Submitted: 20 July, 2024 Accepted: 25 September, 2024 Published: 08 March, 2025 DOI:10.22514/sv.2025.030

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ORIGINAL RESEARCH

Guidelines-recommended tidal volumes are not achieved during continuous mechanical chest compressions—results from a laboratory study

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Abstract

Background: With the continuous chest compressions during cardiac arrest, the pressure in the chest cavity increases. This limits the achievement of tidal volumes as recommended by the guidelines. We aimed to determine the tidal volumes, peak airway pressures and static lung compliance achieved during continuous chest compressions using two different commonly used mechanical devices (Lucas® device and Autopulse® device). **Methods**: The resuscitation manikin was endotracheally intubated. Mechanical ventilation was performed using a ventilator with the following settings: controlled mechanical ventilation (CMV) mode,inspiratory rate 10 per minute, tidal volume (Vt) 500 mL, inspiratory expiratory time ratio (I:E) 1:5, fraction inspired oxygen (FiO_2) 100%, positive end expiratory pressure (PEEP) 0. Lucas® device was used in continuous operation mode and Vt, Peak airway pressure, and static lung compliance (Cstat) were measured during mechanical ventilation for 4 minutes. The same procedure was repeated with the Autopulse® device. Lucas® performs chest compressions on sternum and active decompression. Autopulse® not only compresses the sternum, but also around the chest, and the decompression is passive. **Results**: The parameters (Vtinsp, Cstat) of 41 breaths were measured during the 4 minutes of simulated continuous chest compressions. When using the Lucas® device, an average tidal volume of 364 mL was achieved, with an average Cstat of 43.6 mL/cmH_2O. When using the Autopulse device, an average tidal volume of 240 mL was achieved, while the average Cstat was 29.6 mL/cmH_2O. Statistically significant higher tidal volumes were achieved when using the Lucas® device compared to the Auropulse®. **Conclusions**: Tidal volumes achieved during continuous chest compressions using two devices (Lucas® and Autopulse®) are significantly lower compared to guidelines-recommended tidal volumes, with lower volumes, higher peak airway pressures and higher static compliance measured when using the Autopulse device. Additional meassures should be utilised to assess the effectiveness of ventilations during mechanical chest compressions for cardiac arrest.

Keywords

Resuscitation; Continuous mechanical chest compression; Tidal volume

1. Introduction

Current European Resuscitation Council guidelines recommend 30:2 synchronization between chest compressions and artificial ventilation before intubation, and asynchronous ventilation during chest compressions when the patient is intubated [1].

The Lucas3® device (Stryker Way Portage, Michigan, MI 49002 USA) has a piston mounted on a frame that can be placed above the patient's chest. The piston is driven up and down by a power source such as compressed air or oxygen, thereby functioning similar to manual chest compressions and releases. The device originally functioned not only as a device for mechanical chest compressions, but also for active chest decompression because of cup-like pliable material on the piston designed to facilitate active decompression during the release phase of chest compression. Halperin and associates' new concept of the mechanism of blood flow during chest compressions for cardiac arrest led them to develop the Autopulse® device (ZOLL Medical Corporation, medical equipment, Chelmsford, MA, USA), a mechanical device for cardiopulmonary resuscitation that not only compresses the chest but also increases the intrathoracic pressure, the so-called thoracic pump theory [2].

Passive tidal volumes resulting from chest compressions and decompressions during resuscitation, are not sufficient to establish alveolar ventilation and gas exchange [3]. The

compression phase results in an increase in intrathoracic pressure above 45 cmH_2O, which limits the achievement of adequate tidal volumes [4]. As a result of chest compressions, the intrapleural pressure also increases to 25–40 mmHg [5]. Intrapleural pressure is different from intrathoracic pressure. The thoracic cavity is the space that includes the pleura, lungs and heart, while the pleural space is only the space between the parietal pleura and visceral pleura surrounding lungs. Intrapleural pressure depends on the ventilation phase, atmospheric pressure, and the volume of the intrapleural cavity. Reduction of respiratory volumes due to chest compressions plays an important role in ventilation and gas exchange disorders and is associated with worse outcomes [6]. Patients who received effective ventilation due to pauses between compressions for more than 50% of the duration of resuscitation had a significantly higher percentage of recovery of spontaneous cardiac action, better survival and better neurological outcome after resuscitation [7]. Guidelines recommended ventilation settings are 500 mL (around 8 mL/kg ideal body weight), PEEP set to 0, FiO_2 100%, respiratory rate 10 breaths per minute, maximum inspiratory pressure ("peak pressure") 60 cmH_2O, the inhalation trigger ("trigger") set to 0 and the inspiratory to expiratory ratio (I:E ratio) 1 to 5 [4]. There is a lack of evidence on the interaction between the continuous performance of chest compressions with devices and the achievement of tidal volumes.

In our laboratory research, we aimed to determine the differences in parameters of mechanical ventilation during chest compressions with two devices; a mechanical device for performing chest compressions with active decompression, compared to a mechanical device without active decompression.

2. Materials and methods

We used a quantitative methodological approach in the research. A descriptive causal experimental research method was used, the experiment was conducted in a controlled simulation laboratory environment.

2.1 Description of experiment

We used the high-performance Laerdal Resusci Anne Advanced SkillTrainer® manikin with the SimPad Plus LLEAP® computer simulator to perform artificial ventilation and install mechanical chest compressions. The manikin has a closed system that simulates the human respiratory system. The lungs are made of plastic elastic materials, and the compliance of the lungs is ensured by a special ring. The manikin is intended for advanced life support training. A Portex® endotracheal tube (ICU Medical inc. Products, medical equipment, 951 Calle Amanecer, San Clemente, Canada) was used to establish airway. We used a Tracoe® device (Tracoe cuff pressure monitor, Tracoe medical GmbH, medical equipment, Nieder-Olm, RP, Germany) to check the cuff pressure at the beginning of artificial ventilation. We used a Hamilton G5® ventilator for artificial respiration. We used the Lucas3® device (Stryker Way Portage, MI 49002 USA) for mechanical chest compressions with active decompression. For mechanical chest compressions without active decompression the Autopulse® device (ZOLL Medical Corporation, medical equipment, Chelmsford, MA, USA) was used. We used the manufacturer's instructions when installing the Autopulse® device (ZOLL Medical Corporation, medical equipment, Chelmsford, MA, USA) and Lucas3® device (Stryker Way Portage, MI 49002 USA).

2.2 Measuring instruments

Tidal volume, peak inspiratory pressure and lung static compliance were measured instrumentally, with the use of a flow sensor, which is an integral part of the breathing system of the Hamilton G5® ventilator. The flow sensor (flow sensor Hamilton®) is part of the coaxial breathing system, it allows measurement of flow, pressure and volume during controlled ventilation, gas flow in the range from 0 to 180 L/min and dead space is less than 11 mL. The resistance is accurate to within than 0.027 cmH_2O/L/min, measured at a flow rate of 180 L/min. Flow sensor also continuously measures tidal volume leakage. The weight of the sensor is 14 g. The accuracy of the measurement after calibration is less than 10% of the actual value. The sensor's operating temperature range is from −20 °C to + 50 °C. The cuff pressure will be measured using an analog scale on the Tracoe® meter. The device enables cuff pressure measurements in the range from 0 to 100 mmHg. The accuracy of the measurement is +/− 2 mmHg.

2.3 Experiment procedure

We used a high-performance manikin, which was first endotracheally intubated through the mouth with a tube with an internal diameter of 8.5 with the help of direct laryngoscopy to the depth of 21 cm at the right corner of the mouth. Cuff pressure was adjusted to 25 cmH_2O and the tube was secured with Intersurgical® tape (Intersurgical complete respiratory systems, Crane House, Molly Millars Lane Wokingham, Berkshire United Kingdom). A Hamilton G5® ventilator (Hamilton Medical, Inc., Reno, NV, USA) was used for controlled ventilation. We used the original Hamilton® breathing system, *i.e.*, coaxial breathing system with flow sensor. Before use, we calibrated the device according to the manufacturer's instructions. We chose volume-controlled artificial ventilation with the CMV® mode. We set the following parameters: respiratory volume (Vt) 500 mL, breathing frequency 10 times/min, maximum inspiratory pressure 60 cmH_2O, positive end-expiratory pressure (PEEP) 0 cmH_2O, trigger 0, oxygen concentration in the inhaled gas mixture 100% and the ratio of inspiration to expiration (I:E ratio) 1:5. A Lucas® chest compression system (Lucas3 Chest compression system, Physio control, Medical equipment, Portage, MI, USA) was installed on the mannequin. When installing, we followed the manufacturer's instructions. The initial position was marked on the chest with the outline of a bell. In the operating mode, we chose asynchronous mode. Controlled breathing and Lucas® operation were performed for 4 minutes. We recorded the experiment and observed the contact between the piston and the manikin.

Then, a mechanical device for performing chest compressions Autopulse® (Autopulse Resuscitation System, model 100, ZOLL Medical Corporation, Medical equipment, Chelmsford, MA, USA) was installed on the mannequin.

When installing, we followed the manufacturer's instructions. The initial position of the chest strap was marked by its outline on the chest. In the operating mode, we chose asynchronous mode. Controlled breathing and Autopulse® operation were performed for 4 minutes.

2.4 Statistical methods

We used the IBM SPSS Statistics program, version 27.0 (SPSS Inc., Chicago, IL, USA, 2021) for computer data processing. Numerical variables were analyzed using descriptive statistics, where maximum and minimum values, mean value, average, standard deviation, asymmetry, and flatness were presented. The distribution of values was also shown with histograms. The normal distribution was evaluated as a comparison between the coefficient of asymmetry and flattening if the latter is equal to 0. Comparison of the frequency of occurrence of the studied variable on the sample data (empirical frequency), with the frequency of occurrence of the normal distribution of the variable with the same arithmetic mean and standard deviation of the studied empirical distribution, we checked with the Kolmogorov Smirnov test. Based on the data on the uneven distribution of values, we used the Mann Whitney test for further analysis.

3. Results

3.1 Measurement results when using Lucas®

During resuscitation of 4 minutes and 41 breaths with continuous operation of the Lucas® device, we achieved an average tidal volume of 364 mL (SD (standard deviation) 9.589), the average value of static lung compliance was 43.6 mL/cmH_2O (SD 0.45), and the average maximal inspiratory pressure was 16 cmH_2O (SD 0.00). The flow sensor did not detect air leakage. The data are shown in Table 1.

3.2 Measurement results when using Autopulse®

During resuscitation for 4 minutes and 41 breaths with continuous operation of the Autopulse device, we achieved an average respiratory volume of 240.8 mL (SD 88.867), the average value of static compliance of the lungs was 29.6 mL/cmH_2O (SD 38.7), the average maximum inspiratory pressure and 43.6 cmH_2O (SD 2.376). The flow sensor did not detect air leakage. The data are shown in Table 2.

3.3 Kolmogorov Smirov test to determine the uniformity of the distribution of the measured values of inspiratory tidal volume

The Kolmogorov Smirnov test was used to test the normal distribution of the results of tidal volume measurements when using the Lucas® and Autopulse® devices. We found that the variables are unevenly distributed ($p < 0.001$) both in the group of measurements when using Lucas® and when using Autopulse®. The data are shown in Table 3 and Figs. 1,2.

3.4 Mann Whitney test to comparison of the achievement of tidal volumes when using the Lucas® and Autopulse® device

The Mann Whitney test was used to analyze the comparison of the equality of the average ranks of respiratory volumes when using Lucas® and Autopulse®. We found that the two mean ranks differ from each other (62 *vs*. 21). They are statistically significant differences between achieving tidal volumes when using Lucas® and Autopulsa® ($U = 0.000$ and $p < 0.001$). The data are shown in Table 4.

3.5 Comparison of values of inspiratory volume, static lung compliance and maximal inspiratory pressure when using Lucas® and Autopulse®

We compared values of tidal volume, static lung compliance and maximum inspiratory pressure when using the Lucas® and Autopulse® devices during chest compressions. The data are shown in Table 5. The use of the Lucas® device was associated with higher tidal volumes compared to the Autopulse® device, and the use of Lucas® device was associated with lower maximal inspiratory pressures. Static compliance of the lungs was higher when using the Lucas® device compared to the Autopulse® device, but it should be emphasized that the lung model on the manikin used does not completely imitate the real condition of the patient's lungs.

4. Discussion

The interaction between artificial ventilation and compressions is complex. Increasing tidal volume or respiratory rate during resuscitation increases intrathoracic pressure and decreases venous blood flow to the right heart, increases pulmonary vascular resistance, decreases cardiac output, and decreases blood flow through the coronary arteries, and decreases aortic

TABLE 1. Descriptive statistics measurements of respiratory volume, lung compliance and maximal respiratory pressure when using the Lucas® device.

Descriptive Statistics					
	N	Minimum	Maximum	Mean	Std. Deviation
Peak pressure	41	16	16	16.00	0.000
Tidal volume	41	334	373	364.27	9.589
Compliance lung static	40	42.1	44.2	43.609	0.451
Valid N (listwise)	40				

N: number; Std. Deviation: standard deviation.

TABLE 2. Results of measurements of respiratory volume, lung compliance and maximum respiratory pressure when using the Autopulse® device.

Descriptive Statistics					
	N	Minimum	Maximum	Mean	Std. Deviation
Peak pressure	41	40	47	43.610	2.376
Tidal volume	41	128	397	240.800	88.867
Compliance lung static	41	4.0	115.0	29.644	38.754
Valid N (listwise)	41				

N: number; Std. Deviation: standard deviation.

TABLE 3. Kolmogorov Smirnov test for determining the uniformity of the distribution of tidal volume values when using the Lucas® and Autopulse® devices.

One-Sample Kolmogorov Smirnov Test			
		Tidal volume Autopulse®	Tidal volume Lucas®
N		41	41
Normal Parameters[a,b]			
	Mean	240.80	364.27
	Std. Deviation	88.867	9.589
lMost Extreme Differences			
	Absolute	0.280	0.384
	Positive	0.280	0.202
	Negative	−0.176	−0.384
Test Statistic		0.280	0.384
Asymp. Sig. (2-tailed)		<0.001[c]	<0.001[c]

a: Test distribution is Normal; b: Calculated from data; c: Lilliefors Significance Correction. Std. Deviation: standard deviation; Asymp. Sig.: asymptotic significance.

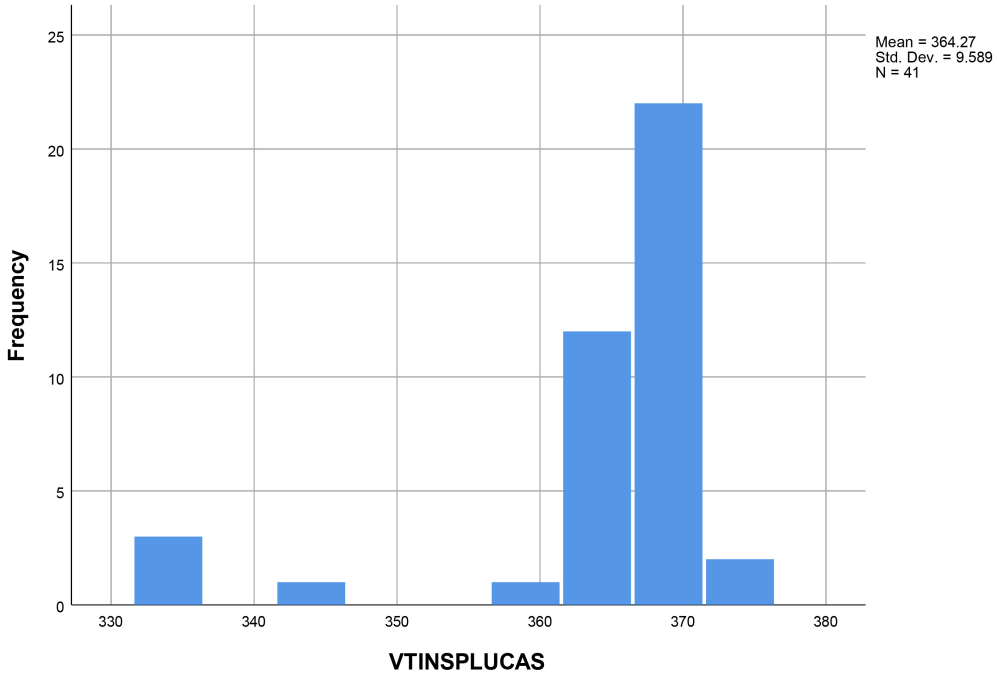

FIGURE 1. Histogram of the distribution of tidal volume values when using Lucas®. N: number; Std. Dev.: standard deviation.

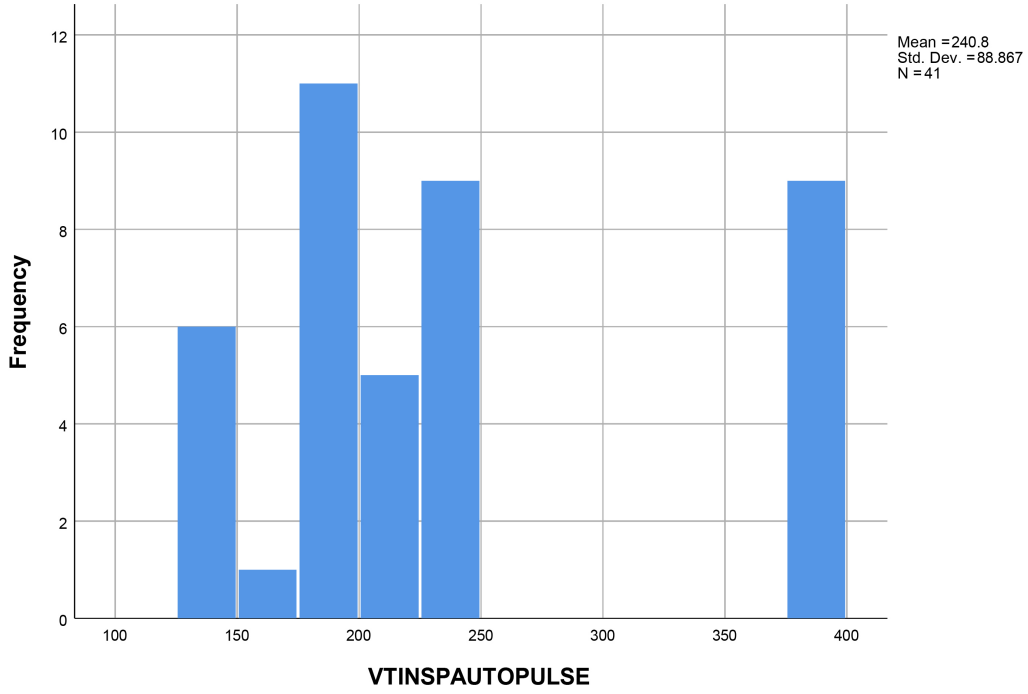

FIGURE 2. Histogram of the distribution of tidal volume values when using Autopulse®. N: number; Std. Dev.: standard deviation.

TABLE 4. Mann Whitney test of equality of mean ranks of tidal volume values when using Lucas and Autopulse.

Ranks			
Ventilacija	N	Mean Rank	Sum of Ranks
Tidal volume			
Lucas®	41	62.00	2542.00
Autopulse®	41	21.00	861.00
Total	82		
Test Statistics[a]			
		Tidal volume	
Mann-Whitney U		0.000	
Wilcoxon W		861.000	
Z		−7.839	
Asymp. Sig. (2-tailed)		<0.001	

a: Grouping Variable: tidal volume. N: number; Asymp. Sig.: asymptotic significance.

TABLE 5. Comparison of values of inspiratory volume, static lung compliance and maximal inspiratorypressure when using Lucas and Autopulse.

Descriptive Statistics					
	N	Minimum	Maximum	Mean	Std. Deviation
Peak pressure Autopulse®	41	40	47	43.61	2.376
Tidal volume Autopulse®	41	128	397	240.80	88.867
Compliance static Autopulse®	41	4.0	115.0	29.644	38.7541
Tidal volume Lucas®	41	334	373	364.27	9.589
Compliance static Lucas®	40	42.1	44.2	43.607	0.451
Peak pressure Lucas®	41	16	16	16.00	0.000
Valid N (listwise)	40				

N: number; Std. Deviation: standard deviation.

pressure 8. Two undesirable effects on artificial ventilation occur during chest compressions. With an unprotected airway, higher intrathoracic pressures increase the risk of regurgitation of gastric contents and the possibility of esophageal or stomach rupture. Chest compressions without artificial ventilation can reach up to 156 mL of tidal volume in endotracheally intubated patients, but tidal volumes are significantly lower or undetectable in non-intubated patients. When using mechanical devices to perform chest compressions without artificial ventilation with positive pressure, respiratory volumes of 41.5 mL were achieved [3]. Abandoning artificial ventilation based on passive airflow during chest compressions leads to hypercapnia and hypoxemia [9]. When the airway is secured with an endotracheal tube, the risk of lung barotrauma increases due to high inspiratory pressures caused by chest compressions [9]. When using a mechanical device for performing chest compressions without active decompression (Piston®), with volume-controlled ventilation with transport ventilators (Medumat®, Oxylog3000®, MonnalT60®), significantly lower actual respiratory volumes were achieved compared to ventilator settings, but their values exceeded anatomical dead space and probably provided part of the effective alveolar ventilation [10].

Although artificial ventilation during resuscitation is characterized by the achievement of smaller tidal volumes and high inspiratory pressures due to increased intrathoracic pressure caused by chest compressions [11], in our case we did not detect extremely increased inspiratory pressures, which is probably the result of active compression and active decompression during resuscitation. Autopulse®, Corpulse® and Lucas2® have proven to be reliable, safe and effective devices for performing chest compressions during transport [12]. Similar static lung compliance values were also observed during artificial ventilation on human cadavers 10. The values of maximum inspiratory pressures also differ depending on the mechanism of action of mechanical chest compression devices. In the clinical setting, the survival of patients who suffered out-of-hospital cardiac arrest did not differ whether mechanical compression devices were used or not [13]. Oxygen delivery to the brain during resuscitation did not differ when patients received manual chest compressions compared to the use of mechanical aids during resuscitation [14]. For safe artificial ventilation, artificial respiration with 6–7 mL of breathing volume per kg of ideal body weight is recommended, or 400–600 mL for an adult.

Lung compliance can be calculated by dividing volume by pressure (C = V/P). If we increase the pressure for the same volume, the compliance will decrease. When using Lucas®, compliance was 43.6 mL/cmH_2O, and when using Autopulse® compliance was 29.6 mL/cmH_2O. When using Lucas®, the peak pressure was 16 cmH_2O compared to a peak pressure of 43.6 cmH_2O when using Autopulse®. The achieved tidal volumes were 364 mL when using Lucas®, and 240 mL when using Autopulse®. Considering a dead space of approximately 150 mL, this means 214 mL of alveolar ventilation when using Lucas® and 90 mL of alveolar ventilation when using Autopulse® with continuous chest compressions during resuscitation.

We demonstrated statistically significant differences in the achievement of tidal volumes when using mechanical devices for performing chest compressions during resuscitation. Higher tidal volumes were achieved when using Lucas®, with a lower peak pressure than when using Autopulse®. Both when using Lucas® and Autopulse®, the same tidal volumes and the same frequency of chest compressions were set. The difference was in the operation of the two devices: with Lucas®, in addition to compression, there is also active decompression, while with Autopulse®, compression around the chest. Although artificial ventilation is an important part of resuscitation with an impact on survival, there remains a lack of evidence on the effectiveness of ventilation during the performance of mechanical chest compressions [14]. With our study, we proved that these volumes cannot be achieved with the continuous use of mechanical chest compressions. Further studies would be needed to examine the impact of decompression to achieve tidal volumes (not constant contact between the skin and the Lucas® piston, *e.g.*, cloth, skin wetness, body tilt, chest rigidity, lung compliance, *etc*.).

5. Conclusions

Tidal volumes achieved during continuous chest compressions using two commonly available devices (Lucas® and Autopulse®) are significantly lower compared to guidelines-recommended tidal volumes, with lower volumes, higher peak airway pressures and higher static compliance measured when using the Autopulse device. The findings from our laboratory study are not fully comparable in the clinical setting. Additional research is needed on the interaction of chest compressions and tidal volume, possibly in animal models.

ABBREVIATIONS

ID, internal diameter; CMV, controlled mechanical ventilation; PEEP, positive end expiratory pressure; Cstat, static lung compliance; FiO_2, fraction inspired oxygen; SD, standard deviation; Vt, tidal volume; I:E, inspiratory expiratory time ratio; Asymp. Sig., asymptotic significance.

AVAILABILITY OF DATA AND MATERIALS

The data presented in this study are available on reasonable request from the corresponding author.

AUTHOR CONTRIBUTIONS

MM and AM—designed the research study; wrote the manuscript. MM—performed the research; analyzed the data. AM—provided help and suggestions. Both authors contributed to editorial changes in the manuscript. Both authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study was reviewed and approved by the Commission for Ethical Affairs at the Faculty of Health Sciences of the Uni-

versity of Novo Mesto, Slovenia (document number: UNM 119/2024).

ACKNOWLEDGMENT

Author would like to thank the management of General and teaching hospital Celje for approving the use of simulation mannequins and apparatus for the needs of conducting the experiment.

FUNDING

This research received no external funding.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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How to cite this article: Matej Mažič, Andrej Markota. Guidelines-recommended tidal volumes are not achieved during continuous mechanical chest compressions—results from a laboratory study. Signa Vitae. 2025; 21(3): 1-7. doi: 10.22514/sv.2025.030.