Chest Compression Synchronized Ventilation

CCSV (Chest Compression Synchronized Ventilation) is a new ventilation mode for use in cardiopulmonary resuscitation. It was developed based on over four decades of experience in the development of modern emergency ventilators. The ventilation frequency, tidal volume, and time of inspiration differ in CCSV mode from known ventilation modes. Various studies were able to show that the gas exchange and hemodynamics can be improved considerably as a result.

The goals of cardiopulmonary resuscitation are to maintain a minimum circulation to enable oxygenation, especially of the heart and brain, and to ensure the return of spontaneous circulation (ROSC). For persons who are not health professionals, chest compressions alone without ventilation and utilizing the oxygen reserves in the lungs are sufficient in the initial minutes [11]. However, in the case of professional help, including Advanced Life Support (ALS), the ERC guidelines recommend ventilation with the highest possible oxygen concentration in addition to chest compressions [12].

The perfusion and ventilation situation in the heart and lungs under chest compressions fundamentally differ from physiological conditions. This is because, besides the heart itself ("heart pump"), the lungs, intrapulmonary vascular system, and the other thoracic organs are also cyclically compressed ("chest pump") due to the chest compressions. As a result, a forward-directed blood flow is generated and a small amount of respiratory gas escapes from the lungs.

Besides maintaining blood circulation, during pulmonary circulation, increased blood oxygenation must occur. An adequate oxygen supply to the organs is particularly a challenge with the significantly lower cardiac output.

Against this background, a special ventilation mode for resuscitation was developed in a complex research and development procedure. With a fundamentally different procedure than previously, this ventilation mode equally optimizes oxygenation and perfusion under chest compressions.

Common ventilation modes under resuscitation conditions

Different strategies are available for ventilation during resuscitation. Standard ventilation procedures with an unsecured and a secured airway are presented below.

1. Ventilation with an unsecured airway

The ERC guidelines from 2015 recommend that cardiopulmonary resuscitation with an unsecured airway be performed at a ratio of 30:2. Each breath should be delivered with an inspiratory time of one second and a volume that causes the chest to rise normally [13]. For ventilation at a ratio of 30:2, a ventilation mask is frequently used in combination with a resuscitator, as these are quick and easy to use. However, manual ventilation with bag-valve mask has the following disadvantages compared to mechanical ventilation:

- It is difficult to securely seal the mask and it is often better if the mask is held with two hands. However, this requires a second assistant to use the resuscitator.
- Increased risk of regurgitation due to high ventilation pressures and hyperinflation of the stomach.
- No control over the volume delivered.

As an alternative to ventilation with a bag-valve mask, manual ventilation with an unsecured airway can also be performed using a suitable ventilator. In this case, the so-called MEDUtrigger offers the possibility to administer a mechanical breath "at the touch of a button". This procedure offers the following advantages over bag-valve mask ventilation:

- Only one assistant is required for safe manual ventilation, as the sealing of the mask and the manual triggering of the mechanical breath are executed simultaneously.
- Reduced risk of regurgitation, as the maximum ventilation pressure is limited.
- Full control over the volume delivered, as this is controlled by the ventilator.
- Controlled inspiratory time and therefore minimal hands-off time.

Such manually triggered mechanical ventilation can also be combined with a supraglottic airway device (SGA: laryngeal tube and laryngeal mask). In the event of leaks in the SGA, the current guidelines also recommend ventilation at a ratio of 30:2 [12].

2. Ventilation with a secured airway

As soon as the airway has been secured with an endotracheal tube, the ERC recommends ventilation at a frequency of 10/min with the highest possible inspiratory oxygen concentration – however, no specific ventilation mode is recommended [12].

Ventilation can therefore be performed either manually using a combination of a bag-valve mask and a tube or mechanically using a ventilator. Although frequently used in practice, manual ventilation has a number of disadvantages compared to mechanical ventilation, e.g.:

- The recommended ventilation frequency of 10/min is not guaranteed and is often exceeded in practice [10].
- The manually applied tidal volume is not constant and cannot be measured.
- The maximum ventilation pressure (peak pressure) is not measured and cannot be set with many bag-valve masks.
- Manual ventilation requires a second rescuer in order to be done properly.

Essentially, mechanical ventilation can be performed with both volume-controlled ventilation (IPPV) and pressure-controlled ventilation (PCV/BiLevel). Here, tidal volumes are applied with a defined ventilation frequency, not requiring a second rescuer. However, the classic ventilation patterns of controlled ventilation were designed so that no cyclical gas flows are generated by the patient, thus enabling the preset tidal volumes to be maintained and pressure limits to be guaranteed. However, if controlled ventilation is performed during chest compressions, oscillating volumes are generated in the airway with each chest compression. These can significantly impair the ability to maintain the preset ventilation parameters and cause incalculable changes in tidal volumes and airway pressures in all conventional forms of ventilation [12].

CCSV – background, principle and effect

Continuous chest compressions are crucial for effective resuscitation. However, ERC guidelines provide few concrete recommendations for the choice of ventilation (i.e. the specific ventilation pattern and its ventilation parameters). Nevertheless, ventilation plays an important role in resuscitation. Essentially, its goals are the best possible oxygenation of the arterial blood and the elimination of CO_2 from the venous blood. The latter must take place to a sufficient degree in order to prevent hypercapnia and the associated respiratory acidosis. Furthermore, ventilation should not impair the blood pressure and blood flow generated by the chest compressions. One feature of CCSV mode is that it meets all these requirements for ventilation during resuscitation and, in the process, also has a positive effect on hemodynamics.

What is CCSV?

Today, when performing cardiopulmonary resuscitation, the compressions and ventilations are not synchronized. In contrast, CCSV synchronizes the chest compressions and ventilations automatically. As in the case of any mechanical ventilation, the application of positive pressure produces an inspiratory gas flow; exhalation occurs passively due to the elastic restoring forces of the thorax [1] [9]. Unlike the other forms of ventilation currently being used, in CCSV, every single chest compression triggers a pressure-controlled, small-volume mechanical breath. Initial studies (see ff.) show that this provides a better supply of oxygenated blood to the cardiovascular system.

How does CCSV work from a technical point of view?

CCSV is basically a pressure-controlled ventilation mode. The gas flow directed outwards from the lungs as a result of the chest compression is detected by the pressure and flow sensors of the ventilator and serves as an inspiration trigger.

Then the ventilator produces a pressure-controlled mechanical breath. Therefore, inspiration begins almost simultaneously with the chest compression.

The inspiration lasts about 200 milliseconds. This way, the mechanical inspiration always ends before the next chest compression. A ventilation frequency of 100/min results from a chest compression frequency of 100/min.

Pressure-controlled ventilation is set to an inspiratory pressure of 40 mbar or 60 mbar. High flow rates (at least 80 l/min), especially at the start of inspiration, may be necessary to achieve these pressures within the specified inspiratory time.

CCSV – intrathoracic pressure in the compression phase increased

Due to the synchronized mechanical breath, no gas volume can escape from the thorax during the compression. An increase in intrathoracic volume occurs synchronously with inspiration. The associated increase in intrathoracic pressure has a positive impact on the interaction between the "heart pump" and "chest pump" during compressions. The blood flow generated by the chest compressions is increased as well as the blood circulation with simultaneously improved gas exchange (see Figure 1).

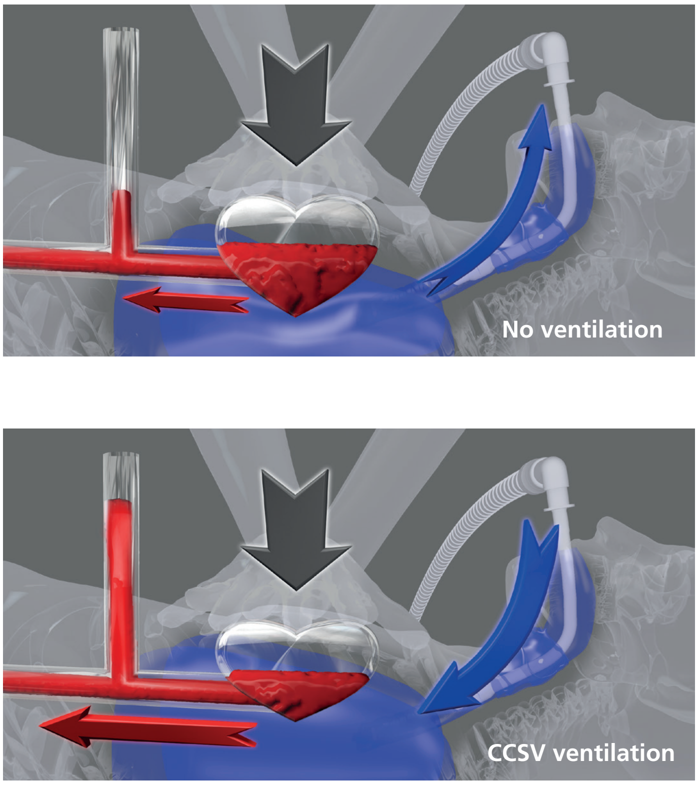

***Figure 1**: Functional principle of CCSV in the compression phase*

Shortly before the decompression phase, the ventilator switches to expiration, which causes air to escape from the lungs. Consequently, the intrathoracic pressure decreases and the venous return to the heart can occur unhindered.

Advantages of CCSV at a glance

- Improved hemodynamics
- Optimal oxygenation
- Adequate alveolar ventilation to eliminate carbon dioxide
- Ventilation optimized for the resuscitation application

Are there contraindications for CCSV?

An airway secured by endotracheal intubation is absolutely indispensable for use of the CCSV mode. This is essential to ensure the necessary trigger function and the secure delivery of the ventilation parameters. CCSV mode cannot be used with an unsecured airway. Furthermore, CCSV mode can only be used with a body weight of ten kilos or more.

Studies on CCSV

In order to investigate the effectiveness and possible adverse effects, extensive animal studies were performed [6] [7]. The results are presented below with the differences between them [3] [6] [7].

1. CCSV – better hemodynamics

Mechanical ventilation offers advantages for CPR with a secured airway. In the following study, Kill et al. examined the effect of volume-controlled ventilation (IPPV), BiLevel (BIPAP) ventilation, and the new CCSV ventilation mode in a pig model with respect to gas exchange and hemodynamics [7].

Figure 2 shows the changes in the invasively measured blood pressure under CCSV ventilation by way of example. The rise in intrathoracic pressure causes the arterial blood pressure and the difference between the arterial and central venous blood pressure to increase. This is crucial for the cardiac and cerebral perfusion pressure.

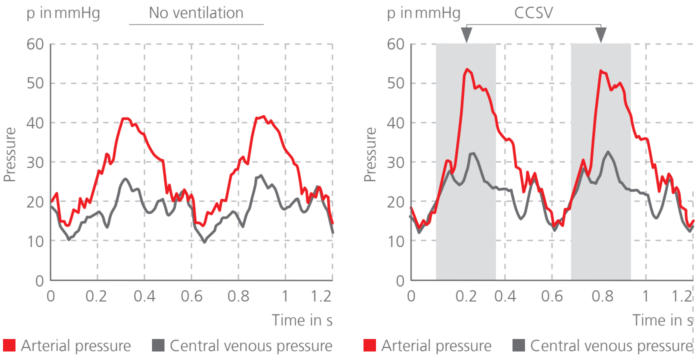

Figure 2: *Arterial (red line) and central venous pressure (gray line) without ventilation (left) and with CCSV (right)*

For the study, after artificially induced cardiac arrest (ventricular fibrillation, electrically induced), 24 female domestic pigs were randomly assigned to the three groups: IPPV, BiLevel, and CCSV. After ten minutes of continuous resuscitation with chest compressions and mechanical ventilation, the investigators performed advanced life support (ALS) (FiO_2 = 1, up to six defibrillations, vasopressors).

Blood gas samples were taken before the start of the trial as well as 4 and 13 minutes after cardiac arrest. Selected results from the arterial and mixed venous blood gas analysis are shown in tables 1 and 2. Table 1 shows that the oxygenation of the blood (measured as PaO_2) with CCSV was already more than twice as high after four minutes of resuscitation measures as with IPPV and BiLevel. Furthermore, a normal mixed venous pH value was achieved and maintained during resuscitation with CCSV mode (see Table 2).

After 13 minutes, end-inspiratory and end-expiratory hemodynamic parameters were examined, and IPPV was compared with BiLevel and CCSV. The study results in Table 3 show that the arterial blood pressure was significantly higher in CCSV at the end of inspiration than the comparative values for IPPV and BiLevel.

Time (min), median (25%/75% percentile)

Time	**Baseline 0 min (FiO_2 0.21)**	**4 min (FiO_2 1.0)**	**13 min (FiO_2 1.0)**
PaO_2 (mmHg)			
IPPV	88 (79/97)	143 (76/256)	262 (81/340)
Bilevel	84 (77/87)	261 (109/386)	236 (86/364)
	p = 0.505	***p = 0.195***	***p = 0.878***
CCSV	91 (85/94)	598 (471/650)	634 (115/693)
	p = 0.463	***p < 0.001***	***p = 0.054***

Table 1: *Results of the arterial blood gas analysis (shown here: PaO_2) based on the ventilation mode (p values are based on the comparison with the IPPV control group)*

Time (min), median (25%/75% percentile)

Time	**Baseline 0 min**	**4 min**	**13 min**
Venous pH value			
IPPV	7.40 (7.35/7.42)	7.34 (7.31/7.35)	7.26 (7.25/7.31)
Bilevel	7.42 (7.38/7.44)	7.35 (7.29/7.37)	7.27 (7.17/7.31)
	p = 0.382	***p = 0.645***	***p = 0.645***
CCSV	7.40 (7.38/7.42)	7.34 (7.33/7.39)	7.35 (7.34/7.36)
	p = 0.694	***p = 0.189***	***p = 0.006***

Table 2: *Results of the mixed venous blood gas analysis (shown here: pH value) based on the ventilation mode (p values are based on the comparison with the IPPV control group)*

t = 13 min, median (25%/75% percentile)

Group	**Baseline 0 min**	**End-inspiratory**	**End-expiratory**
MAP (mmHg)			
IPPV	73.7 (53.0/82.4)	28.0 (25.0/29.6)	27.9 (24.4/30.0)
Bilevel	66.4 (63.3/80.2)	29.1 (25.6/37.1)	28.7 (24.2/36.5)
	p = 0.916	***p = 0.574***	***p = 0.721***
CCSV	60.4 (59.6/94.4)	32.7 (30.4/33.4)	27.0 (24.5/27.7)
	p = 0.908	***p = 0.021***	***p = 0.779***

Table 3: *Results of the measurement of hemodynamic parameters (shown here: mean arterial pressure) based on the ventilation mode and cycle (p values are based on the comparison with the IPPV control group)*

Summary: CCSV resuscitation resulted in improved oxygenation, a normal venous pH value, and a significantly higher mean arterial blood pressure compared to IPPV and BiLevel. It can be assumed that CCSV supports hemodynamics positively.

2. CCSV – improved oxygenation

Besides the data shown above, another study examined the influence of CCSV mode on the gas exchange and arterial blood pressure compared with IPPV using the pig model [6].

Ventricular fibrillation was induced in twelve anesthetized, intubated pigs. Continuous chest compressions were started after three minutes. The pigs were mechanically ventilated in a crossover setting with five ventilation periods of four minutes each.

During the first and last ventilation periods, ventilation was performed using IPPV (FiO_2 = 1, tidal volume = 7 ml/kg body weight, respiratory rate = 10/min). In between, ventilation was performed with different CCSV settings in three time windows in a random order. CCSV (FiO_2 = 1, respiratory rate = compression frequency) was applied with the following presettings:

- $CCSV_A$: Pinsp = 60 mbar, inspiration time = 205 ms
- $CCSV_B$: Pinsp = 60 mbar, inspiration time = 265 ms
- $CCSV_C$: Pinsp = 45 mbar, inspiration time = 265 ms

The investigators took blood gas samples during the ventilation periods. The results for PaO_2 (median) are shown in Table 4.

	PaO_2 (kPa) (25%/75% percentile)	p value vs. $IPPV_{first}$	p value vs. $IPPV_{last}$
$IPPV_{first}$	19.6 (13.9/36.2)		p = 0.77
$CCSV_A$	48.9 (29.0/58.2)	p = 0.028	p = 0.0001
$CCSV_B$	54.0 (43.8/64.1)	p = 0.001	p = 0.0001
$CCSV_C$	46.0 (20.2/58.4)	p = 0.006	p = 0.0001
$IPPV_{last}$	22.7(5.4/36.9)	p = 0.77	

***Table 4**: Results of the arterial blood gas analysis (shown here: PaO_2) based on the ventilation pattern*

The results show that ventilation with CCSV mode resulted in a significantly higher mean arterial oxygen partial pressure than with IPPV (see Figure 3).

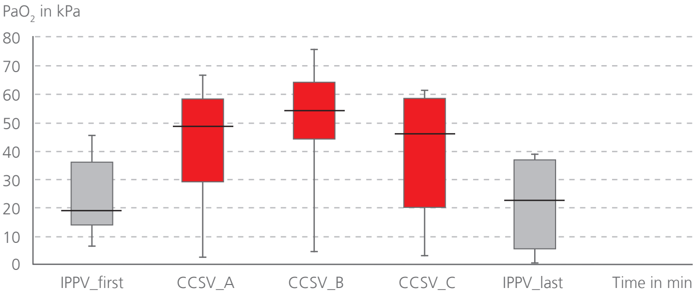

***Figure 3**: Comparison of arterial oxygen partial pressure paO_2 in IPPV and CCSV*

Furthermore, during resuscitation, the mean arterial blood pressure (MAP) was measured for every four-minute ventilation period. The results (median) are shown in Table 5.

	MAP (mmHg) (25%/75% percentile)	p value vs. $IPPV_{first}$	p value vs. $IPPV_{last}$
$IPPV_{first}$	42.5 (33.4/47.5)		p < 0.0001
$CCSV_A$	40.1 (34.4/44)	p = 1.0	p < 0.0001
$CCSV_B$	39.2 (34.5/45.6)	p = 1.0	p < 0.0001
$CCSV_C$	37 (29.5/42.2)	p = 1.0	p < 0.0001
$IPPV_{last}$	22.4 (18.4/29.9)	p < 0.0001	

***Table 5**: Results of the arterial blood pressure measurement (shown here: MAP) based on the ventilation pattern*

Summary: All examined CCSV patterns result in improved oxygenation of the arterial blood compared to conventional IPPV ventilation. The best results were achieved at an inspiratory pressure of 60 mbar. A drop in the arterial blood pressure during resuscitation is also prevented with CCSV.

3. CCSV – improved alveolar ventilation

In addition to the maintenance of perfusion and oxygenation, the elimination of CO_2 (decarboxylation) also plays a crucial role in resuscitation. Sustaining a physiological, compliant arterial carbon dioxide partial pressure that is as normal as possible is particularly relevant in order to avoid respiratory acidosis.

Consequently, another study examined the effect of CCSV on the arterial carbon dioxide partial pressure [3].

In the study, 44 pigs were anesthetized and intubated endotracheally, and ventricular fibrillation was induced in them. Continuous chest compressions were started after three minutes. The pigs were ventilated with either IPPV (FiO_2 = 1.0, tidal volume= 1, tidal volume = 7 ml/kg body weight, respiratory rate = 10/min, PEEP = 0 mbar) or CCSV (FiO_2 = 1.0, Pinsp = 60 mbar, Tinsp = 265 ms). After seven minutes, the pigs were given 1 mg adrenalin IV, after 11 minutes 0.8 IU Vasopressin IV.

The blood gas analyses were performed at the baseline (t = 0), after eight and twelve minutes. For $PaCO_2$, the arterial blood gas analysis showed the following results (median (25%/75% percentile):

$PaCO_2$ (mmHg)

	t = 0 min	t = 8 min	t = 12 min
$PaCO_2$ (mmHg)			
IPPV	39 (36/41)	58 (53/66)	60 (52/75)
CCSV	39 (37/42)	44 (35/49)	41 (35/50)

***Table 6**: Results of the arterial blood gas analysis (shown here: $PaCO_2$) based on the ventilation pattern*

The results show that normocapnia can apparently be achieved during resuscitation with CCSV (see Figure 4). This means that neither hypoventilation or hyperventilation occur during ventilation with CCSV. This is achieved thanks to the continuous administration of low tidal volumes above the dead space volume.

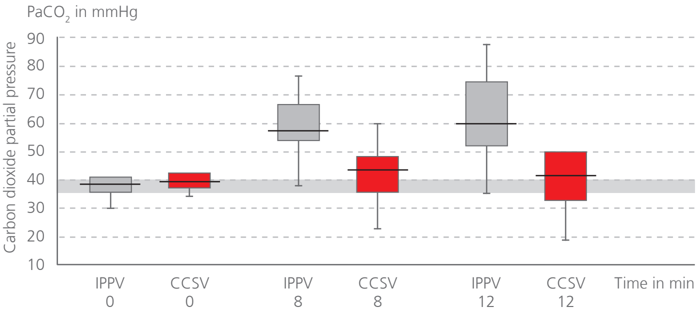

***Figure 4**: Comparison of arterial carbon dioxide partial pressure $PaCO_2$ in IPPV and CCSV*

Summary: The study showed that CCSV can prevent hypercapnia compared to IPPV, and thus respiratory acidosis is avoided.

4. CCSV – improved cerebral oxygenation

In addition to the gas exchange, the trial described above also examined the extent to which CCSV influences cerebral oxygenation under resuscitation [5]. Furthermore, on the basis of histological examinations, it was also analyzed whether there are differences between the various forms of ventilation in terms of damage to the lungs [4].

The intubated domestic pigs received O_2C fiber optic probes implanted in the brain through drill holes to continuously measure cerebral tissue oxygen saturation (ScO_2). This showed that ScO_2 was prevented from falling below the initial value under CCSV, including without the administration of adrenalin (t = 6 min) (see Figure 5).

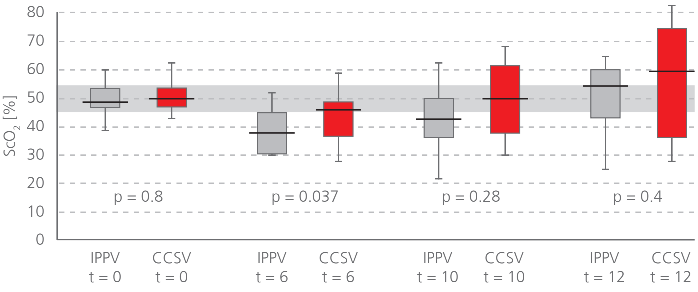

***Figure 5**: Comparison of cerebral oxygenation in IPPV and CCSV [2]*

Furthermore, pulmonary tissue samples were taken postmortem and examined for morphological signs of ventilator-associated lung injury (VALI). The results of the examination are shown in Figure 6 and demonstrate that CCSV and IPPV equally cause only minor changes in terms of VALI under resuscitation.

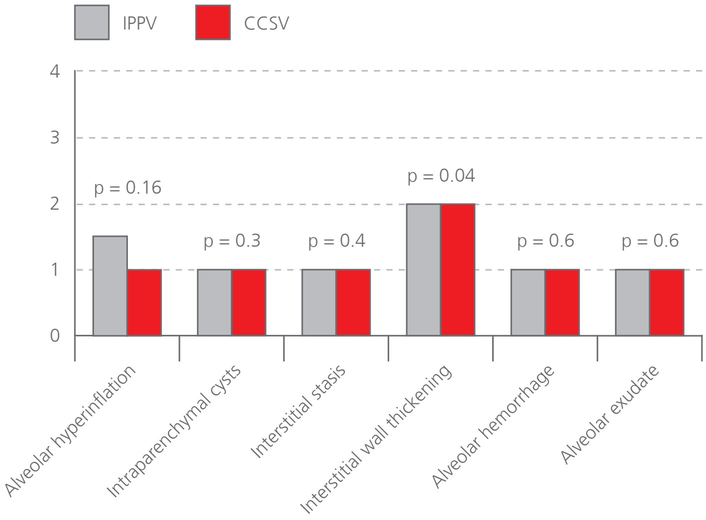

***Figure 6**: Results of the histological examinations into possible damage to the lung tissue [4]*

Summary: The study showed that CCSV improves cerebral oxygenation compared to IPPV. There were no differences between IPPV and CCSV regarding possible damage to the lung tissue.

5. CCSV – more precise ventilation

Another study examined the extent to which manual chest compressions affect the accuracy of ventilation presettings (volume or pressure) in IPPV, BIPAP (BiLevel), and the new CCSV ventilation mode [13].

A simulation model (dummy) was used for the study. 90 experienced EMS field providers performed continuous manual chest compressions on the standardized training dummy with a special, realistic lung model for two minutes. IPPV, BiLevel, and CCSV were used in a randomized order. The presettings of the ventilator (incl. tolerances) were as follows:

- IPPV: Vt = 450 (400–500) ml, PEEP = 0 mbar, f = 10/min
- BiLevel: Pinsp = 19 (17.1–20.9) mbar, PEEP = 5 mbar, f = 10/min
- CCSV: Pinsp = 60 (54–66) mbar, PEEP = 0 mbar, Tinsp = 205 ms, f = rate of chest compressions

The actual tidal volumes applied and the actual ventilation pressure were then measured using flow and pressure sensors on the tube. The results are shown in Figure 7.

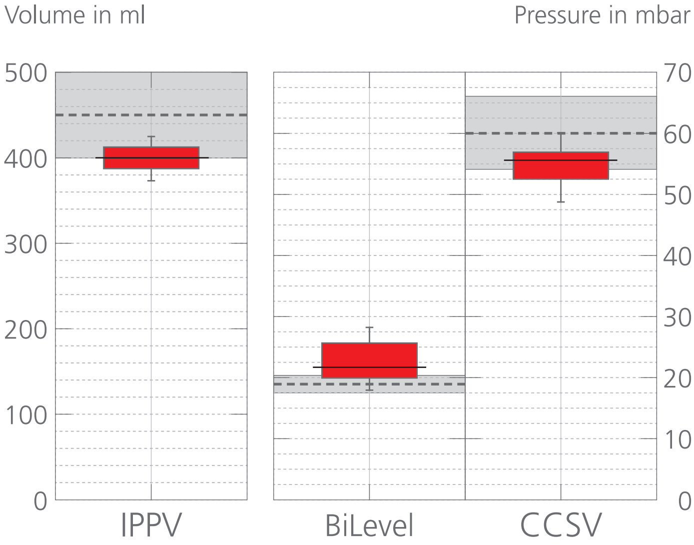

***Figure 7**: Measured Vt and Pinsp values of the ventilation modes IPPV, BiLevel and CCSV (median and 10th to 90th percentile shown as box plots); preset values are shown as a dotted line; the tolerance of the devices is shown as a gray area*

Subsequently, the default values were compared with the measurement results. This showed that an insufficient volume was applied in 51% of all mechanical breaths under IPPV, and the median is slightly below the target range at 399 ml. During BiLevel ventilation, an excessive pressure was applied in 57% of ventilations, which resulted in the median being above the target range at 22 mbar. With CCSV, an insufficient ventilation pressure was measured in 38% of cases, and an excessive ventilation pressure in < 1% of cases. With CCSV, the median is within the target range at 55 mbar.

The quality of the chest compressions was evaluated based of the recommendations of the ERC guidelines. The compression depth was similar for all three ventilation modes.

The measurement of the compression frequency also showed no differences between the individual ventilation modes: Median (25%/75% percentile)

- IPPV: 117 (105/124) /min
- BiLevel: 116 (107/123) /min
- CCSV: 117 (107/125) /min [13]

Summary: In comparison to IPPV and BiLevel, CCSV works best with the preset ventilation values without exceeding the preset ventilation pressure during simulated resuscitation. Both the compression depth and the compression frequency were similar during the application of the different ventilation modes. This demonstrated that none of the examined ventilation patterns had a negative impact on the quality of the chest compressions.

First results from human application

At the firebrigade of Cologne, an urban physician-staffed Emergency Medical Service, ventilation with CCSV following endotracheal intubation was added to the standard ALS algorithm. Retrospectively, all cases of out-of-hospital cardiac arrest (OHCA) with use of CCSV were analyzed. The time of mechanical ventilation with both manual and mechanical chest compressions was evaluated. Furthermore, the number of patients admitted to hospital with ROSC, 24h-survival and the number of patients discharged alive were assessed.

In total, 34 patients with OHCA were ventilated with CCSV between July 2018 and March 2019. CCSV ventilation time was as follows for the different compression types: Median (25%/75% percentile)

- manual chest compressions: 5:04 (2:04/6:38) min
- mechanical chest compressions: 18:26 (7:23/26:42) min

The retrospective analysis of the patient outcome showed the following results:

- Admitted to hospital with ROSC: 61.8% (n=21)
- 24h survival: 35.3% (n=12)
- Discharged alive: 14.7% (n=5)

Total CCSV ventilation times in patients discharged alive were 4:48, 8:42, 25:00, 30:18 and 40:24 min. No serious adverse events in conjunction with CCSV were reported [8].

Another study assessed the cohort of 50 OHCA patients treated with CCSV. Out of these 50 patients n= 25 (50%) were admitted to hospital with ROSC. n = 7 out of 50 patients (14%) survived until discharged from hospital [14].

Summary: First reported cases of CCSV in OHCA show very promising ROSC and outcome rates with a maximum time of ventilation during chest compression of more than 40 minutes.

Conclusion

For the first time, with Chest Compression Synchronized Ventilation (CCSV), there is a ventilation mode that has a positive impact on cardiopulmonary resuscitation. Synchronized with each chest compression, a pressure-controlled mechanical breath is administered by the mechanical ventilator. The intrathoracic pressure in the compression phase increases, which improves cardiac output. The mean arterial blood pressure also increases. The oxygenation of the arterial blood improves significantly, and the carbon dioxide partial pressure remains within the standard range.

Therefore, with CCSV the disadvantages of conventional ventilation during cardiopulmonary resuscitation can be prevented and the gas exchange and hemodynamics can be improved demonstrably. First human data shows very promising ROSC and outcome rates. These results need to be confirmed in further studys.

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[1] Normally, medical therapeutic procedures that are applied during resuscitation cannot be developed and tested on humans. For issues related to resuscitation, the large animal model using a pig is considered to be the "gold standard". Thus the effectiveness, side effects, and complications can be recorded with reasonable certainty. The results of the large animal model are largely transferable to the human resuscitation situation. The large animal model on which the present case is based has been used and published previously for questions in the area of ventilation by laymen in resuscitation. Those results were additionally incorporated into the 2010 resuscitation guidelines.

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