in partial pressure of end-tidal carbon dioxide (29.9 ± 5.2 vs. 32.9 ± 5.5 mmHg, $P = 0.011$), respiratory rate (33.3 ± 9.3 vs. 26.6 ± 7.5 min^{-1}, $P = 0.013$), arterial oxygen saturation (82.0 ± 9.4 vs. 97.3 ± 1.3%, $P < 0.001$), and total number of B-lines (46.9 ± 14.8 vs. 29.0 ± 16.2, $P < 0.001$) in the CPAP group. There was a significant difference in required O_2 added to either therapy to obtain adequate saturation – 40% in the CPAP group versus 100% in the control group ($P < 0.001$). Percentage of positive ultrasound lung scans reduced in the middle axillary line and reached a statistically significant difference in the CPAP group [67 vs. 25% in medium right, $P = 0.017$; 91 vs. 55% in basal right (fourth intercostal space), $P = 0.038$; 83 vs. 33% in medium left, $P = 0.007$; and 92 vs. 58% in basal left (fourth intercostal space), $P = 0.039$].

Conclusion Bedside lung ultrasound is a reliable monitoring tool in a prehospital emergency setting and findings from lung ultrasound scans correspond with improved hemodynamic parameters in patients with ADHF treated with CPAP compared with standard therapy only. *European Journal of Emergency Medicine* 23:50–55 Copyright © 2016 Wolters Kluwer Health, Inc. All rights reserved.

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Introduction

Lung ultrasound as a part of point-of-care ultrasound and its images have their specific sonographic pattern of either 'true' images or sonographic artifacts [1,2], and these allow accurate diagnosis of pneumothorax [3], interstitial syndrome [4,5], pleural effusion, alveolar consolidation [6], and pulmonary embolism [7,8].

B-lines are one of the lung sonographic artifacts and their presence indicates interstitial syndrome of different causes such as pulmonary edema, interstitial pneumonia or pneumonitis, diffuse parenchymal lung disease (pulmonary fibrosis), pulmonary contusion, or infarction [9].

Lung ultrasound could also be used for monitoring the success of treatment in patients with interstitial syndrome [10] or in patients treated with positive end expiratory pressure (PEEP), showing reaeration of the lung [11]. Lung ultrasound is also a useful method for evaluation of real-time changes in the number of B-lines during dialysis [12].

Patients with shortness of breath because of acute decompensated heart failure (ADHF) are usually found in the emergency prehospital setting. Standard treatment of those patients includes morphine, loop diuretics, nitroglycerin, and oxygen. Recent articles have shown that prehospital continuous positive airway pressure (CPAP) ventilation in these patients is feasible and safe [13]. Furthermore, CPAP improves hemodynamic parameters [14–16] and can also reduce the mortality and intubation rate [16].

The aim of this single-center prospective pilot study was to determine the usefulness of prehospital bedside lung ultrasound in monitoring the effectiveness of treatment with CPAP versus standard therapy in patients with ADHF.

Materials and methods

Statement of human rights

The pilot study was approved by the National Medical Ethics Committee of the Republic of Slovenia, which

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decided that the study could be carried out with informed consent from participants.

Study design

A small, prospective, observational, randomized pilot study was carried out in the prehospital emergency setting (Center for Emergency Medicine Maribor, Slovenia, Europe) between December 2011 and February 2014. The Center for Emergency Medicine in Maribor hosts the Maribor Emergency Medical Service system, which also includes two emergency physician-led advanced life support teams working in an ambulance or at the prehospital emergency medical center. After prehospital care, all patients were admitted (for clinical reasons) to the University Clinical Center Maribor and followed until discharge.

Inclusion criteria for the study were severe dyspnea or shortness of breath as a primary complaint, presumed clinical diagnosis of ADHF with value of modified Boston criteria for heart failure of 8 or more. Subsequently, patients in whom ADHF was not confirmed by an internist at the hospital were excluded (two patients from the CPAP group were excluded, one because of acute respiratory distress syndrome and the other because of pneumonia).

The modified Boston criteria was designed according to the Boston criteria and the Framingham criteria for heart failure and have been explained in our previous studies [17,18]. Exclusion criteria were age below 18 years, uncontrolled agitation, angina, ST elevation in the ECG, emesis, aspiration, cardiogenic shock, life-threatening arrhythmias, altered mental status, trauma, other causes of dyspnea, comprising pneumonia, pulmonary embolism, carcinoma, pneumothorax, intoxication (drugs), anaphylactic reactions, and upper airway obstruction.

After enrollment in the study, patients were placed in a semirecumbent position and received an intravenous access and were assigned randomly to either additional ventilatory support (CPAP group) or standard therapy only (control group). All patients were treated with standard drugs for acute heart failure and the control group received 100% oxygen through a facemask. For CPAP ventilation support, the InterFlow CPAP generator with a Twin-port CPAP facemask (both Intersurgical Ltd, Berkshire, UK) was used. The PEEP valve was selected by the emergency physician according to patients' condition and tolerance. If arterial oxygen saturation after initiation of CPAP was less than 94%, oxygen was added to reach the target value. The treatment time was defined as the time of the beginning of the CPAP/standard treatment in an ambulance or in the observatory room of the prehospital emergency medical center to the time just before the admission to the hospital. Ultrasound lung exam was performed before starting treatment and just before admission to the hospital.

The sonographic examination, consisting of 15 intercostal spaces, was performed by a certified WINFOCUS (World Interactive Network Focused On Critical Ultrasound) lung ultrasound provider or under his supervision using a micro convex C60 × 2–5 MHz probe (Sonosite M Turbo ultrasound machine; SonoSite, Bothell, Washington, USA). The chest wall was divided into 15 regions (four anterior and four lateral on the right side and three anterior and four lateral on the left side), for each of which one scan was obtained. On both sides of the chest wall, an ultrasound scan was performed in the midclavicular – anterior region and in the middle axillary line – lateral region [second (superior), third (medium), fourth and fifth (basal) intercostal space], except for the fifth intercostal space in the midclavicular line on the left side of the chest wall because of cardiac interposition. The sonographic signs that were analyzed were the B-lines. B-lines are defined as discrete laser-like, vertical, hyperechoic reverberation artifacts that arise from the pleural line, extend to the bottom of the screen without fading, and move synchronously with lung sliding [9]. In each rib space, the number of B-lines was counted or if confluent, the percentage of the rib space occupied by B-lines was divided by 10 [9]. The sum of B-lines yielded a score indicating the extent of extravascular water. B-lines were counted before and after treatment (at hospital admission).

A positive region was defined by the presence of three or more B-lines in a longitudinal plane between two ribs. A sonographic score was then calculated by simply counting the number of positive scans obtained in each patient before and after treatment.

Measurements

Amino terminal probrain natriuretic peptide (NT-proBNP): During the initial evaluation (before application of medicines), a 5 ml sample of blood was collected into a tube containing calcium disodium edetate for blinded measurements of NT-proBNP. The level of NT-proBNP was measured using a Cardiac Reader (Roche Diagnostics, Mannheim, Germany) and recorded.

Partial pressure of end-tidal carbon dioxide ($PetCO_2$): $PetCO_2$ was obtained by Lifepak 15 (Medtronic Physiocontrol, Corporate Headquarters, Redmond, Washington, USA); an average $PetCO_2$ value of the first three measurements (through nasal cannula) in the first minute (before and after treatment) was registered.

Statistical analysis

SigmaPlot 11.0 (Systat Software, Richmond, California, USA) was used for the statistical analysis. Student's *t*-test was used to compare differences between the two treatment groups. A paired *t*-test was used to compare the effects of treatment within each treatment group. The data were presented as mean ± SD. A two-tailed value of *P*-value less than 0.05 was considered significant.

Results

There were no significant differences between groups at baseline (Table 1).

The maximum PEEP tolerated by the patient in the CPAP group was 5 cmH_2O in 11 out of 12 patients; only one tolerated 7.5 cmH_2O.

There were statistically significant differences in $PetCO_2$, respiratory rate, arterial oxygen saturation, and total numbers of B-lines before and after treatment in the CPAP group. Only arterial oxygen saturation reached statistical significance in the control group (Table 2).

There was a significant difference in the fraction of required O_2 added to either therapy to obtain adequate arterial oxygen saturation (>94%) – 40% in the CPAP group versus 100% in the control group ($P<0.001$).

The number of positive ultrasound lung scans first decreased in the middle axillary line on both sides and reached a statistically significant difference in the CPAP group. The difference in the number of positive lung scans in the control group did not reach statistical significance (Table 3).

All patients in the CPAP group had a negative percentage change in their total number of B-lines with time (Fig. 1) compared with the control group, in whom this effect was not observed (Fig. 2).

There was no difference in the length of hospital stay between the two groups (13 ± 13 days in the CPAP group vs. 7 ± 4 days in the control group, $P=0.269$) or in survival to hospital discharge (58% in the CPAP group vs. 75% in the control group, $P=0.471$).

Table 1 Baseline characteristics

	CPAP group ($n=12$)	Control group ($n=8$)	P-value
Age (years)	80.6 ± 7.4	82.0 ± 9.1	0.707
Male sex [n (%)]	6 (50)	2 (25)	0.288
$PetCO_2$ (mmHg)	29.9 ± 5.2	33.9 ± 8.9	0.225
NT-proBNP (pg/ml)	5468.5 ± 3175.7	5655.0 ± 3503.3	0.903
MAP (mmHg)	109.2 ± 17.1	98.4 ± 35.7	0.375
SaO_2 (%)	82 ± 9.4	84.1 ± 10.1	0.635
Respiratory rate (min^{-1})	33.3 ± 9.3	29.1 ± 8.1	0.320
Heart rate (min^{-1})	103.6 ± 15.6	98.0 ± 24.2	0.537
Total number of B-lines	46.9 ± 14.8	42.4 ± 17.0	0.533
Treatment time (min)	45.3 ± 14.5	40.6 ± 9.8	0.441
Time needed for ultrasound lung scan (total) (min)	12.8 ± 5.8	11.1 ± 4.4	0.487
Drugs			
Furosemide (mg)	34.5 ± 9.3	31.4 ± 10.7	0.523
Morphine (mg)	3.7 ± 2.1	4.0 ± 1.4	0.632
Nitrates (µg)	1.1 ± 0.6	1.6 ± 0.0	0.329

Values are represented as mean ± SD.
CPAP, continuous positive airway pressure; MAP, mean arterial pressure; NT-proBNP, amino terminal probrain natriuretic peptide; $PetCO_2$, partial pressure of end-tidal carbon dioxide; SaO_2, arterial oxygen saturation.

Discussion

Lung ultrasound was used to monitor the effectiveness of treatment with CPAP in patients with ADHF. We found a significant reduction in the total number of B-lines in ADHF patients receiving ventilatory support with CPAP compared with standard therapy only. Our findings are similar to those of Noble and colleagues, who counted the number of B-lines before, at midpoint, and after dialysis in 28 lung zones and found statistically significant reductions in the number of B-lines from predialysis to the midpoint scan and from the predialysis to the post-dialysis scan. They concluded that in hemodialysis patients, B-lines resolution appears to occur real time as fluid is removed from the body and that thoracic ultrasound is a useful method for the evaluation of real-time changes in extravascular lung water [12]. Furthermore, Volpicelli and colleagues showed that the B-line pattern mostly clears after adequate medical treatment of ADHF and represents an easy-to-use alternative bedside diagnostic tool for clinical monitoring of pulmonary congestion in patients with ADHF. They measured the number of B-lines in patients with ADHF in 11 lung zones and found a correlation between the sonographic score with radiologic and clinical scores [10]. In addition, Liteplo and colleagues described a case report of a patient with pulmonary edema treated with CPAP. They reported that B-lines disappear after 3.5 h after initiation of CPAP and suggest that lung ultrasound could be used to diagnose and monitor the response to treatment in real time [19]. Our findings are similar to those of the abovementioned studies. We found a significant reduction in the number of B-lines after 45 min (on average) of treatment with CPAP. However, we did not find a significant reduction in the number of B-lines in the control group. In some patients, we even found an increased number of B-lines, indicating that pulmonary congestion was still evolving and that standard therapy has not been successful as yet. In the present study, B-lines were counted in 15 lung zones as a compromise because measurements in 28 lung zones would be too time-consuming.

In previous studies, the number of sonographic B-lines correlated well with the radiologic estimate of extravascular lung water [20] and NT-proBNP values [21]. The number of B-lines may also indicate the level of wedge pressure [4], but with many limitations [22]. In patients with cardiogenic pulmonary edema, evaluation of B-lines and a change (decrease) in their number enables a noninvasive monitoring of response to therapy [9]. Reductions of B-lines in our study correspond with improved hemodynamic parameters in ADHF patients treated with CPAP. We found a significant reduction in the respiratory rate, improved percutaneous arterial oxygen saturation, and higher values of $PetCO_2$. $PetCO_2$ is a very reliable hemodynamic parameter used as a noninvasive monitor for the evaluation of therapeutic efforts

Table 2 Outcomes

	CPAP group ($n=12$)			Control group ($n=8$)		
	Before treatment	After treatment	*P*-value	Before treatment	After treatment	*P*-value
$PetCO_2$ (mmHg)	29.9 ± 5.2	32.9 ± 5.5	0.011	33.9 ± 8.9	32.8 ± 7.0	0.411
MAP (mmHg)	109.2 ± 17.1	99.7 ± 23.2	0.183	98.4 ± 35.7	93.5 ± 30.3	0.477
SaO_2 (%)	82.0 ± 9.4	97.3 ± 1.3	< 0.001	84.1 ± 10.1	97.1 ± 2.2	0.007
Respiratory rate (min^{-1})	33.3 ± 9.3	26.6 ± 7.5	0.013	29.1 ± 8.1	29.0 ± 6.8	0.905
Heart rate (min^{-1})	103.6 ± 15.6	95.2 ± 18.6	0.053	98.0 ± 24.2	93.1 ± 20.3	0.208
Total number of B-lines	46.9 ± 14.8	29.0 ± 16.2	< 0.001	42.4 ± 17.0	43.3 ± 19.8	0.667

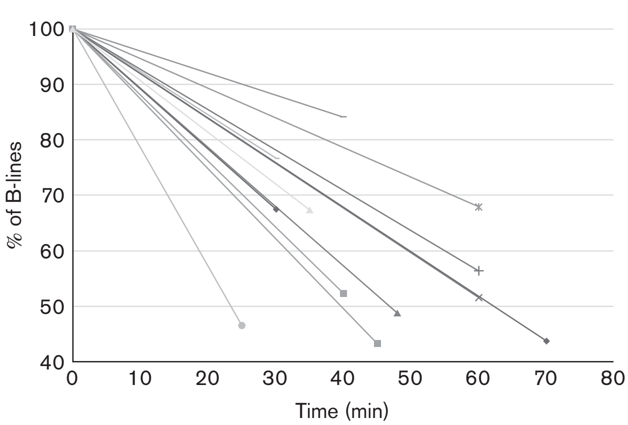
Values are represented as mean ± SD.
CPAP, continuous positive airway pressure; MAP, mean arterial pressure; $PetCO_2$, partial pressure of end-tidal carbon dioxide; SaO_2, arterial oxygen saturation.

Table 3 Percentage of positive ultrasound lung scans before and after treatment in each treatment group

	CPAP group ($n=12$)			Control group ($n=8$)		
Ultrasound scan region	Before treatment	After treatment	*P*-value	Before treatment	After treatment	*P*-value
Anterior superior right	42	25	0.166	38	50	0.351
Anterior medium right	67	50	0.166	38	38	1.000
Anterior basal right (fourth intercostal space)	75	50	0.082	75	75	1.000
Anterior basal right (fifth intercostal space)	63 (8)	50 (8)	0.351	86 (7)	86 (7)	1.000
Lateral superior right	50	17	0.039	50	50	1.000
Lateral medium right	67	25	0.017	75	75	1.000
Lateral basal right (fourth intercostal space)	91 (11)	55 (11)	0.038	100	100	1.000
Lateral basal right (fifth intercostal space)	100 (10)	60 (10)	0.037	100 (7)	100 (7)	1.000
Anterior superior left	58	42	0.339	25	25	1.000
Anterior medium left	58	33	0.082	38	50	0.351
Anterior basal left	67	50	0.166	80 (5)	80 (5)	1.000
Lateral superior left	50	25	0.082	38	50	0.351
Lateral medium left	83	33	0.007	100	100	1.000
Lateral basal left (fourth intercostal space)	92	58	0.039	100	100	1.000
Lateral basal left (fifth intercostal space)	100 (8)	63 (8)	0.080	100 (6)	100 (6)	1.000

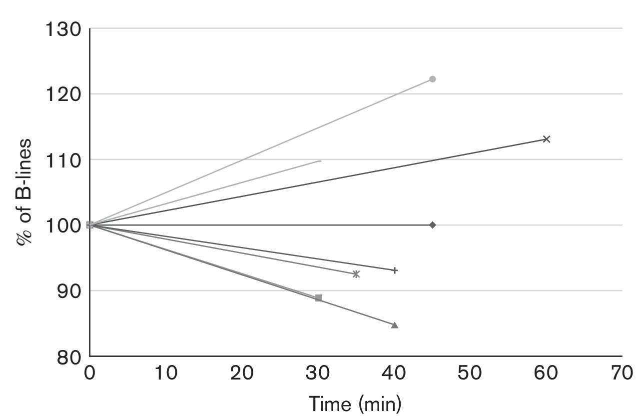
Values are represented as percentages. Numbers in parentheses indicate the number of available data if they differ from the sample size.
CPAP, continuous positive airway pressure.

Fig. 1



CPAP group B-line score: Change in percentage of B-lines over time in the CPAP group. Numbers of B-lines at the beginning and end of treatment are presented as percentages of the initial number. Each line represents measurements in an individual patient. CPAP, continuous positive airway pressure.

Fig. 2



Control group B-line score: Change in percentage of B-lines over time in the control group. Numbers of B-lines at the beginning and end of treatment are presented as percentages of the initial number. Each line represents measurements in an individual patient.

in the prehospital environment in various clinical settings [23,24]. Findings from our study are similar to those of other studies of prehospital CPAP usage [14–16,25,26]. CPAP improves lung mechanics (pulmonary compliance) and thus reduces the work of breathing [27] and improves oxygenation by recruiting atelectatic alveoli and by decreasing intrapulmonary shunt [28]. Increased airway pressure causes a pressure gradient that forces alveolar and interstitial fluid back into capillaries, improving gas exchange over the membrane [19]. Positive airway pressure reduces venous return to both the left and the right ventricle and this reduction in preload improves cardiac function [29]. Positive airway pressure is also transmitted to the left ventricle, reducing transmural pressure and thereby enhancing left ventricular performance [30].

There are some controversies on the impact of CPAP on survival and mortality. Some report a trend toward reduced mortality [16,31,32]. In the present study, the overall mortality and hospital length of stay were equally distributed between the compared groups. Some trials came to the same conclusion [33]. Results from mortality and hospital length of stay from the present study should be interpreted with caution because of the small sample size and the fact that the most critically ill patients were excluded from the study.

Many CPAP devices in prehospital settings are oxygen driven and deliver a high concentration of supplemental inspired oxygen (Boussignac CPAP system; Vygon, Wiltshire, UK). To avoid hyperoxia, CPAP using a low fractional concentration of inspired oxygen (FiO_2 28–35%) was highly effective in the treatment of prehospital respiratory emergencies [16,25]. In our study, ADHF patients treated with CPAP also needed significantly lower average FiO_2 (40%) to obtain adequate arterial oxygen saturation (>94%).

The total average time (before and after treatment) for lung ultrasound scan was longer (≈12 min) compared with other studies (<3 min) [10,20]. The reason for this is that some of the lung ultrasound scans were performed by trainees under a trainer's supervision as part of their lung ultrasound training and consequently more time was needed to complete the lung ultrasound scan. The authors do agree that the lung ultrasound scan is a quick and easy to comprehend method [34].

Our pilot study has several limitations. First, the same sonographer performed both scans (before and after treatment) and thus he was not blinded to the results of the initial lung ultrasound scan. Second, our sonographers were not blinded as to whether a patient had been treated with CPAP or standard therapy only. Third, our sample size was small and patients enrolled in the study were not selected consecutively and this could include some biases. The limitations of our study are mainly because of the fact that only one emergency physician works at a time and only two of all of the emergency physicians who work in our prehospital emergency medical service are certified lung ultrasound providers.

Conclusion

Our small pilot study suggests that lung ultrasound is a reliable tool to monitor response to prehospital treatment with CPAP in patients with ADHF, showing a significant decrease in the total number of B-lines resolving in real time. These findings from lung ultrasound scans correspond with improved hemodynamic parameters with CPAP treatment in ADHF. Because of the several limitations of the present pilot study, further randomized and blinded studies with a larger number of patients are needed to validate these findings.

Acknowledgements

Conflicts of interest

There are no conflicts of interest.

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