LUCAS - Lund University Cardiopulmonary Assist System

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LUCAS

Lund University

Cardiopulmonary Assist System

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This thesis is dedicated to my father,
Xiaobai Liao

将此书献给我的父亲

廖小白

Contents

List of publications

This thesis is based on studies reported in the following papers, which are referred to in the text by their Roman numerals:

I. Steen S, Liao Q, Pierre L, Paskevicius A, Sjöberg T: Evaluation of LUCAS, a new device for automatic mechanical compression and active decompression resuscitation. Resuscitation 2002;55:285-299.

II. Steen S, Liao Q, Pierre L, Paskevicius A, Sjöberg T. The critical importance of minimal delay between chest compressions and subsequent defibrillation: a haemodynamic explanation. Resuscitation 2003;58:249-258.

III. Liao Q, Sjöberg T, Paskevicius A, Wohlfart B, Steen S, Manual versus mechanical cardiopulmonary resuscitation. An experimental study in pigs. BMC Cardiovascular Disorders 2010;10:53. www.biomedcentral.com/1471-2261/10/53.

Summary

Lund University Cardiopulmonary Assist System (LUCAS) is a mechanical device providing automatic 5 cm deep chest compressions and active decompressions back to normal anatomical position with a frequency of 100 per minute, and a duty cycle of 50%, i.e., LUCAS is constructed to give chest compressions according to the latest international guidelines in cardiopulmonary resuscitation (CPR).

The aim of the thesis was to study cardiac arrest using different porcine models of ventricular fibrillation. Four hypotheses were formulated:

1. LUCAS-CPR is superior to manual CPR regarding coronary perfusion pressure (CPP) and return of spontaneous circulation (ROSC).
2. Hypothermic LUCAS-CPR is superior to normothermic LUCAS-CPR in treating prolonged ventricular fibrillation.
3. The rate of ROSC after prolonged ventricular fibrillation will increase if LUCAS-CPR is given before defibrillation, and if defibrillation is given during on-going chest compressions.
4. LUCAS-CPR will cause fewer rib fractures than manual CPR.

LUCAS-CPR gave significantly higher rates of ROSC and significantly higher CPP than manual CPR. LUCAS-CPR combined with surface cooling to 34°C was superior to normothermic LUCAS-CPR during 1 hour of CPR for ventricular fibrillation. Defibrillation was more effective to obtain ROSC after prolonged ventricular fibrillation if chest compressions were done before the shock, and if the shock was given during on-going LUCAS-CPR. LUCAS-CPR caused significantly fewer rib fractures during 20 minutes of CPR compared to manual CPR.

INTRODUCTION

Background

Sudden cardiac arrest, either as ventricular fibrillation (VF) or as asystole, is the single condition causing the most deaths in the Western world. It has been estimated that 375 000 people in Europe (1) and 275 000 in the USA (2) are victims of sudden cardiac arrest each year. The great majority of these cases occur out of hospital. In Sweden, about 10 000 people suffer sudden cardiac arrest each year, and it causes more than 10% of all deaths.

Since Kouwenhoven and coworkers published their landmark article in 1960 (3), manual closed-chest compressions (combined with mouth-to-mouth/mask ventilation) has been established as the initial treatment of choice for cardiac arrest, followed by defibrillation as soon as the equipment is available and if VF is the cause of the collapse.

For the last 50 years, the one-year survival rate after sudden cardiac arrest has remained extremely poor, in most studies less than 5%. In Sweden, the 30-day survival rate after sudden cardiac arrest was 7% in 2008 (4).

Several studies have been published showing how difficult it is to give optimal chest compressions manually (5-14). These studies have identified many factors that make manual CPR difficult (see Table 1).

Table 1. Difficulties with manual CPR.

- Rescuer fatigue within 2 minutes (ineffective CPR).
- Too shallow chest compressions (ineffective CPR).
- Too deep chest compressions (multiple rib fractures, visceral injuries).
- Too high/low compression rate (ineffective CPR).
- Too high ventilation rate (impaired venous return).
- Too small body size of rescuer (ineffective CPR).
- Too long pre-shock pauses (ineffective defibrillation).
- Too many interruptions of the chest compressions (ineffective CPR).

One of the problems with manual chest compressions is that during prolonged CPR, the thorax flattens due to multiple bilateral rib fractures with reduced thoracic wall recoil and venous return as a consequence. The CardioPump (AMBU, Copenhagen) was developed with the intention to overcome this problem (Fig 1).

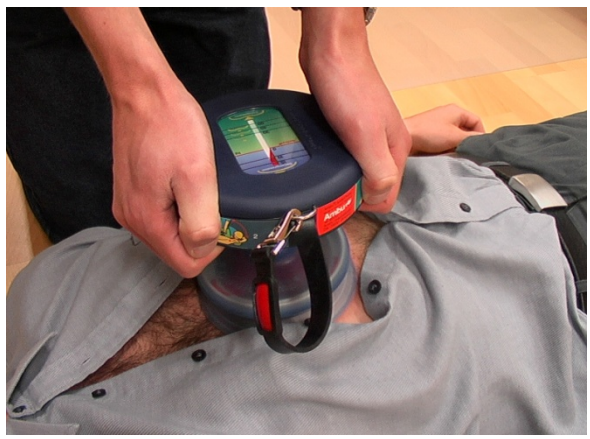

Fig 1. The CardioPump in action.

Due to the suction-cup on the CardioPump active decompression can be obtained after each compression. Plaisance and coworkers (15) compared standard manual CPR (n=377 patients) with active compression/decompression CPR performed

manually with the CardioPump (n=373 patients). The 1-year survival rate was very poor in both groups, 2% versus 5% (p=0.03); all resuscitation efforts with either method were performed only at the scene of the cardiac arrest, and only if the victims were successfully resuscitated at the scene were the patients transported to hospital. To use the CardioPump correctly, compressing and decompressing the thorax 100 times each minute, is very demanding, and in the study of Plaisance et al., to prevent fatigue, the rescuers alternated after every 3 min of CPR. Due to the difficulty to know the correct compression depth after each decompression, some compressions may become too deep, with injuries to visceral organs as a consequence (16-18).

History of LUCAS

Willy Vistung was a Norwegian inventor. Once he happened to see the treatment of a patient with cardiac arrest in an ambulance speeding very fast through Oslo toward the hospital. One paramedic tried to give chest compressions, kneeling over the patient, losing his balance every time the ambulance rounded a corner. Another person gave ventilation with an AmbuBag connected to a cylinder with oxygen. Willy Vistung had the idea during this ambulance transport of constructing a pneumatic mechanical system to do chest compressions. He bought the necessary components and made his first prototype. No enthusiasm for his project was to be found in Norway.

In 1995 he had a meeting with Stig Steen at the Department of Cardiothoracic Surgery in Lund. Stig Steen, also a Norwegian, was a cardiothoracic surgeon in charge of the cardiothoracic surgical laboratory, situated within Lund University Hospital. Stig Steen had never met Willy Vistung before, but the personal chemistry between them was perfect. Ethical permission was obtained to run a randomized study on pigs to test Willy Vistung's prototype, and the result of that study showed that mechanical compressions with his device gave superior results as compared to manual compressions.

Willy Vistung became the victim of cardiac arrest and died. Stig Steen and coworkers, in full agreement with Vistung's widow, and with economic support from Lund University Hospital, built a pneumatic universal machine where all relevant parameters for chest compression and decompression could be studied in pigs of all sizes (Fig 2-3). The results obtained with optimal mechanical chest compression/decompression were superior to manual CPR.

Professor Steen contacted the Swedish industry entrepreneur Lars Sunnanväder, the owner of Jostra AB, a company producing heart-lung machines in Lund. Lars Sunnanväder and Jostra's CEO, Lennart Sjölund, enthusiastically supported the plans to make industry out of mechanical CPR, and Sunnanväder started a new company, Jolife AB, for this purpose. Professor Steen and his research team were given generous economic support from Jolife to continue the research and test different new prototypes (Fig 4-5). The first commercial version needed a name, and LUCAS was chosen, which stands for Lund University Cardiopulmonary Assist System.

1. Compression force
2. Downstroke-time
3. Stroke length
4. Time down
5. Decompression force
6. Upstroke-time
7. Time up
8. Frequency

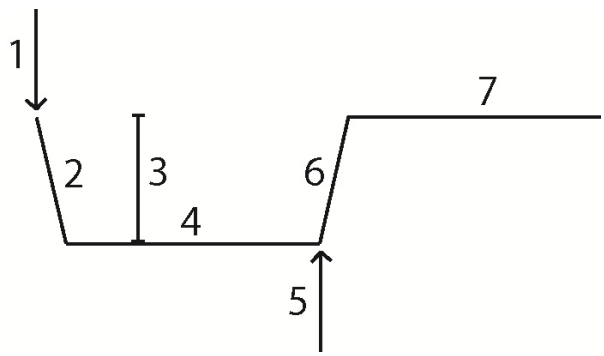

Fig 2. Chest compression/decompression variables.

Compression phase = "duty cycle" = "systole" = 2+4.

Decompression phase = "diastole" = 6+7.

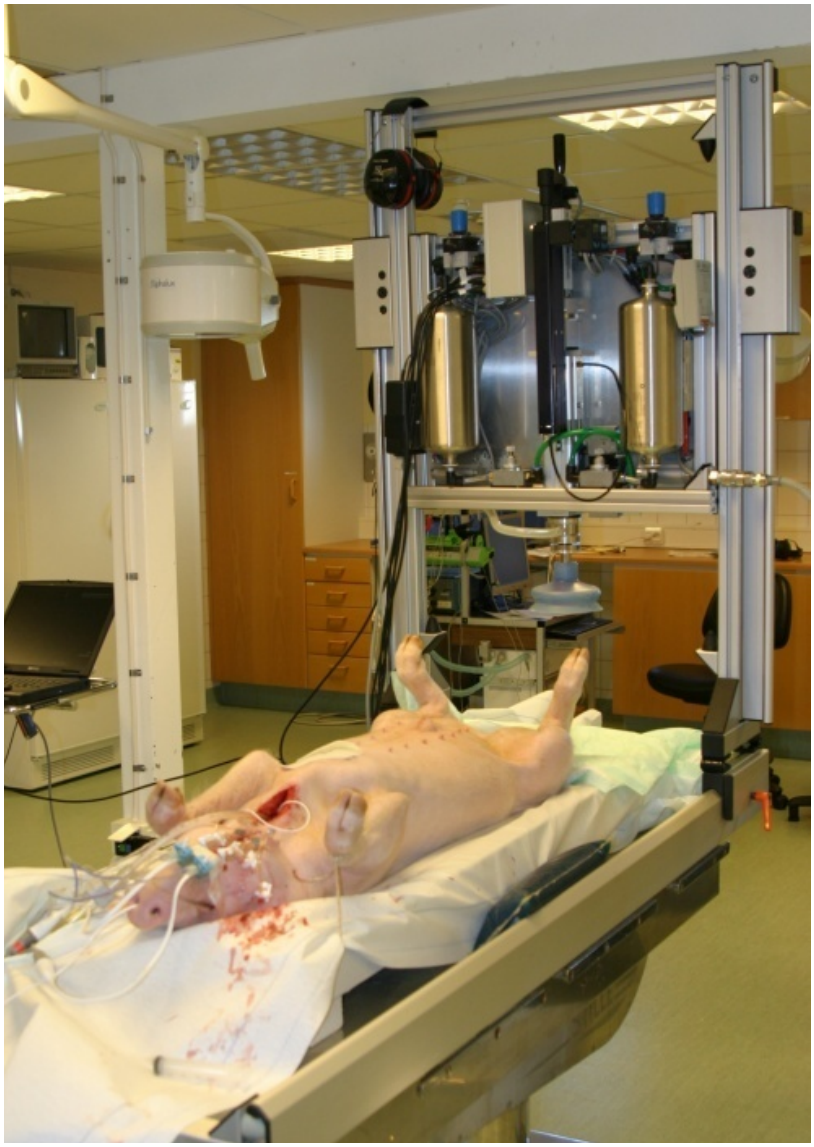

Fig 3. The Universal Igelösa research machine constructed to study all parameters of mechanical chest compression and active decompression on all sizes of animals.

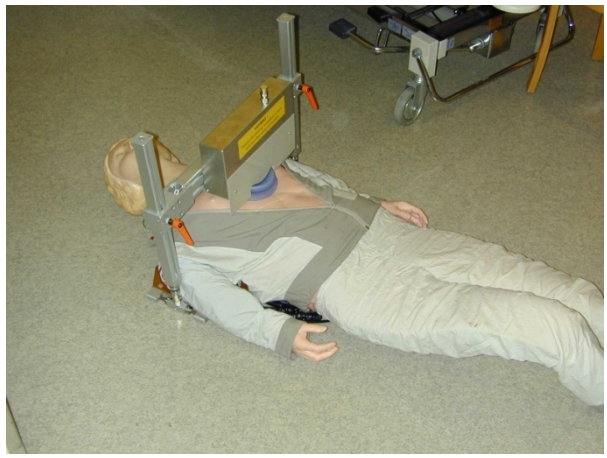

Fig 4. The first model used on patients at Lund University Hospital. This apparatus was the first to save the life of a patient after conventional CPR failed, see paper I.

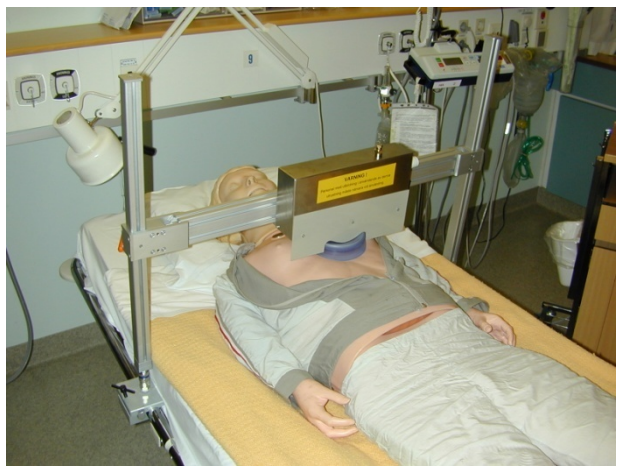

Fig 5. This model was used in the heart intensive care unit of Lund University Hospital in the year 2000.

Due to the suction cup that makes active decompression possible, LUCAS moves the chest both down and up, thereby creating both circulation and ventilation, which is the reason that C in LUCAS stands for “cardiopulmonary”.

LUCAS was introduced in clinical practice by Professor Steen and coworkers in the year 2000, and the first scientific report on its properties, based on 100 pig experiments and the use on 20 patients, was published in 2002 (I).

Properties of LUCAS

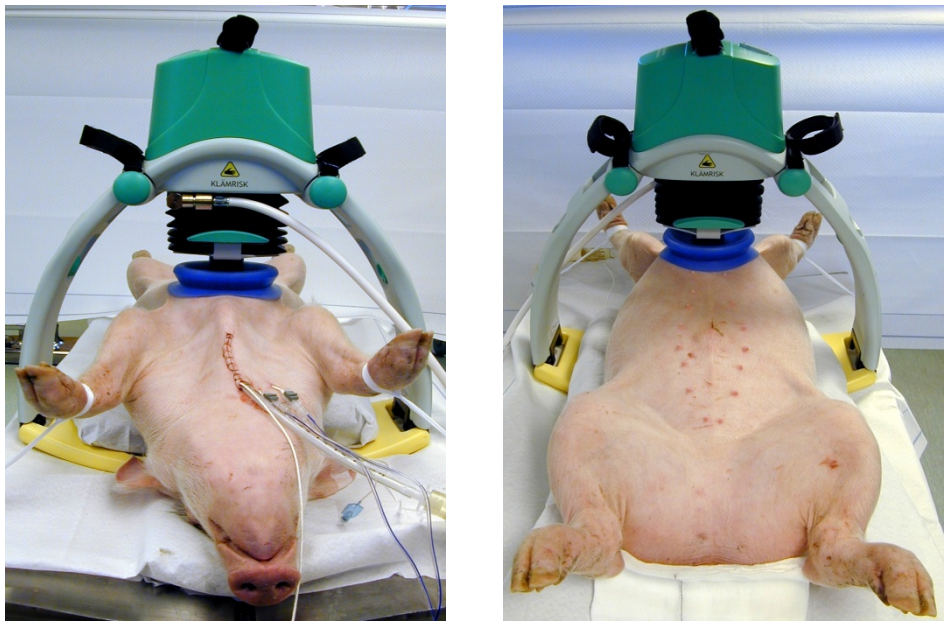

Fig 6. The first commercial LUCAS model tested on a pig.

LUCAS provides automatic compressions and decompressions back to the initial chest position (Fig 6). The maximum compression depth is 5 cm, the maximum compression force is 500 N, and the compression frequency is 100 per minute with a duty cycle of 50%. LUCAS is programmed to give compressions according to the recommendation from the international resuscitation guidelines (19-22). The

weight of the device is 6.5 kg. The first versions were gas-driven (Fig 7). Since 2009 LUCAS exists also in an electrically-driven version (Fig 8).

Fig 7. A pneumatic version of LUCAS.

Fig 8. Since 2009, LUCAS is commercially available as an electrical version, LUCAS2.

Aim of the thesis

The aim of the thesis was to study cardiac arrest using different porcine models of ventricular fibrillation. Four hypotheses were formulated:

1. LUCAS-CPR is superior to manual CPR regarding coronary perfusion pressure (CPP) and return of spontaneous circulation (ROSC).
2. Hypothermic LUCAS-CPR is superior to normothermic LUCAS-CPR in treating prolonged ventricular fibrillation.
3. The rate of ROSC after prolonged ventricular fibrillation will increase if LUCAS-CPR is given before defibrillation, and if defibrillation is given during on-going chest compressions.
4. LUCAS-CPR will cause fewer rib fractures than manual CPR.

MATERIAL AND METHODS

For a complete description of the materials and methods, see I – III.

Research animals

In study I and II, 124 pigs with body weights in the range of 20-25 kg were used. In study III, 16 pigs with body weights in the range of 28-33 kg were used. The anterio-posterior chest diameter for the smaller pigs is around 20 cm, i.e., the same as for adult humans of mean size (I). The larger pigs simulate humans larger than of mean size. Ketamine was used as the main anesthetic drug.

Methods

The parameters listed below were used to evaluate the efficiency of CPR. Rib fractures and other injuries were documented at the autopsy.

- Intrathoracic aortic pressure
- Right atrial pressure
- Intrapericardial pressure
- Coronary perfusion pressure
- Intratracheal pressure (via Boussignac tube)
- Cardiac output (via Swan Ganz catheter)
- End-tidal CO_2
- Left carotid artery blood flow
- Esophageal temperature
- Blood gases
- Electrocardiogram (ECG)

Figure 9 shows a schematic drawing of the porcine vascular system. The placement of pressure catheters and a blood flow probe are also shown.

1. *Ascending Aorta*
2. *Right coronary artery*
3. *Left coronary artery*
4. *Coronary sinus*
5. *Right atrium*
6. *Right carotid artery*
7. *Catheters (two in each position) for continuous pressure measurements and blood gases*
8. *Left carotid artery with an ultrasonic blood flow probe*

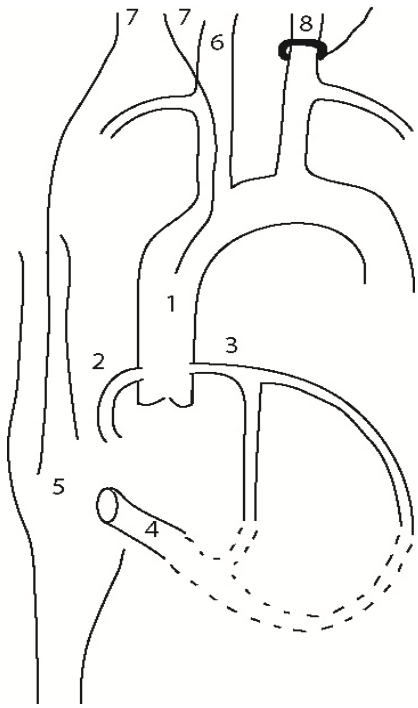

Fig 9. Schematic drawing of the porcine vascular system of importance for the present thesis. The pig anatomy is slightly different from human anatomy, having 2 brachiocephalic trunks.

Results

Manual CPR compared to LUCAS-CPR

20-25 kg pigs (I)

Twelve 20-25 kg pigs were randomized to manual or LUCAS-CPR for 10 min after 90 s of ventricular fibrillation. No pharmacotherapy was allowed. None of the pigs in the manual group achieved ROSC, whereas 5 of 6 pigs in the LUCAS-CPR group achieved ROSC ($p<0.02$, Fischer's Exact Test). There was no difference in aortic compression pressure between the 2 groups, indicating that the manual compressions were given with the same force as the mechanical compressions (Fig 10). The following parameters were significantly better in the LUCAS-CPR group: coronary perfusion pressure (Fig 11), cardiac output, $ETCO_2$, and carotid arterial blood flow.

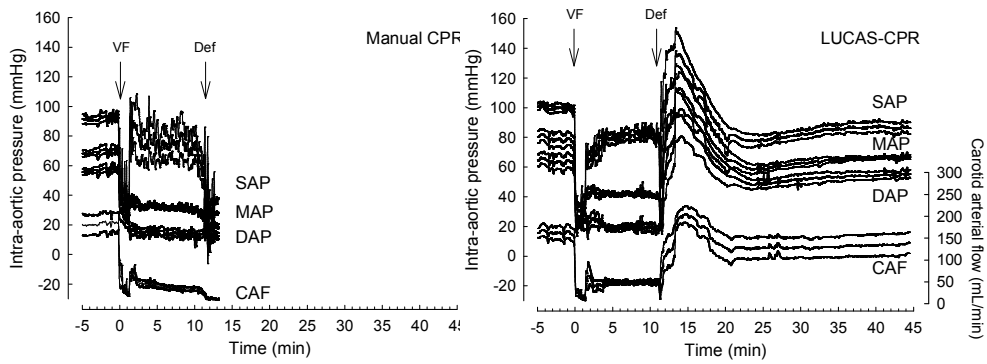

Fig 10. The pressure- and carotid flow curves. There was no ROSC in the manual group, whereas 5 of 6 animals obtained ROSC with LUCAS-CPR. Data shown as mean ± SEM, n = 6. CAF = carotid arterial blood flow, SAP, MAP, DAP = systolic, mean and diastolic intrathoracic aortic pressure. VF = induction of ventricular fibrillation. Def = defibrillation.

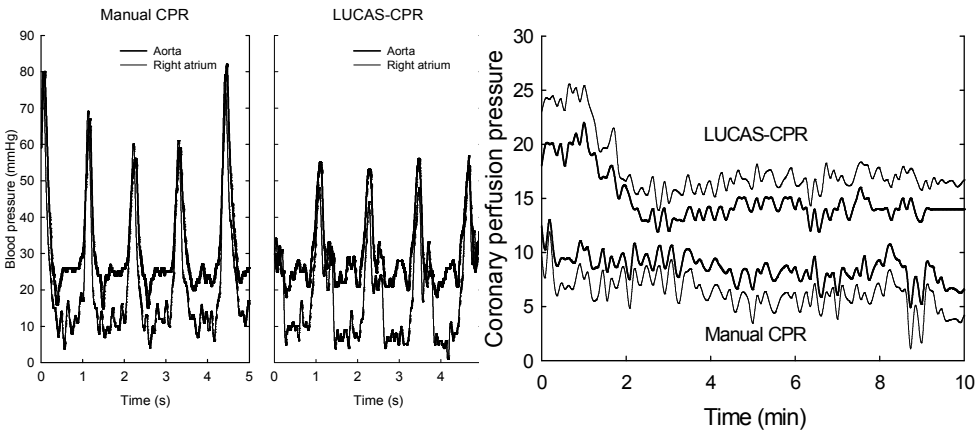

Fig 11. Typical pressure curves obtained in a 20-25 kg pig during manual CPR and LUCAS-CPR (left two panels). The area between the curves for intrathoracic aortic pressure and right atrial pressure gives a picture of the coronary perfusion pressure. Note the biphasic positive curves and greater area between the curves during LUCAS-CPR. In the right panel is shown the mean coronary perfusion pressure with SEM on one side of the mean.

28-33 kg pigs (III)

Sixteen 28-33 kg pigs were stratified into 2 groups of 8 animals. After 5 minutes of ventricular fibrillation, CPR was run for 20 minutes before the first defibrillation was given (simulating prolonged CPR for VF resistant to defibrillation) (Fig 12).

All animals in the LUCAS group achieved ROSC, compared to 3 of 8 animals in the manual group ($p<0.03$, Fischer's Exact Test). The coronary perfusion pressure in the LUCAS group varied between 18 and 25 mmHg, whereas in the manual group it varied between 5 and 10 mmHg (Fig 13). The compression pressure in the ascending aorta and the $ETCO_2$ were significantly higher in the LUCAS group.

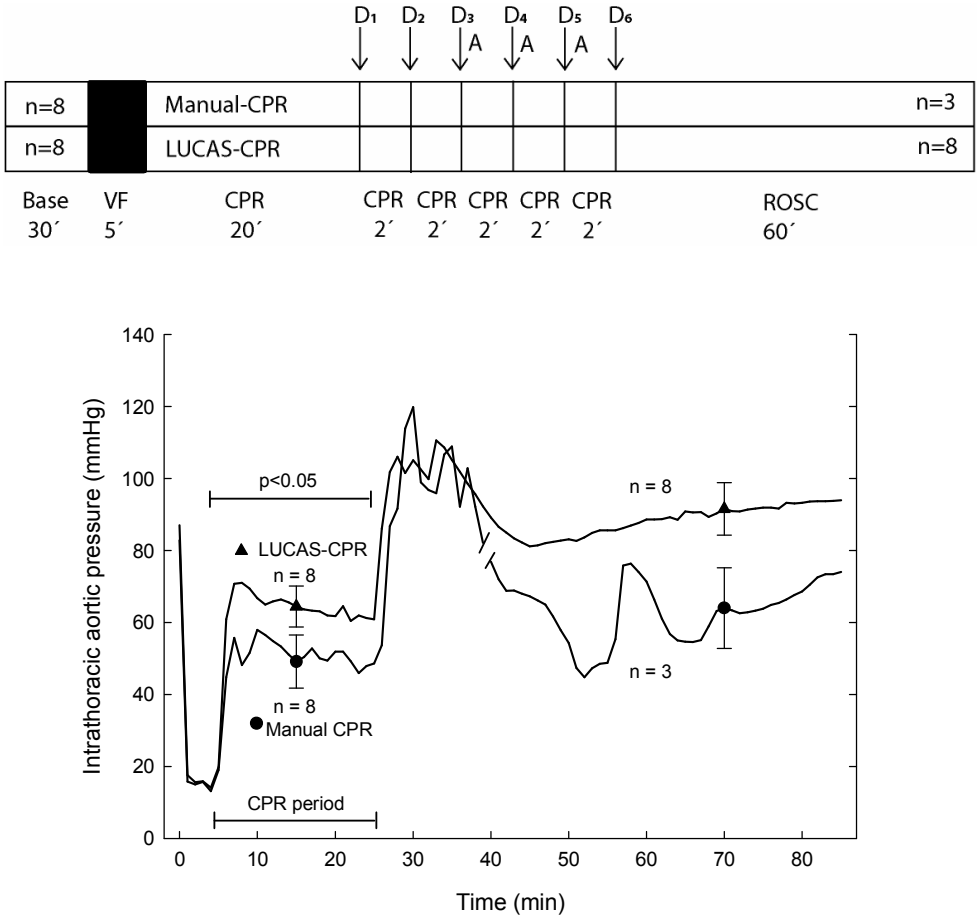

Fig 12. The design of the study (upper panel). The number of pigs with return of spontaneous circulation (ROSC) is indicated within the ROSC rectangle. VF: ventricular fibrillation; CPR: cardiopulmonary resuscitation; D_1-D_6: defibrillations; A: adrenaline 0.01 mg/kg given intravenously. The lower panel shows the mean systolic pressure and during CPR the compression pressure, in the intrathoracic aorta during the experiment. The CPR period is marked. The break in the manual CPR curve marks where n is changed from 8 to 3 individuals. Mean±SEM is included in 2 places in each curve; n=8, except for the ROSC period for manual CPR, where n=3.

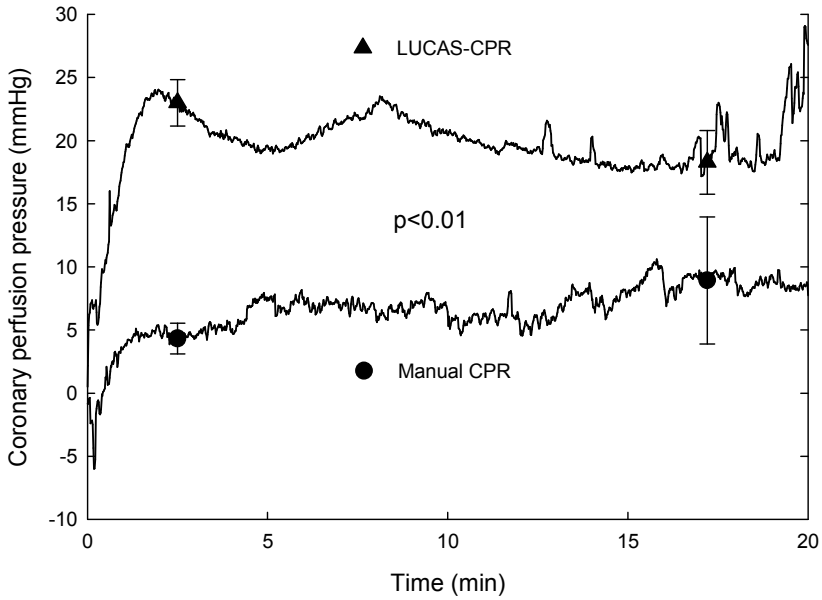

Fig 13. The coronary perfusion pressure during LUCAS-CPR and manual CPR.

Normothermic versus hypothermic CPR (I)

Three of the 8 pigs achieved ROSC in the normothermic group and 6 of the 8 in the hypothermic group (Fig 14). The surface cooling was done with ice placed directly on the skin during the first 30 minutes of the 1-hour LUCAS-CPR period. In the normothermic group, the coronary perfusion pressure, which was between 15 and 18 mmHg during the first 20 minutes, then began to decrease and at the

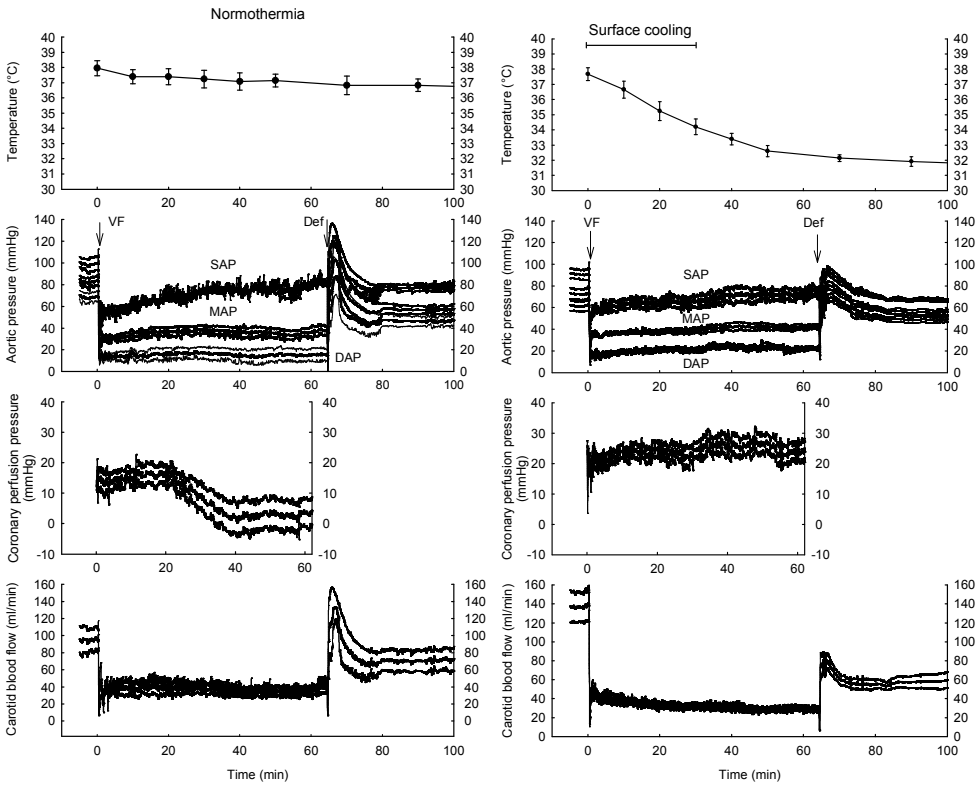

Fig 14. LUCAS-CPR during 1 hour of ventricular fibrillation (VF) with normothermia (left panel) and surface cooling (right panel) during the first half hour. Temperature, systolic, mean and diastolic (SAP, MAP, DAP) intrathoracic aortic pressure, coronary perfusion pressure, and right carotid arterial blood flow are shown as mean ± SEM. n=8.

end of the 60-minute period it was between 0 and 5 mmHg. In the surface cooling group, the coronary perfusion pressure increased from 15 to 20 mmHg within 5 minutes of cooling, and continued to increase to 25 mmHg over the next 55 minutes. The esophagus temperature was 34°C after 30 minutes, the ice was then removed, but an afterdrop of 2°C occurred, so that after 1 hour of LUCAS-CPR the esophagus temperature was 32°C. The reactive hyperaemia after ROSC was higher in the normothermic group (Fig 14).

Hemodynamics of ventricular fibrillation (II)

Figure 15 shows frozen pictures from a video uptake after induction of ventricular fibrillation and figures 16-18 shows the blood pressure, blood flow and intrapleural pressure curves. Blood circulation continues for 5 minutes after ventricular fibrillation, i.e., it continues as long as the aortic pressure is higher than the pressure in the right atrium. The right ventricle increases gradually in size, as the right atrial pressure increases, and this causes a form of tamponade since the pericardial pressure increases in parallel with the right atrial pressure. After 5 minutes, the right ventricle is distended, and there is no coronary perfusion pressure. Defibrillation of such a heart, even if sinus rhythm is obtained, will give no return of spontaneous circulation due to the distended right ventricle without coronary perfusion. It takes a minimum of 90 seconds of chest compressions to build up an adequate coronary pressure. As seen in figure 16, during the first minute of chest compressions the coronary perfusion pressure is negative, i.e., the pressure in the right atrium during the decompression phase is higher than the pressure in the descending aorta.

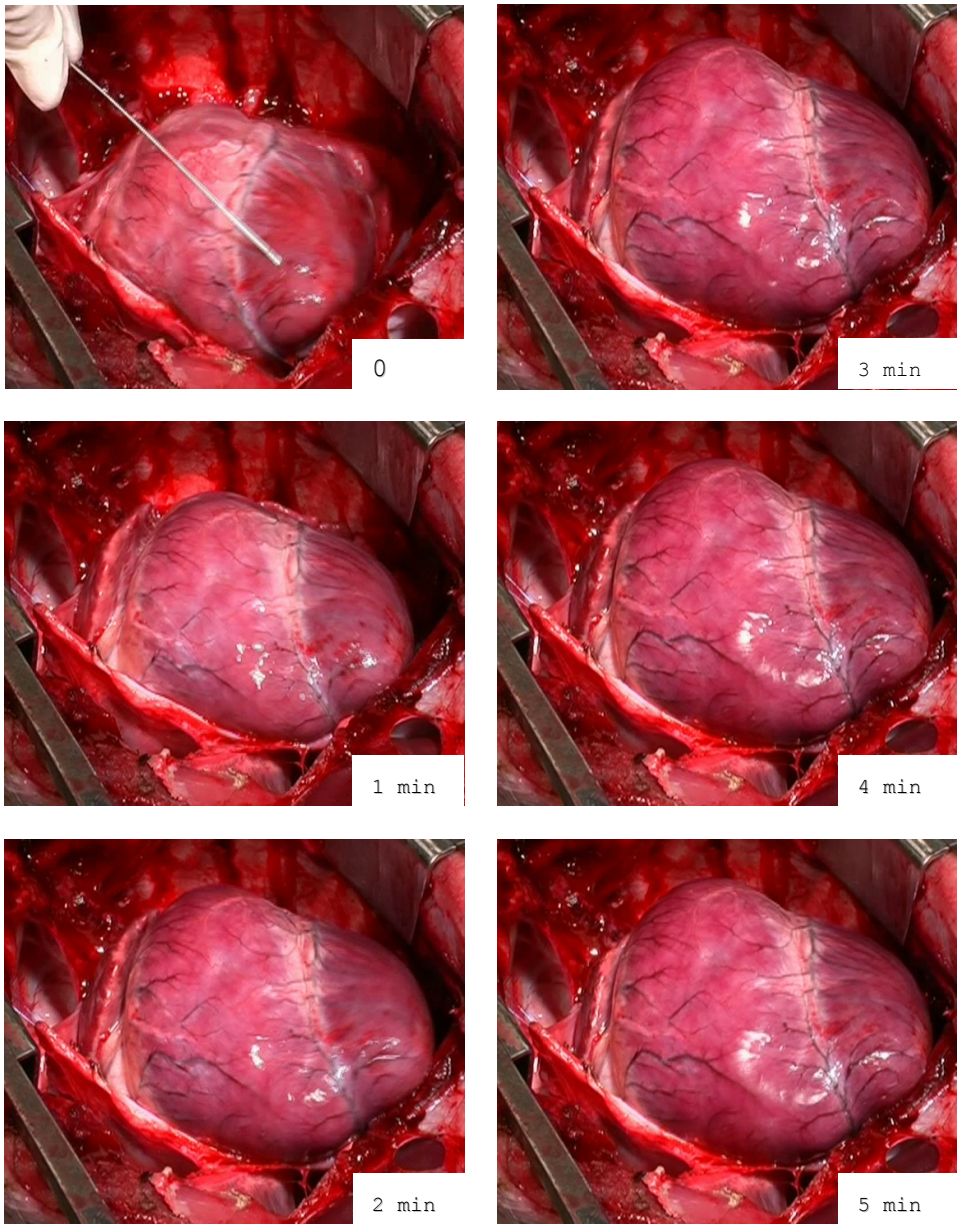

Fig 15. Frozen pictures from the video uptake after induction of ventricular fibrillation. The anterior part of the right and the left ventricle on each side of LAD is seen. The right ventricle grows in size and is severely distended after 5 minutes.

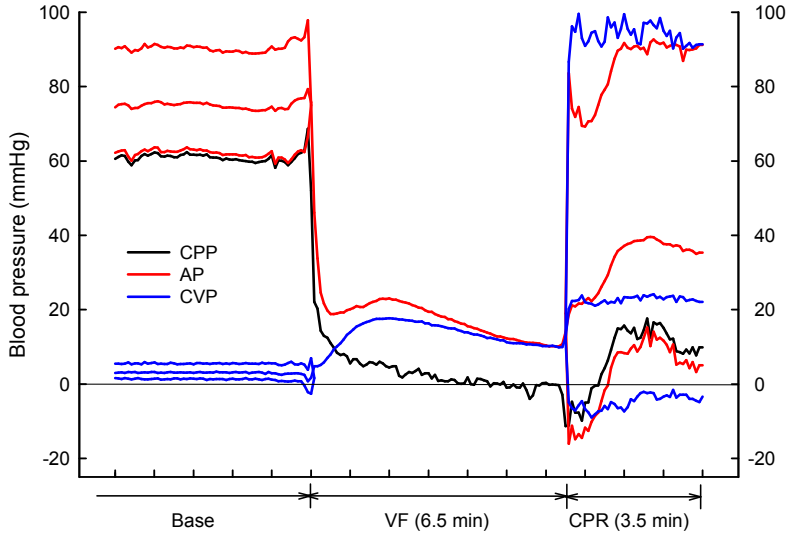

Fig 16. Intrathoracic aortic pressure (red curves), pressure in the right atrium (blue curves) and computed coronary perfusion pressure (black curve) are shown during 6.5 min of ventricular fibrillation followed by 3.5 min of mechanical chest compressions. Systolic, diastolic and mean pressure are shown to the left (Base), and compression, decompression and mean pressure to the right (during CPR). The curves represent the mean values from 12 pigs. For the sake of clarity, the standard error of the mean is not shown.

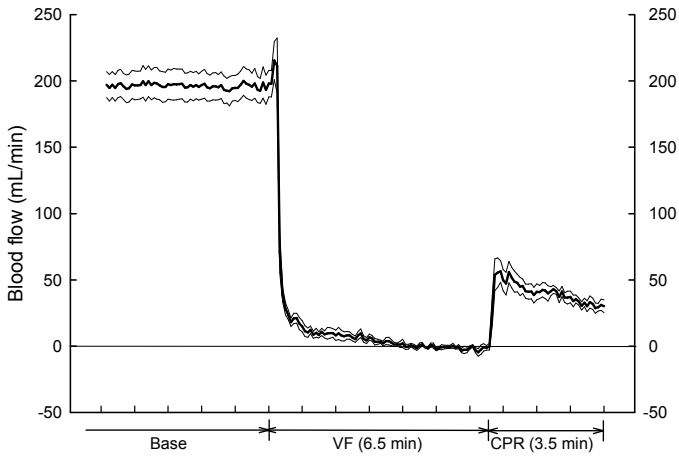

Fig 17. The blood flow in the left internal carotid artery during 6.5 min of ventricular fibrillation followed by 3.5 min of mechanical chest compressions. The mean value ± SEM is shown from 12 pigs.

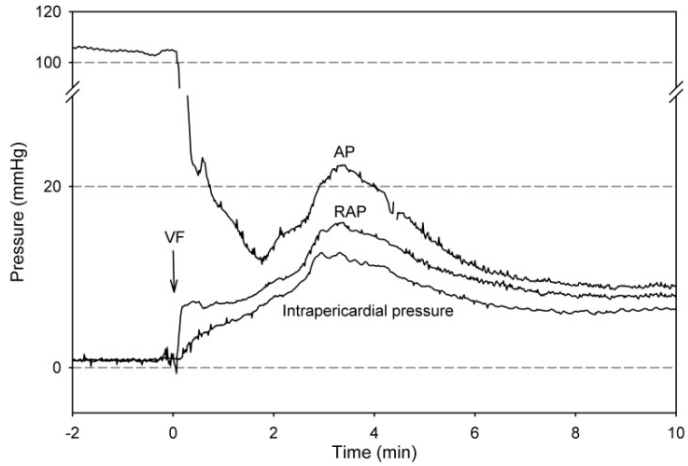

Fig 18. Pressure recordings of the first 10 min of ventricular fibrillation in one pig in which intrapericardial pressure was also registered. AP=intrathoracic aortic pressure, RAP=right atrial pressure.

Defibrillation of prolonged ventricular fibrillation (II)

The design of the experiments is shown in figure 19.

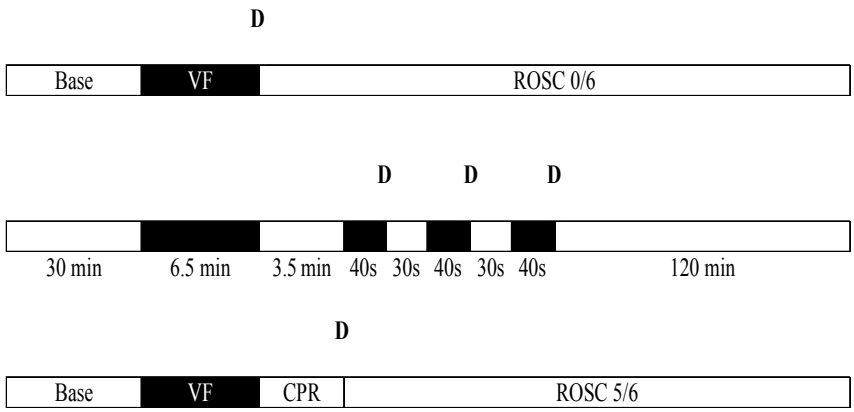

Fig 19. The design of the experiments. The number of pigs with ROSC (return of spontaneous circulation) is indicated within the ROSC rectangle. D=Defibrillation. VF=Ventricular Fibrillation. CPR=CardioPulmonary Resuscitation.

Group I: defibrillation was done after 6.5 minutes of ventricular fibrillation without chest compressions before or after. Four of six animals were successfully defibrillated on the first attempt and sinus rhythm with bundle branch block was recorded. However, this was pulseless electrical activity without arterial pressure or blood flow.

Group II: Delayed defibrillation after chest compressions. After 2 minutes of chest compressions, an adequate coronary perfusion pressure was obtained, but when the chest compressions were interrupted, to obtain readable ECG, the adequate coronary perfusion pressure was lost within seconds, and when defibrillation was done, ROSC was obtained in only one pig (Fig 20). The 30-second LUCAS-CPR periods between the defibrillations were too short to obtain a coronary perfusion pressure as seen in the figure: during LUCAS-CPR it was negative, i.e., the right atrial pressure was higher than the ascending aortic pressure during the decompression phase with no flow in the coronary arteries as a consequence.

Group III: Defibrillation was done after 3.5 minutes during on-going LUCAS-CPR. Five of six animals achieved ROSC (Fig 20).

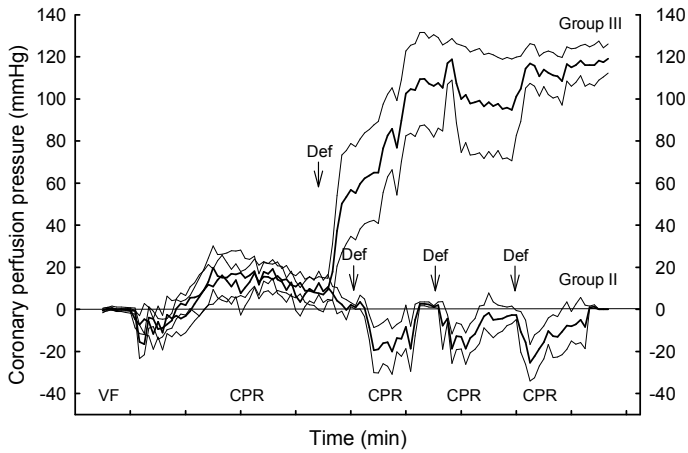

Fig 20. Coronary perfusion pressure during 3.5 min of mechanical compressions and during defibrillation attempts with (II) and without (III) interrupting the chest compressions. Mean value ± SEM, n=5 in each group.

Injuries after manual CPR versus LUCAS-CPR (III)

There were significantly ($p<0.01$) more rib fractures in the manual group: 33 on the left side and 21 on the right side, as compared to 30 on the left side and 2 on the right side in the LUCAS group. Two serious injuries occurred in the manual group, one right sided pressure pneumothorax and one vertical deep liver rupture with 500 ml blood in the abdomen, which is about 20% of the blood volume of a pig this size.

COMMENTS

The results from the three studies have been discussed in detail in each article. The comments below deal with issues that must be considered for a better understanding of the results.

Porcine versus human thorax

The human thorax in the supine position is like an egg lying on its side, whereas in the same position the porcine thorax is like an egg standing on its end, see figure 21.

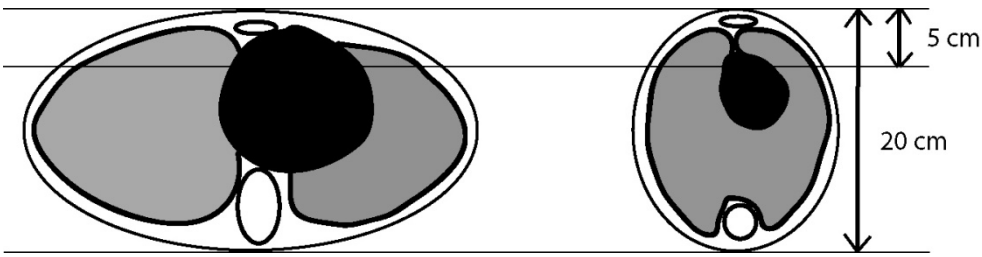

Fig 21. Schematic drawings of a human (left) and porcine (right) thorax.

The anterior-posterior diameter of 20-25 kg pigs is around 20 cm, which is the same as for adult humans of mean size (I).

The Utstein-style guidelines for uniform reporting of laboratory CPR-research (23) advocate the use of 20-25 kg pigs, because a compression depth of 5 cm will give a 25% reduction of the anterio-posterior diameter, and that is what the international guidelines recommend (19-22).

There are important differences between human and pig thorax anatomy that have implications in CPR studies. In pigs, the heart is positioned more centrally in the thorax cavity surrounded by lung tissue on all sides (I). In humans the right ventricle is positioned just under the sternum. This difference makes it more difficult to get a compression effect on the heart in pigs where the compressions affect the heart only by `the thoracic pump mechanism´, i.e., a chest compression increases the intrathoracic pressure which in turn affects the heart. In humans not only `the thoracic pump mechanism´ but also a `heart pump mechanism´ works, i.e. direct compression of the heart by chest compressions. Patients with chronic obstructive pulmonary disease (COPD) have a thorax that is more like the porcine thorax with lungs surrounding the heart on all sides. Due to these differences it is more difficult to obtain high arterial compression pressures in pigs than in humans.

Coronary perfusion pressure during CPR

During adequate chest compression the right atrial pressure rises to the same peak value as the intrathoracic aortic pressure. During the compression phase, there is practically no difference between the ascending aortic pressure and right atrial pressure, i.e., the coronary pressure is zero, see fig 22.

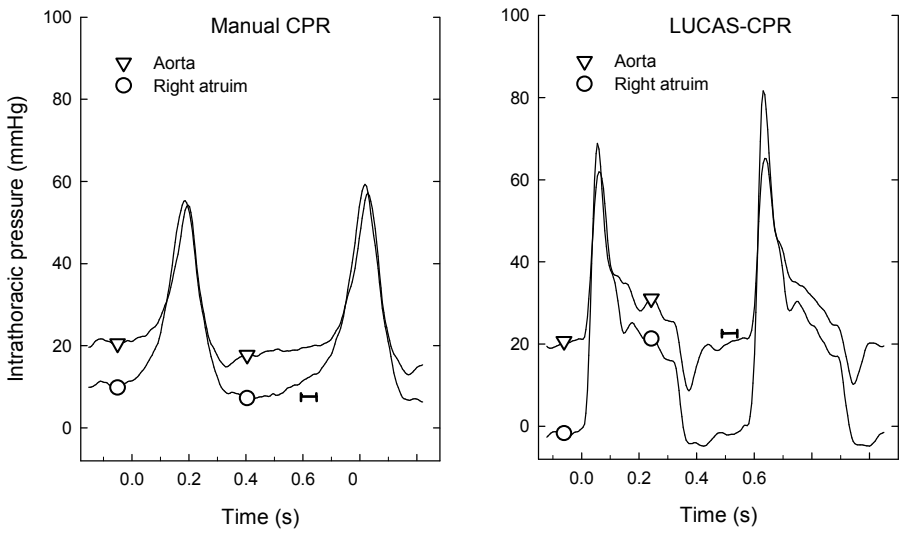

Fig 22. The coronary perfusion pressure curves in the intrathoracic aorta (triangles) and the right atrium (circles) during two cycles of CPR in the manual CPR (left) and LUCAS-CPR (right) groups just after a ventilation. A bar is inserted before one compression in both panels. The 0.05-second long bar shows where in the cycle CPP is calculated (as the difference between the pressure in

aorta and right atrium). The level of the bar shows the CPP in this registration; 7 mmHg in the manual group and 22 mmHg in the LUCAS group.

During the decompression phase, both the ascending aortic pressure and right atrial pressure diminish, and right atrial pressure most. The difference between these 2 pressures during the decompression phase is the coronary pressure resulting in a coronary blood flow. It can be measured as the lowest registered intraaortic pressure minus the lowest registered right atrial pressure during the decompression phase, or it can be measured as the difference at the end of the decompression phase (III). A coronary perfusion pressure higher than 15 mmHg is one indication that the coronary flow is at the minimum for ROSC to be obtained, both in humans (24-26) and in pigs (I).

$ETCO_2$ as an indication of cardiac output during CPR

If the ventilation during CPR is standardized, $ETCO_2$ is an indication of cardiac output during CPR, the higher the $ETCO_2$, the higher the cardiac output. It is easy to hyperventilate during CPR if the ventilation is done manually, and then $ETCO_2$ is not to be trusted. But for experimental use, with standardized ventilation in all groups to be compared, it is a valuable tool to judge the cardiac output obtained during CPR.

Carotid artery blood flow in pigs

In pigs the carotid artery supplies mainly extracranial muscles, and cannot be used as an indication of cerebral flow (27).

Hypothermia induced during on-going CPR

In cardiac surgery hypothermia has been used routinely since the 1950-ties. For routine cardiac surgery with extracorporeal circulation, the patient is cooled to 32°-28°C, and when major surgery is needed, e.g., for dissection of the ascending aorta, target temperatures between 22°-16°C are often used.

There is no consistent definition of hypothermia, but for doctors treating hypothermic patients without extracorporeal circulation, mild hypothermia is defined as temperatures down to 32°C and moderate hypothermia down to 28°C.

A patient with a body temperature below 28°C would by most doctors be characterized as being in deep hypothermia.

In study I we wanted to study the effect of mild hypothermia. In pigs the metabolism will be reduced by about 6-7% per degree Celsius that the body temperature is lowered (28-29). A reduction of body temperature from 38°C (normal in pigs) to 32°C will reduce the metabolism by 35-45%, with the consequence that less circulation will be needed to ensure an adequate organ perfusion. The pigs treated with hypothermia and LUCAS-CPR for 1 hour developed a metabolic acidosis over time, indicating that the organ perfusion was not adequate, although it was better than for the normothermic pigs.

Injuries during chest compressions

It is difficult to give manual compressions consistently, many compressions are either too shallow or too deep. People are trained to give correct chest compressions on mannequins which do not get rib fractures, i.e., what is registered as adequate forceful compressions in the beginning will not take into consideration the human condition that for each rib broken, less and less force will be needed to compress the chest 5 cm (16-18). If you use the same force as needed in the beginning to compress a human thorax 5 cm, also after several ribs have been broken, then the compressions will be too deep, with the risk of creating severe injuries. This was the case with the CardioPump, in which a scale indicated the force you should use in each compression, and this force was constant throughout the CPR period, regardless of the number of broken ribs, and regardless of the flattening of the thorax. Baubin demonstrated in studies on human corpses, that the CardioPump fractured the sternum in 9 out of 17 women and in 2 out of 20 men after 1 minute of CardioPump CPR (17). The female sternum is usually thinner and broader than the male sternum (30), and thus prone to greater fragility during chest compressions.

If manual CPR has been given before the application of LUCAS, it is important to judge if the thorax is already flattened due to multiple bilateral rib fractures. If LUCAS is applied too tight on an initially flattened thorax of a normal sized or on a small patient, the compression depth of 5 cm might diminish the antero-posteroir diameter too much with the risk of causing visceral injuries.

Multiple rib fractures will diminish the elastic recoil of the thorax after each compression. The elastic recoil of an intact thorax reduces the right atrial pressure and thereby will increase the venous return. Active decompression will lower the right atrial pressure in each decompression phase, and thereby increase both coronary perfusion pressure and venous return (Fig 22).

In the manual CPR group in paper III, one pig suffered a serious liver injury. It is important to consider that one too deep compression can cause such an injury. One of the disadvantages with manual CPR is the difficulty in controlling the depth of each compression. It was not surprising that LUCAS-CPR gave significantly fewer rib fractures than manual CPR, since the compression depth with LUCAS never can be more than 5 cm.

In clinical papers studying injuries after chest compressions with LUCAS, manual CPR was given before the application of LUCAS and therefore the injuries reported could have been caused before LUCAS was applied. A prospective human study comparing manual and LUCAS-CPR showed no increased rate of injuries in the LUCAS-CPR group (31). A study (32) on 106 pigs showed fewer injuries with LUCAS-CPR (n=53) compared to manual CPR (n=53). Autopsy was done on all animals. Sternal fractures were identified in 18 animals in the manual group and only two in the LUCAS group ($p=0.003$). Rib fractures were present in 16 pigs in the manual group and only four pigs in the LUCAS group ($p=0.001$). Nine animals in the manual group and two in the LUCAS group had liver hematomas ($p=0.026$), and eight animals had spleen hematomas in the manual group, whereas no such injury was identified in the LUCAS group ($p=0.003$) (32).

Since the first scientific paper published on LUCAS (I) in 2002, several studies and reports have shown the efficacy of LUCAS-CPR (II, III, 33-65).

Conclusion

1. LUCAS-CPR is significantly more effective than manual CPR regarding coronary perfusion pressure and return of spontaneous circulation in different porcine models with ventricular fibrillation.

2. LUCAS-CPR combined with surface cooling to 34°C is superior to normothermic LUCAS-CPR during one hour resuscitation of pigs with ventricular fibrillation.

3. Chest compressions before defibrillation and defibrillation during on-going chest compressions increase return of spontaneous circulation in a porcine model with prolonged ventricular fibrillation.

4. LUCAS-CPR causes significantly fewer rib fractures during 20 minutes of CPR compared to manual CPR in pigs.

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References

1. The Hypothermia After Cardiac Arrest Study Group. Mild therapeutic hypothermia to improve the neurologic outcome after cardiac arrest. N Engl J Med 2002;346:546 2002;346:549-556.
2. Curfman GD. Hypothermia to protect the brain. Perspective. N Engl J Med 2002;346:546.
3. Kouwenhoven WB, Jude JR, Knickerbocker GG. Closed-chest cardiac massage. J Am Med Assoc 1960;173:1064-1067.
4. Nationellt register för hjärtstopp utanför sjukhus. Årsrapport 2009. http://www.hlr.nu/sites/hlr.nu/files/attachment/rapport2009_0.pdf
5. Hightower D, Thomas SH, Stone CK, Dunn K, March JA: Decay in quality of closed-chest compressions over time. Ann Emerg Med 1995; 26:300-303.
6. Sunde L, Wik K, Steen PA: Quality of mechanical, manual standard and active compression-decompression CPR on the arrest site and during transport in a manikin model. Resuscitation 1997;34:235-242.
7. Ocha FJ, Ramalle-Gómara E, Lisa V, Saralegui I: The effect of rescuer fatigue on the quality of chest compressions. Resuscitation 1998;37:149-152.
8. Thorén AB, Axelsson A, Holmberg S, Herlitz J: Measurement of skills in cardiopulmonary resuscitation - do professionals follow given guidelines? Eur J Emerg Med 2001;8:169-176.
9. Ashton A, McCluskey A, Gwinnutt CL, Keenan AM: Effect of rescuer fatigue on performance of continuous external chest compressions over 3 min. Resuscitation 2002;55:151-155.
10. Wik L, Kramer-Johansen J Myklebust H, Sørebø H, Svensson L, Fellows B, Steen PA: Quality of cardiopulmonary resuscitation during out-of-hospital cardiac arrest. JAMA 2005;293:299-304.
11. Heidenreich JW, Berg RA, Higdon TA, Ewy GA, Kern KB, Sanders AB: Rescuer fatigue: standard versus continuous chest-compression cardiopulmonary resuscitation. Acad Emerg Med 2006;13:1020-1026.

12. Aufderheide TP, Pirrallo RG, Yannopoulos D, Klein JP, von C, Sparks CW, Deja KA, Kitscha DJ, Provo TA, Lurie KG: Incomplete chest wall decompression: a clinical evaluation of CPR performance by trained laypersons and an assessment of alternative manual chest compression-decompression techniques. Resuscitation 2006;71:341-351.

13. Kim JA, Vogel D, Guimond G, Hostler D, Wang HE, Menegazzi JJ: A randomized, controlled comparison of cardiopulmonary resuscitation performed on the floor and on a moving ambulance stretcher. Prehosp Emerg Care 2006;10:68-70.

14. Olasveegen TM, Tomlison AE, Wik L, Sunde K, Steen PA, Myklbust H, Kramer-Johansen J: A failed attempt to improve quality of out-of-hospital CPR through performance evaluation. Prehosp Emerg Care 2007;11:427-433.

15. Plaisance P, Lurie KG, Vicaut E, Adnet F, Petit JL, Epain D, Ecollan P, Gruat R, Cavagna P, Biens J, Payen D. A comparison of standard cardiopulmonary resuscitation and active compression - decompression resuscitation for out-of-hospital cardiac arrest. N Engl J Med 1999;341:569-575.

16. Baubin M, Suman G, Rabl W, Eibl G, Wenzel V, Mair P. Increased frequency of thorax injuries with ACD-CPR. Resuscitation 1999;41:33-38.

17. Baubin M, Rabl W, Pfeiffer KP, Benzer A, Gilly H. Chest injuries after active compression-decompression cardiopulmonary resuscitation (ACD-CPR) in cadavers. Resuscitation 1999;43:9-15.

18. Rabl W, Baubin M, Broinger G, Scheithauer R. Serious complications from active compression-decompression cardiopulmonary resuscitation. Int J Legal Med 1996;109:84-89.

19. European Resuscitation Council Guidelines 2005. Resuscitation 2005;67:53-189.

20. 2005 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Circ 2005;112:1-203.

21. European Resuscitation Council Guidelines for Resuscitation 2010. Resuscitation 2010;81:1219-1452.

22. 2010 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science. Circ 2010;122:S250-946.

23. Idris AH, Becker LB, Ornato JP, Hedges JR, Bircher NG, Chandra NC, Cummins RO, Dick W, Ebmeyer U, Halperin HR, Hazinski MF, Kerber

RE, Kern K, Safar P, Steen PA, Swindle MM, Tsitlik JE, Planta v I, Planta v M, Wears RL, Weil MH. Utstein-style guidelines for uniform reporting of laboratory CPR research. Resuscitation 1996;33:69-84.

24. Paradis NA, Martin GB, Rivers EP, Goetting MG, Appleton TJ, Feingold M, Nowak RM. Coronary perfusion pressure and the return of spontaneous circulation in human cardiopulmonary resuscitation. J Am Med Assoc 1990;263:1106-1113.

25. Kern KB, Niemann JT, Steen S. Coronary perfusion pressure during cardiopulmonary resuscitation. In: Cardiac arrest, The Science and practice of resuscitation medicine. Eds: Paradis NA, Halperin HR, Kern KB, Wenzel V, Chamberlain DA. Cambridge University Press, Cambridge, England. 2007:369-388.

26. Frenneaux M, Steen S. Hemodynamics of cardiac arrest. In: Cardiac arrest, The Science and practice of resuscitation medicine. Eds: Paradis NA, Halperin HR, Kern KB, Wenzel V, Chamberlain DA. Cambridge University Press, Cambridge, England. 2007:347-366.

27. Ghoshal NG, Nanda BS. Porcine heart and arteries. In: The anatomy of the domestic animals. Ed. Getty R. W.B. Saunders Company, Philadelphia, USA. 1975:1306-1342.

28. Wetterberg T, Steen S. Combined use of hypothermia and buffering in the treatment of critical respiratory failure. Acta Anaesthesiol Scand. 1992;36:490-492.

29. Wetterberg T, Sjöberg T, Steen S. Effects of hypothermia in hypercapnia and hypercapnic hypoxemia. Acta Anaesthesiol Scand. 1993;37:296-302.

30. Leopold D, Geschlechtsbestimmung durch untersuchung der einzelnen knochen des skeletts – der knöcherne thorax. In: Identifikation. Eds: Hunger H, Leopold D. Johannes Ambrosius Barth Verlag. Leipzig, Germany. 1978:113-182.

31. Smekal D, Johansson J, Huzevka T, Rubertsson S. No difference in autopsy detected injuries in cardiac arrest patients treated with manual chest compressions compared with mechanical compressions with the LUCAS device - a pilot study. Resuscitation 2009;80:1104-1107.

32. Xanthos T, Pantazopoulos I, Roumelioti H, Lelovas P, Iacovidou N, Dontas I, Demestiha T, Spiliopoulou H. A comparison of autopsy detected injuries in a porcine model of cardiac srrest treated with either manual or mechanical chest compressions. Eur J Emerg Med 2010;00:00-00. DOI: 10.1097/MEJ.0b013e32833e79cf

33. Steen S, Liao Q, Pierre L, Paskevicius A, Sjöberg T. Continuous intratracheal insufflation of oxygen improves the efficacy of mechanical chest compression-active decompression CPR. Resuscitation. 2004;62:219-227.

34. Steen S, Sjöberg T, Olsson P, Young M. Treatment of out-of-hospital cardiac arrest with LUCAS, a new device for automatic mechanical compressions and active decompression resuscitation. Resuscitation. 2005;67:25-30.

35. Rubertsson S, Karlsten R. Increased cortical cerebral blood flow with LUCAS, a new device for mechanical chest compressions compared to standard external compressions during experimental cardiopulmonary resuscitation. Resuscitation. 2005;65:357-363.

36. Holmström P, Boyd J, Sorsa M, Kuisma M. A case of hypothermic cardiac arrest treated with an external chest compression device (LUCAS) during transport to re-warming. Resuscitation. 2005;67:139-141.

37. Wik L, Kiil S. Use of an automatic chest compression device (LUCAS) as a bridge to establishing cardiopulmonary bypass for a patient with hypothermic cardiac arrest. Resuscitation. 2005;66:391-394.

38. Vatsgar TT, Ingebrigtsen O, Fjose LO, Wikstrøm B, Nilsen JE, Wik L. Cardiac arrest and resuscitation with an automatic mechanical chest compression device (LUCAS) due to anaphylaxis of a woman receiving caesarean section because of pre-eclampsia. Resuscitation. 2006;68:155-159.

39. Chan LW, Wong TW, Lau CC. Mechanical cardiopulmonary resuscitation device in an accident and emergency department: a case report and literature review. Hong Kong J Emerg Med. 2008;15:49-52.

40. Olivecrona G, Bondesson P. Mechanical Chest Compressions in a Patient with Left Main Closure During PCI. www.tctmd.com, Case of the week, 24th of October 2006.

41. Agostoni P, Cornelis K, Vermeersch P. Successful percutaneous treatment of an intraprocedural left main stent thrombosis with the support of an automatic mechanical chest compression device. Int J Cardiol 2008;124:e19–21.

42. Larsen AI, Hjørnevik AS, Ellingsen CL, Nilsen DW. Cardiac arrest with continuous mechanical chest compression during percutaneous coronary intervention. A report on the use of the LUCAS device. Resuscitation. 2007;75:454 -459.

43. Farmery JS, Carter M. Use of the Lund University Cardiopulmonary Assist System in the MD902: a fire safety assessment. Emerg Med J. 2007;24:110–111.

44. Ristagno G, Tang W, Wang H, Sun S, Weil MH. Comparison between mechanical active chest compression/decompression and standard mechanical chest compression. Circulation. 2007;116:II_929-930.

45. Bonnemeier H, Olivecrona G, Simonis G, Götberg M, Weitz G, Iblher P, Gerling I, Schunkert H. Automated continuous chest compression for in-hospital cardiopulmonary resuscitation of patients with pulseless electrical activity: A report of five cases. Int J Cardiol. 2009;36:e39-50.

46. Noc M, Radsel P. Urgent invasive coronary strategy in patients with sudden cardiac arrest. Current Opinion in Critical Care. 2008;14:287–291.

47. Sunde K. Experimental and clinical use of ongoing mechanical cardiopulmonary resuscitation during angiography and percutaneous coronary intervention. Crit Care Med. 2008;36:S405-408.

48. Matsuura TR, McKnite SH, Metzger AK, Yannopoulos D, Aufderheide TP, Lurie KG. Impedance threshold compression-decompression CPR device (LUCAS) improves chances for survival in pigs in cardiac arrest. Circulation. 2008;118:S1449-1450.

49. Bonnemeier H, Olivecrona, Simonis, Götberg, Weitz, Barantke, Gerling, Schunkert. The decisive role of effective continuous chest compression for in-hospital resuscitation of pulseless electrical activity. Resuscitation. 2008; 77S: S7-8.

50. Durnez P, Stockman W, Wynendaele R, Gemonpre P, Dobbels P. ROSC and neurologic outcome after in-hospital cardiac arrest and LUCAS-CPR. Resuscitation. 2008;77S:S49.

51. Wilde de R, Weiden P, Haan de M, Bosch J, Nooij de J, Harinck HIJ. ROSC at hospital admission in out of hospital cardiac arrest using LUCAS. Resuscitation. 2008;77S:S49.

52. Bonnemeier H, Gerling I, Barantke M, Schunkert H. Necropsy findings of non-survivors of CPR after mechanical and conventional chest compression. ERC congress in Gent. 2008;Poster 470.

53. Kyrval HS, Ahmad K . Mekanisk hjertemassage under helikoptetransport. Ugeskr. Læger. 2010;172:3190-3191.

54. Greisen J, Golbækdal KI, Mathiassen ON, Ravn HB. Langvarig automatiseret hjertemassage. Ugeskr. Læger. 2010;172:3191-3192.

55. Wagner H, Terkelsen CJ, Friberg H, Harnek J, Kern K, Lassen JF, Olivecrona GK. Cardiac arrest in the catheterization laboratory; a 5-year experience of using mechanical chest compressions to facilitate PCI during prolonged resuscitation efforts. Resuscitation. 2010;81:383-387.

56. Axelsson C, Karlsson T, Axelsson AB, Herlitz J. Mechanical active compression-decompression cardiopulmonary resuscitation (ACD-CPR) versus manual CPR according to pressure of end tidal carbon dioxide (PETCO2) during CPR in out-of-hospital cardiac arrest (OHCA). Resuscitation 2009;80:1099-1103.

57. Matevossian E, Doll D, Säckl J, Sinicina I, Schneider , Simon G, Hüser N. Prolonged closed cardiac massage using LUCAS device in out-of-hospital cardiac arrest with prolonged transport time. Open Access Em Med. 2009;I:1-4.

58. Weise M, Lützner J. Heineck J. Thrombolysis therapy at fulminant pulmonary embolism and a high risk of bleeding – what therapy makes sense? Intensivmedizin und Notfallmedizin. 2009;46:264:14.

59. Friberg H, Rundgren M. Submersion, accidental hypothermia and cardiac arrest, mechanical chest compressions as a bridge to final treatment: a case report . Scand J Trauma, Resuscitation and Emergency Medicine 2009; 17:7:1-4. www.sjtrem.com/content/17/1/7.

60. Simonis G, Ebner B, Strasser RH. Mechanical CPR device: A useful addition to the resuscitation therapy in the emergency department? Clin Res Cardiol. 2009;S98:P93.

61. Sunde K. All you need is flow. Resuscitation 2010;81:371-372.

62. Gottignies P, Devriendt J, Tran Ngoc E, Roques S, Devriendt A, Vercruyssen M, De Bels D. Thrombolysis associated with LUCAS (Lund University Cardiopulmonary Assist System) as treatment of valve thrombosis resulting in cardiac arrest. Am J of Emerg Med 2010. In press.

63. Bonnemeier H, Simonis G, Olivecrona G, Weidtmann B, Götberg M, Weitz G, Gerling I, Strasser R, Frey N. Continuous mechanical chest compression during in-hospital cardiopulmonary resuscitation of patients with pulseless electrical activity. Resuscitation 2011;82:155-159.

64. Larsen AI, Hjørnevik A, Bonarjee V, Barvik S, Melberg T, Nilsen DW. Coronary blood flow and perfusion pressure during coronary angiography in patients with ongoing mechanical chest compression: A report on 6 cases. Resuscitation. 2010;81:493–497.

65. Wyss CA, Fox J, Franzeck F, Moccetti M, Scherrer A, Hellermann JP, Lüscher TF. Mechanical versus manual chest compression during CPR in a cardiac catheterisation setting. Cardiovasc Med. 2010;13:92-96.

Enclosures

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RESUSCITATION

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Evaluation of LUCAS, a new device for automatic mechanical compression and active decompression resuscitation

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Abstract

LUCAS is a new gas-driven CPR device providing automatic chest compression and active decompression. In an artificial thorax model, superior pressure and flow were obtained with LUCAS compared with manual CPR. In a randomized study on pigs with induced ventricular fibrillation significantly higher cardiac output, carotid artery blood flow, end-tidal CO_2, intrathoracic decompression-phase aortic- and coronary perfusion pressures were obtained with LUCAS-CPR (83% ROSC) compared to manual CPR (0% ROSC). In normothermic fibrillating pigs, the ROSC rate was 100% after 15 min and 38% after 60 min of LUCAS-CPR (no drug treatment). The ROSC rate increased to 75% if surface cooling to 34 °C was applied during the first 30 min of the 1-h resuscitation period. Experience with the first 20 patients has shown that LUCAS is light (6.5 kg), easy to handle, quick to apply (10–20 s), maintains a correct position, and works optimally during transport both on stretchers and in ambulances. In one hospital patient with a witnessed asystole where manual CPR failed, LUCAS-CPR achieved ROSC within 3 min. One year later the patient's mental capacity was fully intact. To conclude, LUCAS-CPR gives significantly better circulation during ventricular fibrillation than manual CPR.

Keywords: Active compression–decompression; Cardiopulmonary resuscitation (CPR); Coronary perfusion pressure; End-tidal carbon dioxide; Hypothermia; Return of spontaneous circulation (ROSC)

Resumo

LUCAS é um novo aparelho de RCP que funciona com gás e que faz compressão torácica automática e descompressão activa. Num estudo randomizado em porcos com fibrilhação ventricular induzida foram estudados o débito cardíaco, fluxo sanguíneo da artéria carótida, CO_2 no final da expiração e pressões de perfusão coronária e aórtica na fase de descompressão intratorácica , que se verificou serem significativamente mais elevadas com a RCP com LUCAS (83% ROSC) quando comparado com RCP Manual (0% ROSC). Em porcos normotérmicos em fibrilação a taxa de ROSC foi 100% ao fim de 15 min e 38% ao fim de 60 min de RCP-LUCAS (sem tratamento farmacológico). A taxa de ROSC aumentou para 75% se fosse aplicado arrefecimento superficial até aos 34 °C nos primeiros 30 min da primeira hora do período de reanimação. A experiência com os primeiros 20 doentes mostrou que o LUCAS é leve (6.5Kg), fácil de manejar, rápido de aplicar (10–20 s), mantém uma posição correcta e trabalha de forma óptima durante o transporte em macas ou em ambulâncias. Num doente hospitalar com uma assistolia testemunhada em que a RCP manual falhou a RCP-LUCAS conseguiu ROSC em 3 min. Um ano mais tarde a capacidade intelectual do doente estava intacta. Para concluir, a RCP-LUCAS dá uma circulação significativamente melhor que a RCP manual durante a fibrilação ventricular.

Palavras chave: Compressão-descompressão activa; Ressuscitação cárdio-pulmonar (RCP); Pressão de perfusão coronária; Dióxido de carbono tele-expiratório; Hipotermia; Retorne de circulação espontânea (ROSC)

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Resumen

LUCAS es un nuevo aparato para reanimación cardiopulmonar impulsado por gas que proporciona compresiones torácicas y descompresiones activas automáticas. En un modelo de tórax artificial, se obtuvo presión y flujo superiores con LUCAS comparado con reanimación cardiopulmonar manual. En un estudio randomizado en cerdos con fibrilación ventricular inducida se alcanzaron valores significativamente mayores de gasto cardíaco, flujo de arteria coronaria, CO_2 espiratorio, presiones de perfusión coronaria y aórtica en fase de descompresión con reanimación con LUCAS (83% ROSC) comparado con reanimación manual (0% ROSC). En cerdos normotérmicos en fibrilación ventricular, la tasa de retorno a circulación espontánea (ROSC) fue de 100% después de 15 minutos y de 38% después de 60 minutos de LUCAS-RCP (sin tratamiento con drogas).La tasa de ROSC a 75% si se aplicaba enfriamiento superficial a 34 °C en los primeros 30 minutos de el período de una hora de resucitación. La experiencia con los primeros 20 pacientes ha mostrado que LUCAS es liviano (6.5 kg), fácil de usar, rápido para aplicar (10–20s), mantiene la posición correcta, y trabaja óptimamente durante el transporte, tanto en camillas como en ambulancias. En un paciente de hospital con un paro presenciado en asistolía, sonde la RCP manual falló, RCP-LUCAS consiguió ROSC en tres minutos. Un año más tarde la capacidad mental del paciente estaba intacta. Para concluir, durante la fibrilación ventricular la RCP-LUCAS proporciona una circulación significativamente mejor que la RCP manual.

Palabras clave: Compresión–descompresión activa; Reanimación cardiopulmonar (RCP); Presión de perfusión tisular; Dióxido de carbono espiratorio; Hipotermia; Retorno a circulación espontánea

1. Introduction

Cardiac arrest, either as asystole or as ventricular fibrillation (VF), is the most dramatic situation in medicine. Since Kouwenhoven and coworkers published their landmark article in 1960 [1], manual closed-chest compressions (combined with mouth-to-mouth ventilation) has been established as the initial treatment of choice for circulatory arrest, followed by defibrillation as soon as the equipment is available, if VF is the cause of the collapse. With proper training, anyone, anywhere can initiate cardio-pulmonary resuscitation (CPR). However, due to fatigue, manual CPR cannot be given for more than a few minutes before it becomes ineffective [2], and it cannot be given effectively at all during transport [3]. Most cardiac arrests occur out-of-hospital and the survival rates are very poor; in most published reports the 1-year survival rate is less than 5%. In a randomized study, Plaisance and coworkers [4] compared standard manual CPR ($n = 377$ patients) with active compression/decompression CPR performed manually with the CardioPump (AMBU, Copenhagen, Denmark) ($n = 373$ patients). The 1-year survival rate was very poor in both groups, 2 versus 5% ($P = 0.03$); all resuscitation efforts with either method were performed only at the scene of the cardiac arrest, and only if they were successfully resuscitated at the scene were the patients transported to hospital. To prevent fatigue, the rescuers were instructed to alternate after each 3 min of CPR. The study of Plaisance et al. demonstrates the need for a mechanical device giving adequate compressions/decompressions continuously until the patient can be delivered to a hospital with all facilities for the treatment of heart disease, including direct PTCA and heart surgery.

Most devices for mechanical chest compression in use today have operational limitations because they take too long to apply, they are cumbersome to install and operate, they are unstable on the chest, heavy, and expensive to purchase [5]. Therefore, no mechanical device for chest compression/decompression currently is used routinely in clinical practice, in spite of the obvious limitations of manual CPR. Recently, a new device named LUCAS, has been made commercially available (Figs. 1 and 2). It is designed to give automatic mechanical chest compression and active decompression. It is portable and works during transport both on stretchers and in ambulances.

The aim of the present investigation was to compare the efficacy of LUCAS with that of manual compressions on an artificial thorax model allowing exact analysis of pressure- and flow-curves, and on a pig model in which relevant physiological variables could be registered. In an earlier study using the same pig model we studied the effects of adrenaline (epinephrine) and noradrenaline (norepinephrine) on end-tidal CO_2, coronary perfusion pressure and cardiac output during cardiopulmonary resuscitation [6]. In the present study we decided to eliminate all drug therapy in order to elucidate the effects of chest compressions per se. Data from the first clinical pilot study with LUCAS are also presented.

2. Material and methods

2.1. The artificial thorax model

A 25 l plastic drum made of polyvinyl chloride (PVC) was used as an artificial thorax (Fig. 3). A soft plastic bag (150 ml), simulating a heart, was included in the

Fig. 1. LUCAS is designed to fit on stretchers and to be easy to operate while walking and within ambulances. Defibrillator pads illustrate that defibrillation may be done under on-going compression–decompression.

drum. Pressure (P) was continuously measured in the bag. By means of a stiff tube penetrating the tight cork of the drum, the soft bag was connected to an artificial circulatory system including two artificial heart valves for flow direction. The plastic drum was filled with 20 l water and 5 l air, and regained its original shape after deformation. During compression of the drum manually or by means of the LUCAS, the soft plastic bag ejected fluid through the outlet valve (Vo) (Carbomedics aortic valve, 25 mm Ø). To mimic the Windkessel effect of the aorta, a side tube with trapped air (C) was included in the system. Resistance in the flow system was generated using a tube compressor (R), set to give a systolic pressure of around 100 mmHg when standard manual compressions were given by a normal-sized adult male trained in CPR. (The degree of clamping was adjusted on the base of pressure measurements before and after the resistance.) The flow created by drum compression was measured continuously by a flow probe (F), (Transonic Systems Inc. HT207, New York, USA). The filling pressure of the balloon ('ventricle') was adjusted by letting the flow run into an open reservoir (OR) placed at an appropriate level above the soft bag. Between the reservoir and the connection to the soft bag an inlet valve (Vi) (Medtronic Hall, mitral valve, 29 mm Ø) was inserted. Flow and pressure signals were sampled on a computer.

2.2. Manual chest compressions in the pig

Manual chest compressions were given by three male surgeons trained in CPR and with clinical experience of the procedure. The surgeons were of normal size with a body weight in the range of 70–80 kg. Each surgeon worked in 3-min periods, compressing the lower one third of the sternum at a target rate of 100 compressions/min. The surgeons were instructed to give the compressions with the force they would have used on an

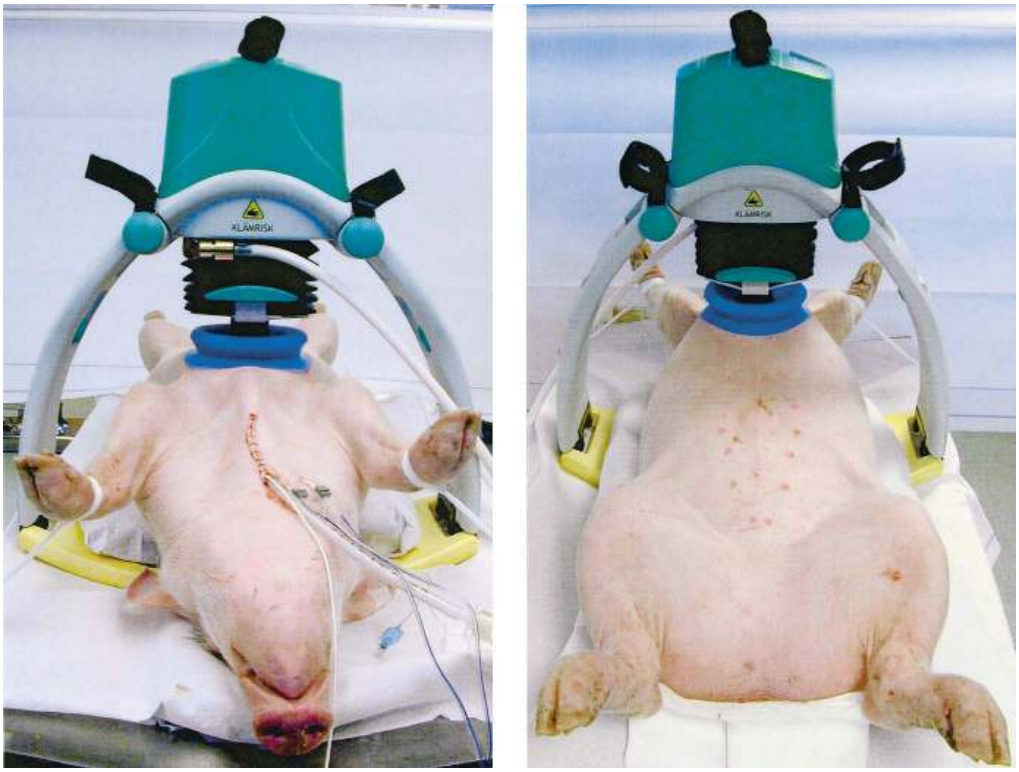

Fig. 2. LUCAS in place on a 23 kg pig. Due to the narrow upper thorax in pigs of this size, the silicon rubber suction cup does not fit snugly to the chest, and active decompression cannot be adequately tested.

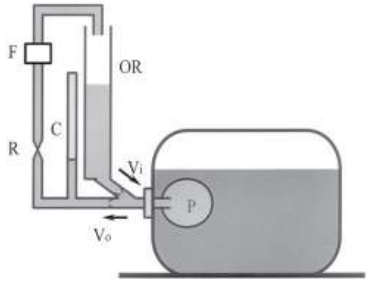

Fig. 3. The artificial thorax model used. P = pressure measurement within a soft plastic bag. Vo = mechanical outlet valve. R = resistance, regulated with a tube compressor. C = compliance (Windkessel effect), regulated by an air-filled side tube. F = flow measured continuously by a flow probe. OR = open reservoir for regulation of filling pressure. Vi = a large inlet valve for rate-unlimited filling of the bag during the decompression phase.

adult patient of normal size. The experimental protocols are depicted in Fig. 4.

2.3. The properties of LUCAS

The LUCAS is a gas-driven device that provides automatic mechanical compression and active decompression. It consists of a silicon rubber suction cup similar to that used in the CardioPump and a pneumatic cylinder mounted on two legs which are connected to a stiff back plate (Figs. 1 and 2). The cover of the pneumatics, the legs, and the back plate are made of a composite material that does not conduct electricity. The system is powered by oxygen or air from a cylinder, the gas system in ambulances or the gas outlets in hospitals. The maximum compression depth is 52 mm and the maximum compression force is 500 N. The decompression force is 410 N. A regulator inside LUCAS ensures that the same force will be obtained if it is run on air or oxygen. The gas connector fits the outlets for both oxygen and air and it can be used with

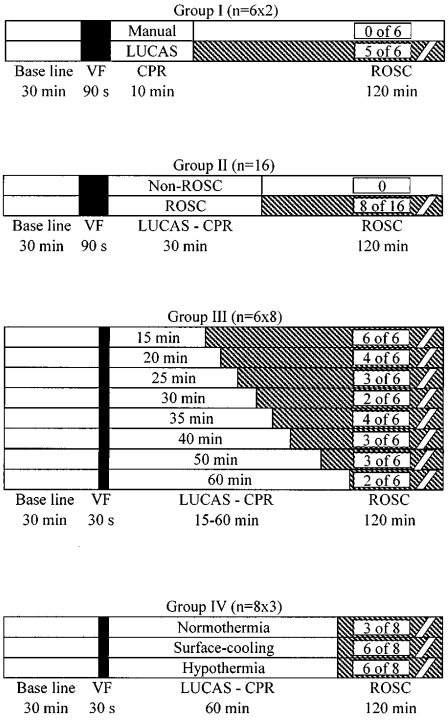

Fig. 4. The design of the pig experiments. The number of pigs with ROSC (return of spontaneous circulation) is indicated within the ROSC rectangle. In each case, defibrillation occurred at the end of the CPR.

gas sources with pressures ranging from 4 to 7 bar (400–700 kPa). The default setting for the compression/decompression frequency is 100 per minute. The height of the suction cup can be adjusted to fit patients with an anteroposterior thorax diameter in the range of 17–26.5 cm. The weight of the device is 6.5 kg and when stowed in a bag, its dimensions are $32 \times 64 \times 23$ cm. When it is mounted, the dimensions are $50 \times 53.8 \times 22.8$ cm. LUCAS is CE-marked and is commercially available in Europe since December 2001 (Jolife AB, Lund, Sweden; www.jolife.com).

2.4. Experimental animals

A total of 100 Swedish-bred specific pathogen free pigs with a mean weight of 22 kg (range 20–26 kg) were used. The mean external anteroposterior diameter of the thorax at the site where the chest compressions were given, i.e., at the inferior one third of the sternum, was 20 ± 1 cm (range, 18–23 cm) (Fig. 5).

All the animals received humane care in compliance with the Guide for the Care and Use of Laboratory Animals, published by the National Institutes of Health (NIH publication 85–23, revised 1985). The Institutional Review Board for animal experimentation at the University of Lund, Sweden, approved the experimental protocols. All animal experiments were designed according to the Utstein-style guidelines [7].

2.5. Anesthesia and preparation

The pigs had free access to water but were not allowed to eat on the day of experiment. They were anaesthetized with an induction dose of intramuscular ketamine (30 ml/kg). Sodium thiopental (5–8 mg/kg) and atropine (0.05 mg/kg) were given intravenously before tracheotomy. Anaesthesia and muscle paralysis were maintained with a continuous infusion of 30 ml/h of a 10% glucose solution containing ketamine (16 mg/ml) and pancuronium (0.6 mg/ml). In study Groups III and IV, midazolam (0.06 mg/ml) was also added to the infusion. Macrodex (up to 250 ml) was given to keep the central venous pressure within a normal range of 3–8 mmHg on a PEEP of 8 cm H_2O.

For monitoring of intrathoracic aortic pressure, a catheter was introduced via a direct puncture of the left carotid artery in order to avoid ligation of the artery. The tip of the catheter was inserted into the thoracic aorta and in the same way a catheter was inserted into the right atrium via the left external jugular vein (at autopsy these positions were confirmed). Separate catheters were placed inside an artery and a vein for withdrawal of blood samples. In Group I, a Swan–Ganz catheter (7.5 F) was inserted into the pulmonary artery via the right external jugular vein. An ultrasonic blood flow probe (3 mm) connected to a flow meter (Transonic Flowmeter T201D) was placed around the right carotid artery. A Foley catheter was inserted into the urinary bladder through a suprapubic cystotomy. The temperature was measured with a temperature probe placed in the oesophagus. The animals were kept normothermic by a heating system in the operation table, if not actively cooled, as for two thirds of the animals in Group IV. The mean temperature for the pigs in Groups I–III at the end of the experiments was 37.2 ± 1.0 °C (range, 36.5–38.4 °C).

2.6. Experimental protocol

For the design of the pig experiments, see Fig. 4. In Group I 12 animals were randomized to manual or mechanical chest compressions for 10 min after 90 s of VF.

In Group II, the LUCAS was started 90 s after start of VF and ran for 30 min before defibrillation. The

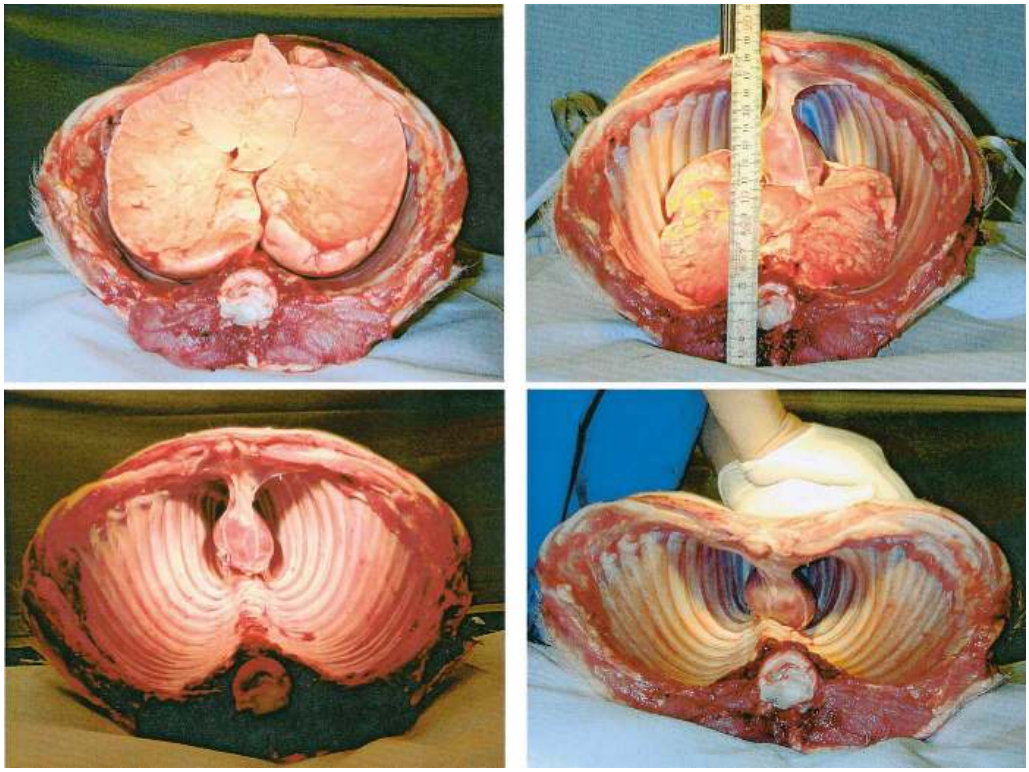

Fig. 5. Transverse section of a 23 kg pig just distal to processus xiphoideus. The heart ventricles are not compressed directly between the sternum and the spine during chest compressions due to the central position of the ventricles within the thoracic cavity. The anteroposterior diameter in this pig was 19.5 cm. Normal ventilated lungs (upper left), atelectatic lungs after disconnection from the ventilator (upper right), lungs extirpated (lower left), and manual forceful compression without direct compression of the ventricles between sternum and the spine (lower right).

intention was to identify potential physiological differences between ROSC and non-ROSC-pigs during CPR.

In Group III, the animals were randomized into eight different subgroups with 15, 20, 25, 30, 35, 40, 50 and 60 min of LUCAS-CPR before defibrillation. The aim was to determine the frequency of ROSC in each group.

In Group IV, the pigs were randomized either to normothermia or to cooling, the latter divided into two subgroups: in one VF was induced before cooling (surface cooling group), and in one after cooling to 32 °C (hypothermia group). The animals were placed within a strong plastic bag with holes for catheters, flow probe cable and the silicon rubber suction cup of LUCAS. In the surface cooling group the plastic bag was filled with ice cubes directly after induction of VF. When the oesophageal temperature reached 34 °C (after about 30 min, range 28–33 min), the ice bag was removed. The temperature continued to fall to about 32 °C at 60 min, the time at which defibrillation was attempted. For the ROSC animals, the oesophageal temperature stabilized at around 31 °C 1 h after ROSC. In the hypothermia group, cooling was done with the method described above but VF was induced at 32 °C and LUCAS-CPR was run for 60 min before defibrillation, at which time the temperature had stabilized at around 31 °C.

VF was induced with a 5–20 mA, 6 Hz and 30 V alternating current delivered to the epicardial surface via a needle electrode. Circulatory arrest was confirmed by a fall in arterial blood pressure and end-tidal CO_2 concentration and an ECG showing VF. Chest compressions were started after an interval of 90 s (Group I and II) or 30 s (Group III and IV).

Defibrillation was attempted as soon as possible (within 10 s) after the interruption of chest compressions with a direct current (DC) countershock of 300 J. In case of persistant VF, DC countershocks of 360 J were administered up to 3 times if necessary. If VF or asystole

persisted after four countershocks (with short periods of manual chest compression between each shock), resuscitation was defined as unsuccessful. The pigs with ROSC were monitored for 2 h, after which they were euthanized and autopsied. The position of the aortic and central venous catheters was especially checked, as were the heart valves, heart septum and ductus arteriosus. The aortic and pulmonary valve function was investigated by testing for leakage in a vertical position, and the tricuspid and mitral valves were tested by a quick injection of saline in a Foley-catheter placed intraventricularly via a stab wound through the ventricular wall. The autopsies did not show any pathology (special care was taken when the hearts of the non-survivors were investigated).

2.7. Haemodynamic measurements

Pressure and blood flow signals were sampled 50 times/s and the mean value for each variable was recorded every 5 s during the whole experiment, using a computer supplied with a data acquisition system (TestPoint, Capital Equipment Corporation, Billerica, MA). Coronary perfusion pressure was continuously calculated by the computer as the difference between the intrathoracic aortic and right atrial pressure during the decompression phase.

2.8. Blood gas analysis

Blood gases and electrolytes were analyzed directly after the sample had been obtained using a blood gas analyzer (ABL 505, Radiometer, Copenhagen). Arterial and mixed venous O_2-saturations (SaO_2, SvO_2) and total haemoglobin concentration were analyzed with a multi-wave-length oximeter (OSM3, Radiometer, Copenhagen) using the pig mode. In the hypothermic animals, the blood gas apparatus was adjusted to measure at the same temperature as the pig.

2.9. Ventilatory settings and measurements

Pressure-regulated, volume-controlled ventilation (Servo Ventilator 300, Siemens, Solna, Sweden) was used to obtain a stable minute volume. Ventilatory support was continued throughout all the experiments with a minute volume of 5 l/min at 20 breaths/min and a PEEP of 8 cm H_2O in Group I and II, and a minute volume of 7.5 l/min at 25 breaths/min and a PEEP of 8 cm H_2O in Group III and IV. An inspired oxygen concentration (FiO_2) of 0.21 was used throughout, except during the periods of chest compressions, when it was set to 1.0.

The ventilation was not synchronized with the chest compressions. A prototype infra-red CO_2 analyzer (Servotek AB, Arlöv, Sweden) was used, which has a function similar to that of the Servo 930 CO_2 analyzer, using an infra-red source and a detector placed astride the Y-tubing (main stream). The analyzer has a response time of 5 ms, a low noise level and a full-scale deflection of 10% CO_2. It was calibrated to zero with air and also calibrated with gas containing $5.05 \pm 0.010\%$ CO_2 in air (Alfax AB, Arlöv, Sweden). End-tidal CO_2 was monitored continuously and the value was recorded once a minute on a computer during the course of the experiment.

2.10. Anteroposterior thorax diameter in humans

The anteroposterior thorax diameter of 50 men and 15 women was measured at the level where external chest compressions should be given. This was done by placing the subjects on their backs close to a wall, lowering a stiff plate angled at 90° to the wall and attached to the wall until it just touch a point between the middle and lower third of the sternum, and measuring the distance from the lower edge of the plate to the floor.

2.11. Clinical pilot study with LUCAS

Permission for a clinical pilot study with LUCAS, including 20 patients, was given by the Medical Ethics Committee at the University of Lund. The study was designed to see if the device was easy and safe to use. The test was done when standard cardiopulmonary resuscitation had failed, as a last extra chance to save the patient's life. The device used on the first patients in this pilot study was a prototype with the same pneumatic properties as in the later model of LUCAS, but with an aesthetically less attractive appearance.

2.12. Statistical analysis

All results are expressed as the mean ± standard error of the mean (S.E.M.). For statistical analysis the unpaired Student's t-test was used.

3. Results

3.1. Manual CPR vs. LUCAS-CPR in the artificial thorax model

Typical pressure-flow curves for the artificial thorax model are presented in Fig. 6; in the left panel the rescuer performs manual CPR as he would have done in a clinical situation, and in the middle panel his performance during 5 s of maximal effort is shown. As seen in the right panel, LUCAS-CPR creates pressure-flow curves quite different from those seen during manual CPR, i.e. the area under the curves produced

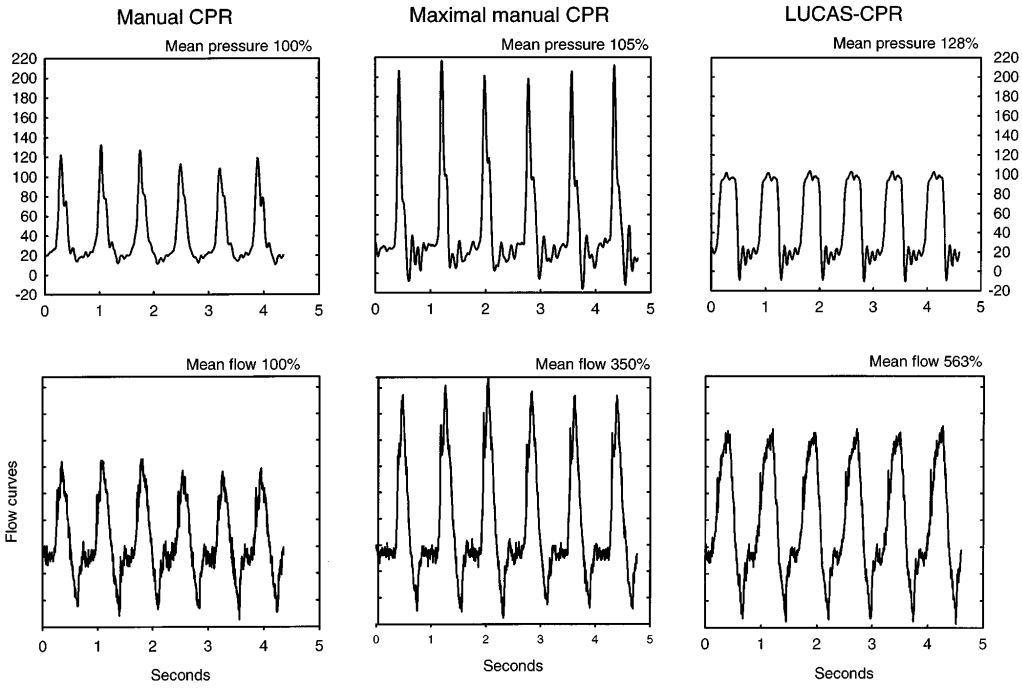

Fig. 6. Typical pressure-flow curves obtained by external compressions on the artificial thorax model. The left panel shows the data obtained when the male rescuer (75 kg body weight) did manual compressions with the force he had been trained to use on an adult patient (these values were defined as 100%). The middle panel shows when the same rescuer performed maximal forceful compressions. The right panel shows LUCAS-compressions. The gas supply was breathing oxygen from a wall outlet (4 bar).

by LUCAS is greater, with a corresponding increase in mean pressure and flow. The explosivity of the gas-driven pneumatics in LUCAS creates an instant increase and decrease in pressure, with a 50% duty cycle regarding both time and flow. The high peak pressures caused by maximal manual CPR cannot be maintained during the compression phase and therefore can not compete in efficiency with the LUCAS-CPR, despite lower peak pressures with the latter.

3.2. Manual CPR vs. LUCAS-CPR in the pig (Group I)

There was no return of spontaneous circulation (ROSC) with manual CPR, whereas five of six animals had ROSC with LUCAS-CPR (Fig. 7). The diastolic and mean arterial pressures were significantly higher with LUCAS-CPR (Table 1). In Fig. 8 the pressure curves obtained from the intrathoracic aorta and the right atrium are superimposed. The areas between the curves in the decompression phase are greater during LUCAS-CPR than during manual CPR, indicating a higher myocardial perfusion pressure during LUCAS-CPR. The coronary artery perfusion pressure was around 10 mmHg with manual CPR and around 15 mmHg with LUCAS-CPR (Fig. 9).

The values obtained after 5 min of CPR are presented in Table 1. The cardiac output, end-tidal CO_2, right carotid arterial blood flow and coronary perfusion pressure were significantly higher with LUCAS-CPR. There was no significant difference in the blood gas values (except for a slightly higher PvO_2 value in the LUCAS-CPR group), which were within normal ranges in both groups. The five pigs with ROSC in the LUCAS-CPR group were followed for 2 h before being euthanized and autopsied. At the end of this observation period, the arterial pressure, carotid flow and blood gases were not significantly different from the baseline values obtained before induction of VF.

3.3. ROSC vs. non-ROSC after 30 min of LUCAS-CPR (Group II)

There was a 50% ROSC rate in this group of 16 animals. Pressure-flow curves during 30 min of LUCAS-

CPR without and with ROSC are shown in Fig. 10, upper and lower panels, respectively. The coronary perfusion pressure is shown in Fig. 11 and the end-tidal CO_2 values in Fig. 12. No significant difference in any variables measured was seen after 5 and 15 min of LUCAS-CPR. In Table 2 values after 25 min of LUCAS-CPR are shown. Coronary perfusion pressure, end-tidal CO_2 and right carotid arterial flow were significantly higher in the ROSC group. There was no significant differences in the blood gases except for $PvCO_2$ at 25 min, 5.6 ± 0.4 vs. 7.7 ± 0.7 ($P < 0.05$) in the ROSC and non-ROSC pigs, respectively. The corresponding values for SvO_2 at 25 min were 54 ± 6 and $34 \pm 9\%$ ($P = 0.093$). The animals with ROSC were followed for 2 h before being euthanized and autopsied. At the end of this observation period, the arterial pressures, blood gases and carotid blood flow were not significantly different from the baseline values obtained before the induction of VF.

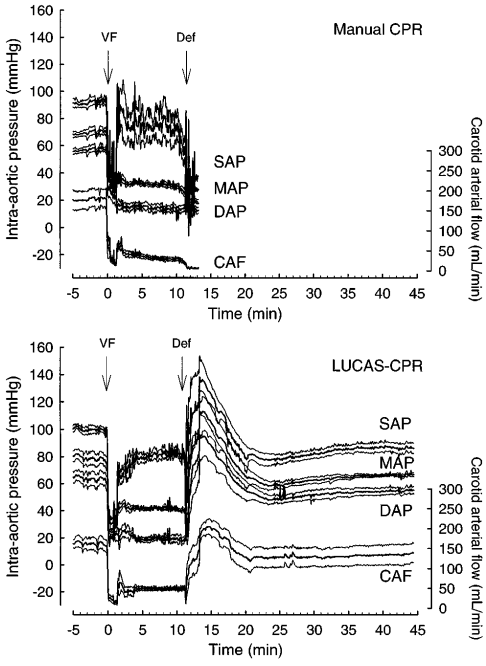

Fig. 7. The pressure- and carotid flow curves in the Group I pigs. There was no ROSC in the manual Group, 5 of the 6 animals obtained ROSC with LUCAS-CPR. Data shown as mean ± S.E.M., $n = 6$ ($n = 5$ after defibrillation in lower panel). CAF = carotid arterial blood flow, SAP, MAP, DAP = systolic, mean and diastolic intrathoracic aortic pressure. VF = induction of ventricular fibrillation. Def = defibrillation.

3.4. ROSC after 15–60 min of LUCAS-CPR (Group III)

All animals achieved ROSC after 15 min of LUCAS-CPR, whereas beyond 15 min there was an increased rate of animals without ROSC without any obvious association with CPR time (Fig. 4). The mean coronary perfusion pressure and the end-tidal CO_2 values of the last 5 min of the resuscitation period were calculated for each pig. For all animals with ROSC ($n = 27$), the mean coronary perfusion pressure was 15 ± 5 mmHg, compared with 2 ± 5 mmHg ($P < 0.01$) for the non-ROSC pigs. The corresponding values for end-tidal CO_2 were 2.6 ± 0.7 and $2.0 \pm 1.0\%$ ($P < 0.01$), respectively. At the end of the observation period of 2 h, all ROSC pigs had blood pressure, end-tidal CO_2, and carotid flow values that were not significantly different from the values obtained before the induction of VF.

3.5. LUCAS-CPR in normothermia versus hypothermia (Group IV)

The results obtained in the Group IV pigs are shown in Figs. 13–15 and in Table 3. The coronary perfusion pressure started to decrease after 20 min of CPR in the normothermic animals. The end-tidal CO_2 values in the hypothermic group were stable throughout CPR whereas a decline over time was seen in the normothermic group. In the surface cooling group, the end-tidal CO_2 value and the oesophagus temperature at 50 min were the same as in the hypothermic group, reflecting the reduced metabolism and CO_2 production in these two groups at this point. The metabolic acidosis (base excess in Table 3) measured after 50 min of CPR was more pronounced in the normothermic pigs. The reactive hyperaemia after ROSC was higher in the normothermic group (Figs. 13–15).

3.6. Anteroposterior chest diameter in 65 adult humans

Both the mean and median anteroposterior diameter was 21 cm (range 17–26 cm).

3.7. Clinical experience with LUCAS

The pilot study, where LUCAS was used as a last resort in 20 cases where standard advanced CPR had failed, documented that LUCAS is easy to apply and easy to use. In most cases it took less than 20 s to apply. The staff appreciated the fact that one person could be used for other purposes during CPR.

In one clinical case the efficacy of LUCAS was demonstrated. A 55-year-old diabetic man undergoing peritoneal dialysis due to renal failure suddenly suffered a witnessed collapse in a nephrology ward. Two nephrologists started manual chest compressions and

Table 1
Physiological variables in experiments comparing manual CPR with LUCAS-CPR (Group I)

		Baseline values			Values after 5 min of CPR		
		Manual CPR	LUCAS-CPR	*P*-value	Manual CPR	LUCAS-CPR	*P*-value
Aortic pressure (mmHg)	Mean	68±2	77±4	ns	33±1	42±1	<0.001
	Systolic	90±2	95±3	ns	77±8	79±3	ns
	Diastolic	56±3	64±4	ns	17±2	25±1	<0.05
Right atrial pressure (mmHg)	Mean	6±1	7±1	ns	23±2	38±4	<0.01
	Systolic	9±1	10±1	ns	60±3	91±9	<0.01
	Diastolic	6±1	6±1	ns	7±1	7±1	ns
Pulmonary arterial pressure (mmHg)	Mean	18±2	21±1	ns	31±4	30±2	ns
Wedge pressure (mmHg)	Mean	8±1	12±1	ns	32±5	29±3	ns
Coronary perfusion pressure (mmHg)		52±3	58±5	ns	10±2	17±1	<0.05
Cardiac output (l/min)		2.9±0.3	3.3±0.4	ns	0.5±0.1	0.9±0.1	<0.05
(%)		100	100	ns	17	27	<0.05
End-tidal CO_2 (%)		4.2±0.3	4.1±0.1	ns	2.0±0.2	2.8±0.1	<0.05
Carotid arterial blood flow (ml/min)		189±24	201±19	ns	32±5	58±4	<0.01
(%)		100	100	ns	17	29	<0.01
Mixed venous blood gas (kPa)	PvO_2	7.3±0.6	8.6±1	ns	4.8±0.3	5.2±0.5	<0.01
(kPa)	$PvCO_2$	5.6±0.3	5.1±0.4	ns	6.1±0.7	5.7±0.5	ns
	pHv	7.40±0.03	7.43±0.02	ns	7.25±0.06	7.30±0.04	ns
(%)	SvO_2	80±4	84±5	ns	43±7	50±7	ns
Arterial blood gas (kPa)	PaO_2	54±6	57±3	ns	46±2	48±5	ns
(kPa)	$PaCO_2$	4.4±0.2	4.1±0.2	ns	2.6±0.3	3.8±0.5	ns
	pHa	7.48±0.03	7.49±0.03	ns	7.51±0.05	7.40±0.05	ns
(%)	SaO_2	100±0	100±0	ns	100	100	ns

Inspired oxygen fraction = 1.0, blood gas apparatus set on the pig mode.

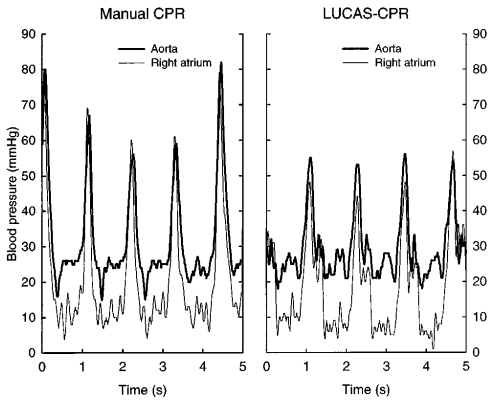

Fig. 8. Typical pressure curves obtained in a 20 kg pig during manual CPR and during LUCAS-CPR. The area between the curves for intrathoracic aortic pressure and right atrial pressure gives a picture of the coronary perfusion pressure. Note the biphasic positive curves and greater area between the curves during LUCAS-CPR.

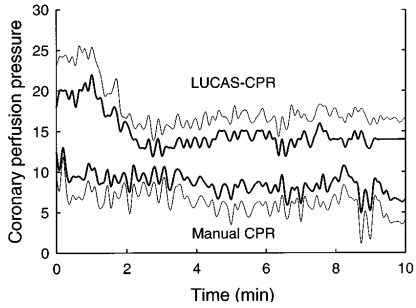

Fig. 9. The coronary perfusion pressure obtained during manual CPR vs. LUCAS-CPR in pigs (Group I). The coarse line shows the mean value. S.E.M. (thin line) is shown only on one side for the sake of clarity. $n = 6$ in both groups.

ventilation with a self-inflating bag, after confirming that the patient had no palpable pulses and no spontaneous respiration. The CPR-team (hospital team consisting of one cardiologist assisted by one specially trained cardiology nurse and one anaesthesiologist assisted by one specially trained anaesthesiology nurse) was called and arrived after 4 min. The ECG showed asystole. The patient was intubated and the heavily built male cardiologist in the resuscitation team continued manual chest compressions. Atropine and adrenaline were given intravenously. After 9 min of standard CPR without signs of ROSC, the cardiologist agreed that LUCAS could be applied to the patient, as a last effort to save the patient's life. The assistant nurse, who had been trained in the use of LUCAS-CPR, quickly applied the device and immediately after the start of LUCAS, strong pulses could be palpated. After 3 min of chest

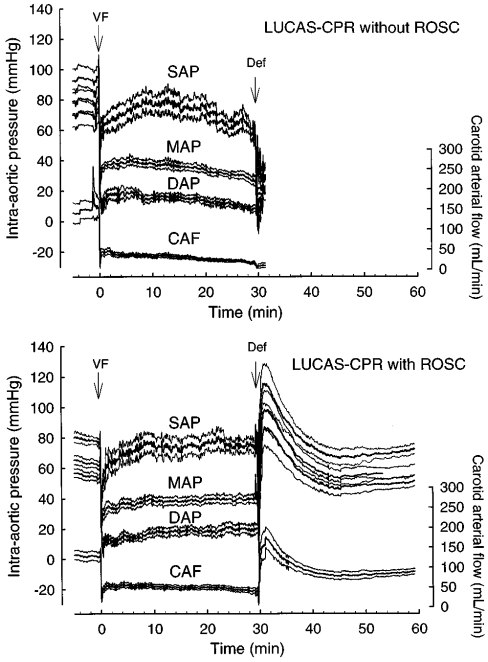

Fig. 10. The pressure- and carotid flow curves in pigs with ROSC vs. pigs without ROSC (Group II). Data shown as mean ± S.E.M., $n = 8$ in each group. VF = induction of ventricular fibrillation. Def = defibrillation.

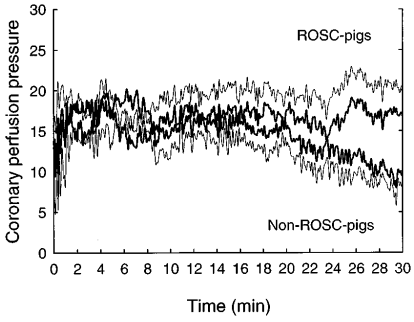

Fig. 11. The coronary perfusion pressure in pigs with ROSC vs. pigs without ROSC (Group II). Data shown as mean ± S.E.M., $n = 8$ in each group. S.E.M. is shown only on one side for the sake of clarity.

compressions/decompressions with LUCAS, the patient regained spontaneous circulation. He was transferred to the intensive care unit and was treated on a ventilator for 1 week. Blood cultures showed severe sepsis. After appropriate antibiotic therapy, the patient was weaned

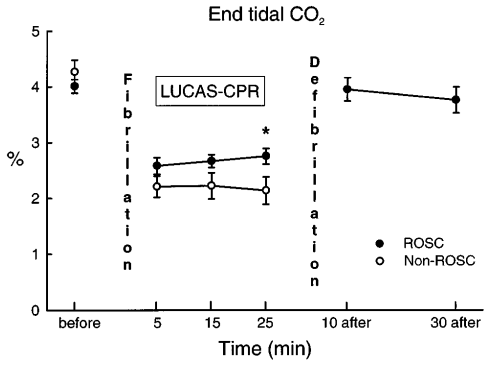

Fig. 12. End-tidal CO_2 in pigs with ROSC vs. pigs without ROSC (Group II). Data shown as mean ± S.E.M., $n = 8$ in each group. * $P < 0.05$.

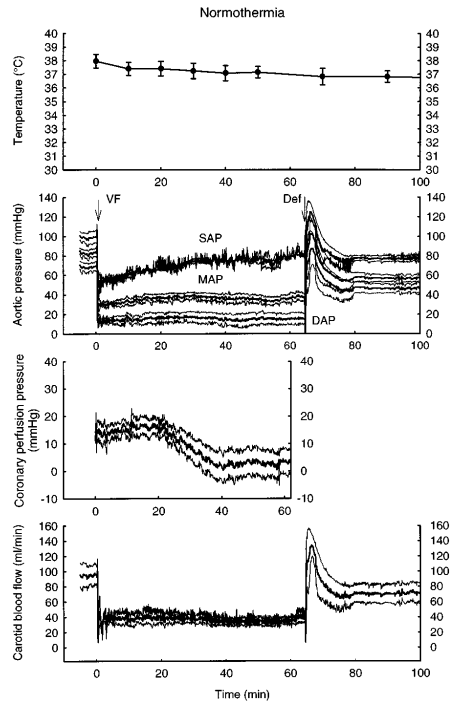

Fig. 13. LUCAS-CPR during 1 h of ventricular fibrillation (VF) in normothermia. Temperature, systolic, mean and diastolic (SAP, MAP, DAP) intrathoracic aortic pressure, coronary perfusion pressure, and right carotid arterial blood flow are shown as mean ± S.E.M. $n = 8$ ($n = 3$ after defibrillation (Def)).

from the ventilator, recovered, and left the hospital. At a follow-up visit 1 year later, his mental capacity was fully intact.

Table 2
Physiological variables in ROSC pigs vs. none-ROSC pigs (Group II)

		Baseline values			Values after 25 min of LUCAS-CPR		
		ROSC	Non-ROSC	*P*-value	ROSC	Non-ROSC	*P*-value
Aortic pressure (mmHg)	Mean	63±3	80±8	ns	39±3	31±2	<0.05
	Systolic	82±	92±	ns	78	72	ns
	Diastolic	58±	72±	ns	22	14	ns
Coronary perfusion pressure (mmHg)		52±3	68±8	ns	18±4	9±2	<0.05
End-tidal CO_2 (%)		4.0±0.1	4.3±0.2	ns	2.8±0.1	2.1±0.3	<0.05
Right carotid blood flow (ml/min)		130±11	148±21	ns	47±5	22±3	<0.01

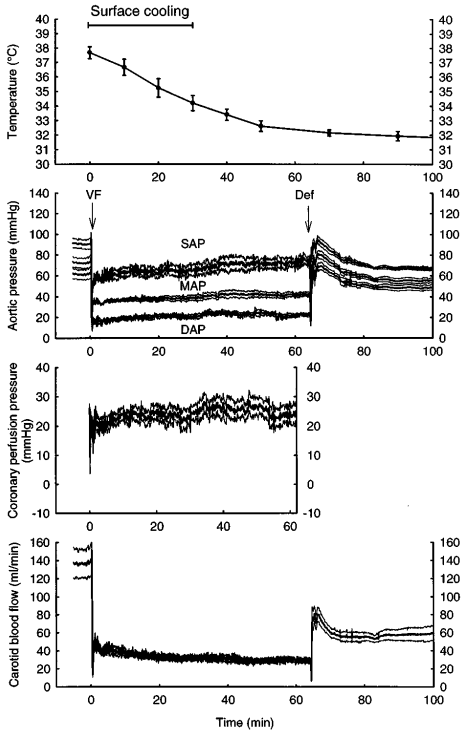

Fig. 14. LUCAS-CPR during 1 h of ventricular fibrillation (VF) with surface cooling during the first half hour. Temperature, systolic, mean and diastolic (SAP, MAP, DAP) intrathoracic aortic pressure, coronary perfusion pressure, and right carotid arterial blood flow are shown as mean±S.E.M. $n=8$ ($n=6$ after defibrillation (Def)).

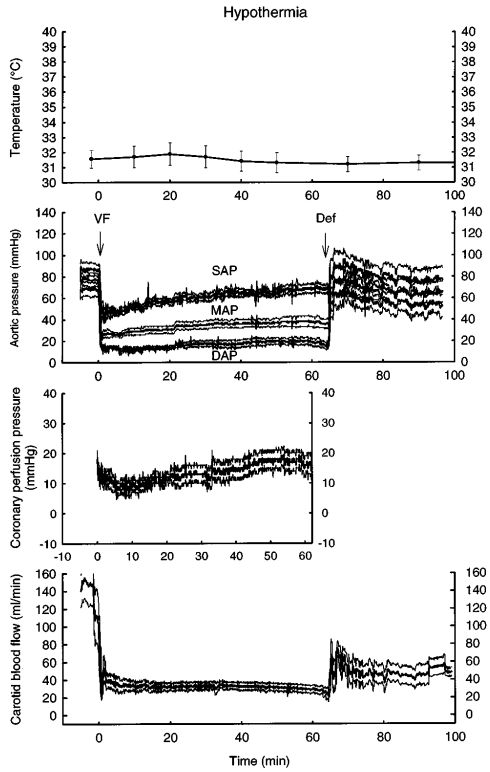

Fig. 15. LUCAS-CPR during 1 h of ventricular fibrillation (VF) in hypothermia. Temperature, systolic, mean and diastolic (SAP, MAP, DAP) intrathoracic aortic pressure, coronary perfusion pressure, and right carotid arterial blood flow are shown as mean±S.E.M. $n=8$ ($n=6$ after defibrillation (Def)).

4. Discussion

The animal experiments in this study were performed and reported according to the Utstein guidelines for laboratory CPR research [7]. These recommend use of swine weighing 20–25 kg. The anteroposterior chest diameter of pigs this size will be similar to that of average sized adult humans. Our measurements of 65 adult humans confirmed this. Swine have the advantage of being uniform in size and shape at similar ages and weights and there are many similarities in metabolic and cardiovascular function between swine and humans

Table 3
Blood gas values in LUCAS-CPR pigs with normothermia vs. surface cooling during CPR and CPR in hypothermia (Group IV)

	Base	10 min CPR	30 min CPR	50 min CPR	10 min after CPR	60 min after CPR	120 min after CPR
End-tidal CO_2 (%)							
Normothermia	4.2±0.2	2.5±0.2	2.0±0.3	1.7±0.5	3.2±0.8	4.2±0.1	4.2±0.1
Surface cooling	4.1±0.2	2.2±0.1	2.0±0.1	1.7±0.1	2.8±0.2	2.2±0.1	2.2±0.1
Hypothermia	4.3±0.2	1.7±0.1	1.9±0.0	1.7±0.1	2.4±0.2	2.5±0.2	2.5±0.2
SvO_2 (%)							
Normothermia	84±3	31±4	33±8	30±10	67±13	75±3	77±4
Surface cooling	91±3	40±6	40±3	39±5	76±3	81±3	82±4
Hypothermia	87±5	38±8	39±5	31±5	66±14	83±12	81±11
Base excess-arterial							
Normothermia	4.3±0.9	−1.1±1.7	−7.5±2.0	−11.2±2.5	−4.1±2.7	−2.1±0.1	−0.7±0.3
Surface cooling	2.4±0.9	−0.5±1.2	−3.3±1.4	−4.9±1.2	−5.5±1.9	−0.8±1.2	−0.2±1.9
Hypothermia	3.3±1.4	−0.3±1.0	−3.9±1.8	−6.0±1.7	−7.3±1.5	−4.5±1.8	−5.3±2.3
pH-arterial							
Normothermia	7.56±0.02	7.56±0.03	7.50±0.04	7.45±0.03	7.39±0.04	7.45±0.03	7.48±0.03
Surface cooling	7.51±0.01	7.59±0.02	7.56±0.03	7.55±0.02	7.46±0.02	7.58±0.02	7.61±0.02
Hypothermia	7.52±0.02	7.68±0.01	7.58±0.03	7.54±0.03	7.45±0.04	7.48±0.06	7.50±0.07

All baseline values were obtained at normothermia. All blood gas values were obtained with $FiO_2 = 1.0$; the blood gas apparatus was adjusted to measure at the same temperature as the pig and with the pig mode.

[8,9]. The coronary vascular anatomy is also similar to that of humans, with the exception of the left azygos vein, which in the pig enters the coronary sinus rather than a precaval vein. An important difference is that in pigs, the ventricles are positioned in the center of the thoracic cavity, surrounded by lung tissue on all sides (see Fig. 5). During the compression phase of CPR, the ventricles of a pig is not compressed by the sternum and spine, but are compressed indirectly by the pressure increase inside the chest. This mechanism is known as 'the thoracic pump theory', in contrast to 'the heart pump theory', in which it is thought that chest compression causes a direct compression of the heart against the spine [5,10,11]. The circulation created by the chest compressions in our study was probably caused by a 'thoracic pump' rather than a 'heart pump' mechanism.

In the present study the ventilation was kept constant throughout, with the intention to use end-tidal CO_2 values as an indication of the efficiency of the chest compressions. Due to the reduced cardiac output during CPR, the animals were relatively hyperventilated, resulting in respiratory alkalosis that compensated for the metabolic acidosis that also developed during prolonged CPR (Table 3). Thus, we think that buffer therapy with this experimental design would not have added any benefits for the animals. The use of drugs to increase the coronary perfusion pressure might have raised the ROSC, but were excluded in order to be able to judge the efficacy of chest compressions/decompressions per se.

In a clinical study comparing manual compression with manual compression/decompression, the latter approach significantly improved long-term survival rates among patients who had cardiac arrest out-of-hospital [4]. What role did the active decompression play in our study? The suction cup of LUCAS was too wide (13.5 cm in diameter) to fit snugly with the precordial chest in the pigs used. The upper thorax is too narrow for real vacuum to be created during the compression phase. This was confirmed by the fact that no suction mark could be seen after CPR. However, in the pigs resuscitated for longer than 20 min, the thorax softened and became more flat. A vacuum was then created, and after the CPR, a suction mark was seen. In a pilot study elucidating the efficacy of manual compressions for 30 min using this pig model, the end-tidal CO_2 fell to zero after about 20 min of manual compressions. At that time the pig thorax had lost its elastic recoil, and the anteroposterior diameter had diminished significantly and no ROSC was obtained. We think that in such a situation active decompression may be of value, if thereby an increase in venous return can be accomplished. As long as the thorax is intact, with normal elastic recoil of the chest in each decompression phase, we think active decompression is of less importance. In the Group II experiments we observed that after about 15–20 min with CPR, the non-ROSC animals started to lose coronary perfusion pressure while the ROSC-pigs did not (Fig. 11). Paradis et al. measured the coronary perfusion pressure in 100 patients with cardiac arrest [12]. In their study 24 patients had ROSC. Initial coronary perfusion pressure was 1.6±8.5 mmHg in patients without ROSC and 13.4±8.5 mmHg in patients with ROSC, whereas the maximal coronary pressure measured was 8.4±10.0 mmHg in those without ROSC and 25.6±7.7 mmHg in those with ROSC. Only patients with maximal coronary perfusion pressures of 15 mmHg

or more had ROSC. These data correspond well with those obtained on the ROSC and non-ROSC pigs in the present study, attesting to the relevance of this model.

End-tidal CO_2 levels reflect cardiac output during CPR. Levine and coworkers monitored end-tidal CO_2 during CPR in 150 consecutive victims of cardiac arrest out-of-hospital [13]. A 20-min end-tidal CO_2 value of 10 mmHg (1.3 kPa) or less was associated with a lack of (ROSC) in their study. In the Group I pigs in our study, manual CPR was able to produce end-tidal CO_2 values of 2 kPa, but the coronary perfusion pressure in those pigs was only around 10 mmHg, and no ROSC was obtained. Thus, in successful CPR, it is not enough to obtain a critical cardiac output (adequate end-tidal CO_2 values); an adequate coronary perfusion pressure is equally essential for ROSC.

Early defibrillation is the most important single factor to influence survival after sudden circulatory arrest, if it can be accomplished within 4 min, according to a study published by Cobb and coworkers [14]. In their study, survival improved if 90 s of external chest compressions were given prior to defibrillation in the group of patients where defibrillation could not be given within 4 min of circulatory arrest. In an experimental study by Sato and coworkers, they describe the adverse effects of interrupting chest compressions during CPR [15]. In their model, the coronary perfusion pressure during CPR was 26 ± 2 mmHg, but 10 s after interruption of CPR, it had decreased to 6 ± 3 mmHg, and after 20, 30 and 40 s it was 4 ± 2, 4 ± 4 and 4 ± 4 mmHg, respectively, i.e. close to zero. If defibrillation was done under ongoing CPR, the 24 h-survival rate was 80%. If it was delayed by 10 s, the 24 h survival rate was reduced to 40%, and if it was delayed by 20 s or more, there were no survivors. With these results in mind, it is easy to understand why defibrillation after 4 min of circulatory arrest is not likely to be successful. After that time, there has been minimal or no coronary circulation for at least 3 min. The advice given by Cobb et al. for routine provision of 90 s of CPR prior to a defibrillation seems most logical. In addition, defibrillation has greater chance of success if it can be delivered under ongoing CPR, as shown by Sato et al., i.e. with blood circulation through the heart muscle tissue [15]. Defibrillation during manual CPR cannot be done for safety reasons, but it would be one obvious advantage of mechanical CPR. The exterior of LUCAS is made of a non-conducting material, and by using electrode pads on the patient, defibrillations can be given safely during CPR.

As the Group IV study indicates, surface cooling as soon as possible after mechanical CPR is initiated may be of great advantage for several reasons. The coronary perfusion pressure increased promptly, probably due to redistribution of the blood volume and increased systemic vascular resistance. The metabolism will be reduced by about 6–7%/°C that the body temperature is lowered [16,17], with the consequence that less circulation will be needed to ensure an adequate organ perfusion. Hypothermia will also protect the brain [18–20].

Preliminary reports from the clinical pilot study with LUCAS are promising. It has been easy to handle, it can be applied to the patient within 10–20 s, it fits on stretchers, the suction cup helps to maintain a correct position and it fits and works well within ambulances. Defibrillation may be delivered during ongoing chest compressions. Several prospective randomized studies within or out-of-hospital are being planned. The most critical factor for successful CPR out-of-hospital is to initiate adequate chest compressions and oxygenation as quickly as possible after cardiac arrest, before the brain has been irreversibly injured. Traditional manual CPR will lose none of its importance with the introduction of mechanical CPR, quite the opposite. Knowing that a machine is under way to take over the chest compressions should only give the rescuer(s) added strength to maintain forceful manual CPR until the ambulance team arrives.

To conclude, gas-driven compressions and active decompressions with LUCAS give significantly better circulation during ventricular fibrillation compared to manual chest compressions.

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References

[1] Kouwenhoven WB, Jude JR, Knickerbocker GG. Closed-chest cardiac massage. J Am Med Assoc 1960;173:1064–7.
[2] Hightower D, Thomas SH, Stone CK, Dunn K, March JA. Decay in quality of closed-chest compressions over time. Ann Emerg Med 1995;26:300–3.
[3] Stapleton ER. Comparing CPR during ambulance transport. Manual vs. mechanical methods. JEMS 1991;16:63–8.
[4] Plaisance P, Lurie KG, Vicaut E, et al. A comparison of standard cardiopulmonary resuscitation and active compression–decompression resuscitation for out-of-hospital cardiac arrest. N Engl J Med 1999;341:569–75.
[5] Wik L. Automatic and manual mechanical external chest compression devices for cardiopulmonary resuscitation. Resuscitation 2000;47:7–25.
[6] Lindberg L, Liao Q, Steen S. The effects of epinephrine/norepinephrine on end-tidal carbon dioxide concentration, coronary perfusion pressure and pulmonary arterial blood flow during cardiopulmonary resuscitation. Resuscitation 2000;43:129–40.

[7] Idris AH, Becker LB, Ornato JP, et al. Utstein-style guidelines for uniform reporting of laboratory CPR research. Resuscitation 1996;33:69–84.
[8] Swindle MM, Smith AC, Hepburn BJS. Swine as models in experimental surgery. J Invest Surg 1988;1:65–79.
[9] Smith AC, Spinale FG, Swindle MM. Cardiac function and morphology of Hanford miniature swine and Yucatan miniature and micro swine. Lab Anim Sci 1990;40:47–50.
[10] Rich S, Wix HL, Shapiro EP. Clinical assessment of heart chamber size and valve motion during cardiopulmonary resuscitation by two-dimensional echocardiography. Am Heart J 1981;102:368–73.
[11] Maier GW, Tyson GS, Olsen CO, et al. The physiology of external cardiac massage: high impulse cardiopulmonary resuscitation. Circulation 1984;70:86–101.
[12] Paradis NA, Martin GB, Rivers EP, et al. Coronary perfusion pressure and the return of spontaneous circulation in human cardiopulmonary resuscitation. J Am Med Assoc 1990;263:1106–13.
[13] Levine RL, Wayne MA, Miller CC. End-tidal carbon dioxide and outcome of out-of-hospital cardiac arrest. N Engl J Med 1997;337:301–6.
[14] Cobb LA, Fahrenbuch CE, Walsh TR, et al. Influence of cardiopulmonary resuscitation prior to defibrillation in patients with out-of-hospital ventricular fibrillation. J Am Med Assoc 1999;281:1182–8.
[15] Sato Y, Weil MH, Sun S, et al. Adverse effects of interrupting precordial compression during cardiopulmonary resuscitation. Crit Care Med 1997;25:733–6.
[16] Wetterberg T, Steen S. Combined use of hypothermia and buffering in the treatment of critical respiratory failure. Acta Anaesthesiol Scand 1992;36:490–2.
[17] Wetterberg T, Sjöberg T, Steen S. Effects of hypothermia in hypercapnia and hypercapnic hypoxemia. Acta Anaesthesiol Scand 1993;37:296–302.
[18] The Hypothermia After Cardiac Arrest Study Group. Mild therapeutic hypothermia to improve the neurologic outcome after cardiac arrest. N Engl J Med 2002; 346: 549–556.
[19] Bernard SA, Gray TW, Buist MD. Treatment of comatose survivors of out-of-hospital cardiac arrest with induced hypothermia. N Engl J Med 2002;346:557–63.
[20] Safar PJ, Kochanek PM. Therapeutic hypothemia after cardiac arrest. Editorial. N Engl J Med 2002;346:612–3.

II

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RESUSCITATION

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The critical importance of minimal delay between chest compressions and subsequent defibrillation: a haemodynamic explanation

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Abstract

Outcome after prehospital defibrillation remains dire. The aim of the present study was to elucidate the pathophysiology of cardiac arrest and to suggest ways to improve outcome. Ventricular fibrillation (VF) was induced in air-ventilated pigs, after which ventilation was withdrawn. After 6.5 min of VF, ventilation with 100% oxygen was initiated. In six pigs (group I), defibrillation was the only treatment carried out. In another six pigs (group II), mechanical chest compression–decompression CPR (mCPR) was carried out for 3.5 min followed by a 40-s hands-off period before defibrillation. If unsuccessful, mCPR was resumed for a further 30 s before a second or a third, 40-s delayed, shock was given. In a final six pigs (group III) mCPR was applied for 3.5 min after which up to three shocks (if needed) were given during on-going mCPR. Return of spontaneous circulation (ROSC) occurred in none of the pigs in group I (0%), in 1 of six pigs in group II (17%) and in five of six pigs in group III (83%). During the first 3 min of VF arterial blood was transported to the venous circulation, with the consequence that the left ventricle emptied and the right ventricle became greatly distended. It took 2 min of mCPR to establish an adequate coronary perfusion pressure, which was lost when the mCPR was interrupted. During 30 s of mCPR coronary perfusion pressure was negative, but a carotid flow of about 25% of basal value was obtained. In this pig model, VF caused venous congestion, an empty left heart, and a greatly distended right heart within 3 min. Adequate heart massage before and during defibrillation greatly improved the likelihood of return of spontaneous circulation (ROSC).

Keywords: Active compression–decompression; Non-interrupted CPR; CPR before defibrillation; Coronary perfusion pressure; Return of spontaneous circulation; LUCAS

Resumo

O resultado após desfibrilhação pré-hospitalar continua mau. O presente estudo teve por objectivo esclarecer a patofisiologia da paragem cardíaca e sugerir formas de melhorar o prognóstico. Foi induzida fibrilhação ventricular (FV) em porcos ventilados com ar, após o que foi suspensa a ventilação. Ao fim de 6.5 min de FV iniciou-se ventilação com oxigénio a 100%. Em 6 porcos (grupo I), a desfibrilhação foi o único tratamento efectuado. Noutros 6 porcos (grupo II) fez-se reanimação cardiopulmonar com compressão-descompressão mecânica do tórax (mRCP) durante 3.5 min, seguido de uma pausa de 40 segundos antes da desfibrilhação. Se não houvesse sucesso, a mRCP era retomada durante mais 30 segundos antes de administrar um segundo ou terceiro choque, precedido de uma pausa de 40 segundos. No último grupo de 6 porcos (grupo III) foi feita mRCP durante 3.5 min, após o que eram administrados até 3 choques (se necessário) sem paragem da mRCP. Não houve recuperação da circulação espontânea (ROSC) em nenhum dos porcos do grupo I (0%), mas conseguiu-se ROSC em 1 de 6 porcos do grupo II (17%) e em 5 de 6 porcos do grupo III (83%). Verificou-se que nos primeiros 3 minutos de FV o sangue arterial era desviado para a circulação venosa, com o consequente do esvaziamento do ventrículo esquerdo o que decorria a par da constatação de que o ventrículo direito ficava largamente distendido. A pressão de perfusão coronária adequada, que se perdia quando era interrompida a mRCP, só se restabeleceu ao fim de 2 minutos de mRCP. A pressão de perfusão coronária era negativa durante os 30 segundos de mRCP, mas obteve-se um fluxo

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carotídeo de cerca de 25% do valor basal. Neste modelo em porcos, a FV provocou congestão venosa, um coração esquerdo vazio e um coração direito largamente distendido em 3 minutos. A massagem cardíaca adequada antes e durante a desfibrilhação aumentou grandemente a probabilidade de ROSC.

Palavras chave: Compressão-descompressão activa; RCP contínua; RCP antes de desfibrilhação; Pressão de perfusão coronária; Recuperação da circulação espontânea (ROSC); LUCAS

Resumen

El resultado después de desfibrilación prehospitalario sigue siendo espantoso. El objetivo de este estudio fue elucidar la fisiopatología del paro cardiaco y los métodos sugeridos para mejorar los resultados. Se indujo fibrilación ventricular (VF) en cerdos ventilados con aire, después de lo cual se suprimió la ventilación. Después de 6.5 minutos de VF, se inició ventilación con 100% de oxigeno. En 6 cerdos (grupo I), la desfibrilación fue el único tratamiento realizado. En otros 6 cerdos (grupo II), se realizó reanimación cardiopulmonar con compresión y descompresión mecánica (mCPR) por 3.5 minutos seguidos de 40 segundos sin compresión antes de la desfibrilación. Si no es exitosa, se reasume por los siguientes 30 segundos antes de dar una segunda o un tercera descarga, retrasada 40 segundos. En un grupo final de 6 cerdos (grupo III) se aplicó mCPR por 3.5 minutos después de lo cual se entregaron hasta tres descargas (si fueron necesarias) durante la reanimación que se llevaba a cabo.Ocurrió retorno a circulación espontánea (ROSC) ocurrió en ninguno de los cerdos del grupo I (0%), en 1 de los 6 en el grupo II (17%) y en 5 de 6 del grupo III (83%). Durante los 3 primeros minutos de VF la sangre arterial fue transportada a la circulación venosa, con la consecuencia del vaciamiento del ventrículo izquierdo y el ventrículo derecho se distendió ampliamente. Requirió 2 minutos de mCPR para establecer una presión de perfusión coronaria adecuada, la que se perdió cuando se interrumpió la mCPR. Durante 30 segundos de mCPR la presión de perfusión coronaria fue negativa, pero se obtuvo un flujo carotídeo de cerca de 25% del valor basal.En este modelo porcino, la VF causó una congestión venosa, un corazón izquierdo vacío, y un ventrículo derecho muy distendido dentro de 3 minutos. Un masaje cardíaco adecuado antes y durante la desfibrilación mejoró ampliamente la posibilidad de ROSC.

Palabras clave: RCP compresión descompresión activa; RCP no interrumpida; RCP antes de desfibrilar; Presión de perfusión coronaria; Retorno a circulación espontánea (RCE); Resucitación intrahospitalaria LUCAS

1. Introduction

Outcome after pre-hospital defibrillation remains dire. Recent evidence, however, has shown that in cases of cardiac arrest that have lasted more than 4 min, outcome can be improved if chest compressions are performed before any attempt at defibrillation [1,2].

The aim of the present investigation was to elucidate three issues. First, why is it so difficult to achieve return of spontaneous circulation (ROSC) after more than 4 min of ventricular fibrillation (VF) cardiac arrest? Second, why is it apparently important to give chest compressions before defibrillation if VF has lasted more than 4 min? Third, what pathophysiological changes occur, that negatively affect ROSC, if chest compressions are interrupted before defibrillation attempts?

We used a porcine model to investigate these issues, and the experiments were designed according to the Utstein guidelines for experimental studies of cardiopulmonary resuscitation (CPR) [3].

2. Materials and methods

We have recently described in detail our experimental method for porcine CPR experiments [4]. The same methods were used and only additional information that is specific to the present study is given here.

2.1. Experimental animals

Twenty-four Swedish domestic pigs with a mean weight of 22 kg (range 20–25 kg) were used. Eighteen of the pigs were randomized into three treatment groups. In addition, three pigs were used for video filming of the fibrillating heart and three pigs for intrapericardial pressure measurements before and during VF.

All the animals received humane care in compliance with the Guide for the Care and Use of Laboratory Animals, published by the National Institutes of Health (NIH publication 85-23, revised 1985). The study was approved by the ethical committee for animal experiments at the University of Lund, Sweden.

2.2. Anaesthesia, ventilation, and haemodynamic measurements

Anaesthesia was induced with one dose of intramuscular ketamine (30 mg/kg). Before tracheotomy, sodium thiopental (5–8 mg/kg) and atropine (0.02 mg/kg) were given intravenously. Anaesthesia and muscular paralysis were maintained with a continuous infusion of 30 ml per hour of a 10% glucose solution containing ketamine (16 mg/ml) and pancuronium (0.6 mg/ml). The animals were kept normothermic by a heating system in the operation table.

Pressure regulated (max. 30 cm H_2O), volume controlled, normo-ventilation (Servo ventilator 300, Siemens, Solna, Sweden) was obtained by using a tidal volume of 200 ml, 25 breaths/min and 8 cm H_2O in PEEP. The inspired oxygen concentration, FiO_2, was 0.21 except during periods of mCPR, when it was set to 1.0. The animals with ROSC were ventilated with a FiO_2 of 0.5. The ventilation was not synchronized with the mechanical compression–decompression cardiopulmonary resuscitation (mCPR). Ventilatory support was withdrawn during the 6.5-min periods of induced VF.

Catheters for blood pressure measurements were placed in the intrathoracic ascending aorta and the right atrium. Their position was checked at autopsy after the experiment. In three separate pigs a small incision was made just distal to the xiphoid process, and careful dissection was carried out until the pericardium could be seen. A catheter (Secalon-T over-needle central venous catheter, 16G/1.70.130 mm) was punctured into the pericardium, and the incision was closed by surgical suturing. Pressure measurements were recorded before and during VF, and compared with the right atrial pressure and the intrathoracic ascending aortic pressure. A blood flow probe was placed on the left internal carotid artery. Pressure and blood flow signals were sampled continuously by a computer during the experiment. The coronary perfusion pressure was computed as the difference between the lowest intrathoracic aortic and the lowest right atrial pressure during the decompression phase.

2.3. Mechanical chest compression-decompression

mCPR was given with LUCAS, a gas-driven device providing automatic chest compression, and active 'physiological' decompression. This is achieved by a rubber vacuum ring that brings a softened, flat, non-recoiling thorax back to its normal position during each decompression phase. Defibrillation can be safely given during on-going mCPR with this device. A detailed description of LUCAS has been given elsewhere [4].

2.4. Pilot studies

Pilot experiments were performed to decide the shortest duration of VF required to produce 100% mortality when defibrillation was the only treatment given. With the above-described protocol of anaesthesia and curarization, ventilation ($FiO_2 = 0.21$) was stopped when VF had been induced. These experiments showed that 6.5 min of VF resulted in no ROSC after three shocks given at 20-s intervals, the animals being ventilated with 100% oxygen.

2.5. Experimental protocol

Animals were randomized into three treatment groups (I–III) with 6 animals in each. The design of the experiment is shown in Fig. 1. Baseline values were registered for 30 min in all groups and did not differ between the groups. VF was induced with a 5–20 mA, 6 Hz and 30 V alternating current delivered to the epicardial surface of the heart via a needle electrode. Cardiac arrest was confirmed by abrupt decreases in arterial blood pressure and end-tidal CO_2 concentration, and an ECG showing VF, after which ventilation was stopped. After 6.5 min of VF, ventilation with 100% oxygen was started in all pigs. Defibrillation was attempted externally in all cases using a direct current (DC) shock, the first time with 200 J, second time with 300 J, and third time with 360 J. If ROSC had not occurred after 3 shocks, resuscitation was defined as unsuccessful.

In group I animals, defibrillation was attempted after 6.5 min of VF. Three shocks were given at 20-s intervals.

In group II animals, mCPR was given for 3.5 min after 6.5 min of VF. mCPR was then interrupted and the ECG and arterial blood pressure were analysed for 40 s before the first shock was given. After the shock, 10 s was allowed to judge the outcome of defibrillation. In cases of persisting VF, mCPR was re-started and continued for 30 s before a second or third shock was given, each time following 40 s periods of withdrawal of CPR. If ROSC had not been obtained after the third shock, resuscitation was defined as unsuccessful.

In group III animals, mCPR was given for 3.5 min following 6.5 min of VF. Then up to three shocks were given, if necessary, at 20-s intervals during ongoing mCPR.

2.6. Video film of the fibrillating heart

Median sternotomy was performed in three additional animals and the heart visualized by opening up the pericardium. A video camera was fixed to a support so that the heart could be filmed before induction of VF and during 6.5 min of VF. Defibrillation with 30 J was attempted after the 6.5 min by means of paddles held

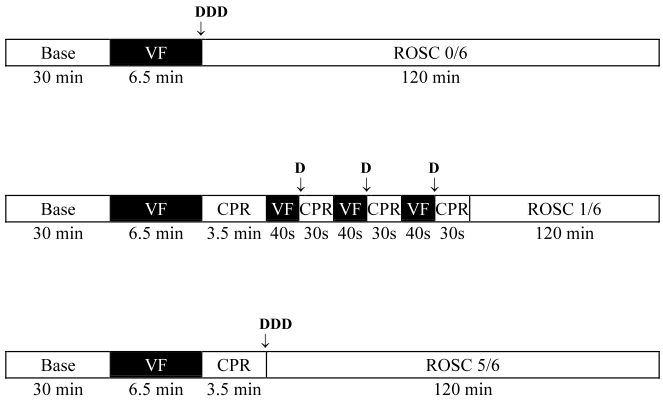

Fig. 1. The design of the experiments. The number of pigs with ROSC is indicated within the ROSC rectangle. D, defibrillation; VF, ventricular fibrillation; CPR, cardiopulmonary resuscitation.

directly against the heart. If ROSC was not obtained, internal manual heart massage was given for 3.5 min after which internal defibrillation was repeated.

2.7. Intrapericardial pressure measurement

After placement of the intrapericardial catheter and the catheters for blood pressure measurements, base line values were obtained over the next 30 min, after which ventricular fibrillation was induced.

3. Results

3.1. All groups

3.1.1. Pathophysiology during 6.5 min of VF

The intra-thoracic aortic pressure decreased rapidly to reach a minimum of 20 mmHg after about 30 s, then it increased slightly to about 25 mmHg at 2 min. Between 2 and 6.5 min it decreased gradually again to about 10 mmHg (Fig. 2). The pressure in the right atrium at first increased abruptly, then gradually to reach a peak of about 18 mmHg after 2 min. It then gradually decreased, until after 5.5 min it was equal to the intra-thoracic aortic pressure. The coronary perfusion pressure decreased from 60 to 15 mmHg within 15 s, and then gradually decreased to reach zero after about 4 min (Fig. 2). The flow in the left carotid artery also decreased quickly from 190 to about 15 ml/min after 15 s, then it gradually decreased to reach zero after about 4 min (Fig. 3). The intrapericardial pressure paralleled the right atrial pressure, but was about 2 mmHg less (Fig. 4).

3.2. Group I

3.2.1. The effect of defibrillation after 6.5 min VF

None of the animals achieved ROSC. Four animals were successfully defibrillated at the first attempt and sinus rhythm with bundle branch block was recorded. However, this was pulseless electrical activity without arterial pressure or flow.

3.2.2. The effect of 3.5 min of mCPR after 6.5 min VF

The compression pressure in the right atrium was higher than that in the intra-thoracic aorta during the first 3 min of CPR, after which the pressures equalized (Fig. 2). The decompression pressure in the intra-thoracic aorta was lower than that in the right atrium during the first minute of compressions, with the result that the coronary perfusion pressure was negative.

After about 1.5 min of mCPR the coronary perfusion pressure had reached a peak of 18 mmHg, thereafter decreasing to 12 mmHg at 3.5 min (Fig. 2). The left carotid arterial blood flow increased to 50 ml/min within 15 s (25% of the flow before VF), but decreased to about 30 ml/min after 3.5 min of compressions (Fig. 5).

3.3. Group II

3.3.1. Delayed defibrillation after 3.5 min of mCPR

Only one of six pigs achieved ROSC in this group. This animal was successfully defibrillated at the first attempt. At the end of the 2-h observation period it had a normal blood pressure. The intra-aortic compression pressure obtained is shown in Fig. 6. During the 40-s delay before defibrillation the coronary perfusion pressure fell to zero (Fig. 7). During the subsequent 30 s of mCPR the coronary perfusion pressure decreased to

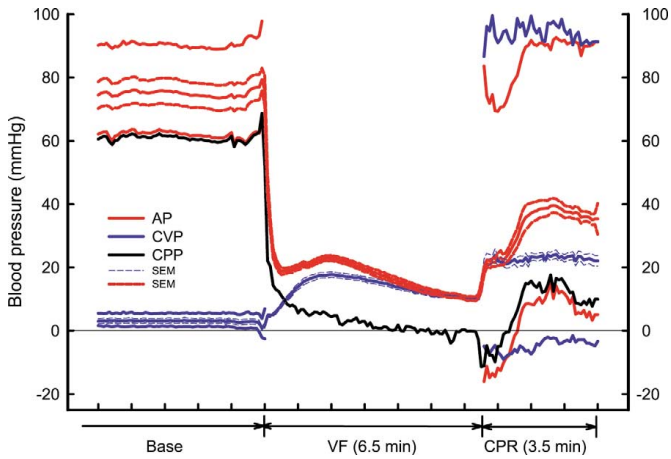

Fig. 2. Intrathoracic aortic pressure, pressure in the right atrium and computed coronary perfusion pressure are shown during 6.5 min of ventricular fibrillation followed by 3.5 min of mechanical chest compressions. Systolic, diastolic and mean pressure are shown to the left (base), and compression, decompression and mean pressure to the right (during CPR). The curves represent the mean values from 12 pigs. For the sake of clarity, the standard error of the mean is not shown in all curves.

negative values, i.e. the pressure in the right atrium was higher than that in the ascending aorta during the decompression phase. Blood flow in the left carotid artery fell to 20 ml/min after the first interruption of compressions, and had fallen to zero when the second and third defibrillation attempts were made (Fig. 5).

3.4. Group III

3.4.1. Defibrillation during on-going mCPR

Five out of six animals achieved ROSC in this group. In four of the animals ROSC was obtained after the first defibrillation attempt. In one pig, three defibrillatory shocks were given before ROSC was obtained, and in another no ROSC was obtained after three shocks. As seen in Fig. 8, the aortic systolic pressure increased by 80% to 160 mmHg 5 min after ROSC and then gradually decreased to basal values over the next 30 min. The carotid arterial blood flow curve (Fig. 9) paralleled the arterial pressure curve. After 2 h, the five animals with ROSC were stable, with pressure and blood flow that did not differ significantly from the basal values.

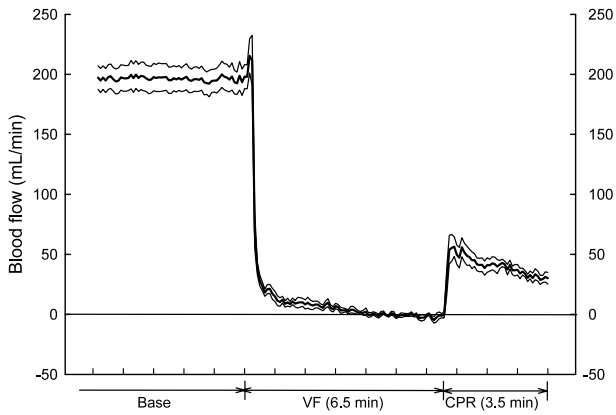

Fig. 3. The blood flow in the left internal carotide artery during 6.5 min of ventricular fibrillation followed by 3.5 min of mechanical chest compressions. The mean value ± S.E.M. is shown from 12 pigs.

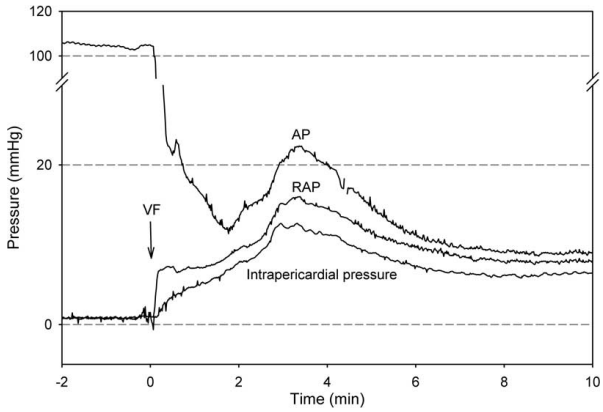

Fig. 4. Pressure recordings of the first 10 min of ventricular fibrillation in one pig in which intrapericardial pressure was also registered.

3.5. Video recording during VF

Before induction of VF, the mean heart rate of the three pigs was 110 per min, and the ECGs showed sinus rhythm. At the start of the 6.5 min VF period, the atria continued to beat with a frequency of 110 per min. By the end of the observation period, the frequency had decreased to about 60 per min. Initially the ECGs showed coarse ventricular fibrillation, but gradually the electrical activity decreased, and after 6.5 min low-voltage ventricular fibrillation was observed.

The right ventricles increased gradually in size up to 3 min, after which no further increase in size was observed by direct vision, but as judged from the light reflexes from the apex of the right ventricles their size continued to increase (Fig. 10). Dilated cardiac veins were seen on the surface of both the right and left ventricles. One attempt was made at internal defibrillation after 6.5 min and sinus rhythm, with a frequency of around 60 beats per min, was obtained in two of the three animals. No increase in blood pressure was observed; the greatly distended right ventricles did not move. The less-than-normal sized left ventricles were seen to contract at the same frequency as the atria, but without creating pressure in the intra-thoracic aorta. After about 20 s, ventricular fibrillation recurred in the two animals with sinus rhythm. Internal manual heart compressions were then given for 3.5 min after which the right ventricles had regained a normal size, and coarse VF could be seen on the ECG in all three animals. One shock was given

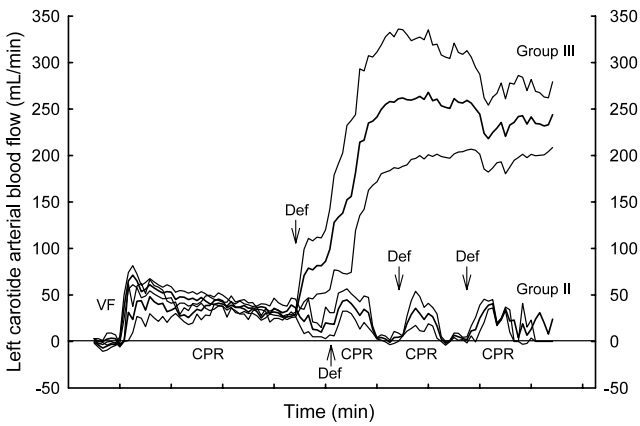

Fig. 5. The blood flow in the left internal carotide artery during 3.5 min of mechanical compressions followed by defibrillation attempts with (II) and without (III) interrupting the chest compressions. Mean value ± S.E.M., $n = 5$ in each group (the one pig which survived in group II and the one pig which died in group III are excluded to get a clear non-ROSC vs. ROSC group).

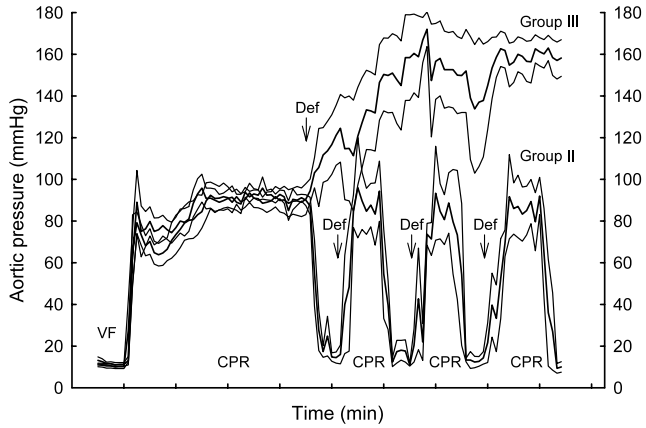

Fig. 6. Intrathoracic aortic compression pressure during 3.5 min of mechanical compressions followed by defibrillation with (II) and without (III) interrupting the chest compressions. Mean value ± S.E.M., $n = 5$ in each group.

directly to the heart while continuing massage with the metallic defibrillation paddles. ROSC was obtained in all three animals.

3.5.1. Intrapericardial pressure recording during VF

In all three pigs, the intrapericardial pressure followed the pressure in the right atrium, but was 1–2 mmHg less. Recordings from one of these experiments are shown in Fig. 4.

4. Discussion

It has been estimated that 375 000 people in Europe [5] and 275 000 in the USA [6] are victims of sudden cardiac arrest each year. The great majority of these cases occur out of hospital. For the last 40 years the 1-year survival rate has remained extremely poor (less than 5%) despite efforts to improve emergency care and the increasing availability of automated external defibrillators (AEDs). About half of all deaths in the Western world are caused by cardiovascular disease, and about half of all cardiovascular deaths are due to out-of-hospital cardiac arrest [6]. These continuing poor results warrant a radical new approach to the treatment of this most common and most dramatic of all diseases.

Cardiac arrest is manifest either as VF or, in an appreciable minority of cases, as pulseless electrical activity (PEA) or asystole. Defibrillation will obviously not save a patient with asystole but has a good chance of

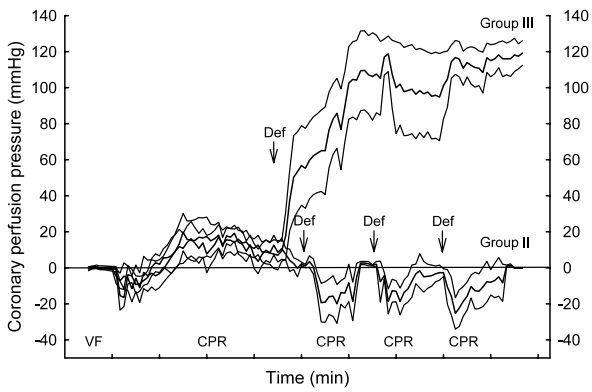

Fig. 7. Coronary perfusion pressure during 3.5 min of mechanical compressions and during defibrillation attempts with (II) and without (III) interrupting the chest compressions. Mean value ± S.E.M., $n = 5$ in each group.

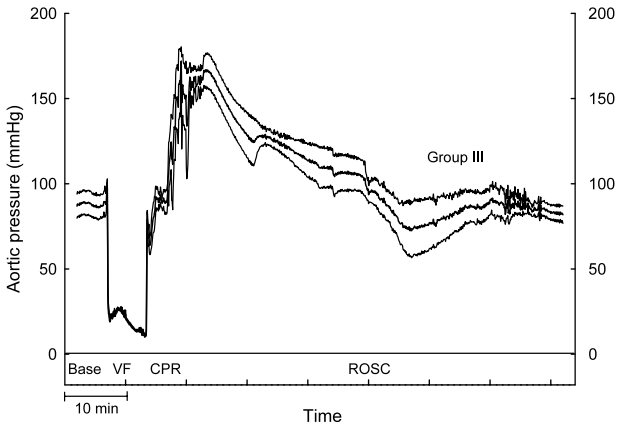

Fig. 8. Systolic intrathoracic aortic pressure during the first hour after ROSC. Mean value±S.E.M., $n = 5$.

success in VF if a shock can be given within 4–5 min of its onset. Only a tiny minority of cardiac arrest victims can be defibrillated within that short period of time.

The present study sheds light on the pathophysiology of acute ventricular fibrillation. Blood is pooled in the venous circulation, with the result that the right heart becomes more and more distended and the left heart more and more empty over about 3 min of VF. When the blood pressure on the arterial side equals that on the venous side, after about 5 min, the coronary perfusion pressure and the carotid flow fall to zero. When chest compressions are initiated, flow in the carotid artery increases to acceptable values within 10 s, but it takes 1 min to bring a negative coronary perfusion pressure back to zero, and a further half minute to bring it up to an adequate level. This time discrepancy is due to the different effects of chest compression on the haemodynamics within and outside the thorax. Extrathoracic organs (e.g. the brain) receive perfusion pressure and flow during both the compression and decompression phases. The arrested heart, however, is only perfused during the decompression phase, since the pressure in the ascending aorta is less or equal to the pressure in the right atrium during the compression phase (Fig. 2). Furthermore, as the right heart becomes more and more distended, the coronary pressure needed to provide adequate perfusion increases correspondingly.

In the group I animals, sinus rhythm was achieved by defibrillation after 6.5 min of VF, but there was no detectable arterial pressure or flow (PEA). At this time the right ventricle remained greatly distended and did not move, while the empty and non-stretched left

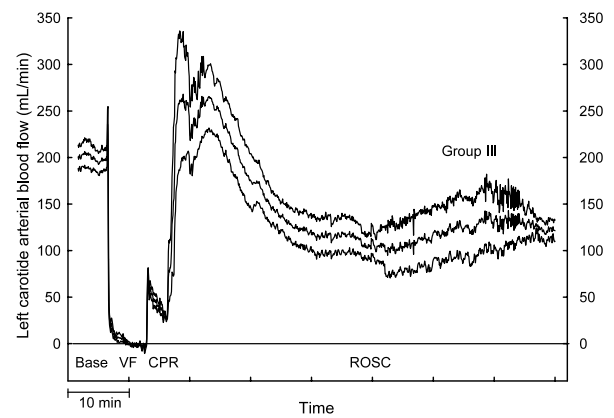

Fig. 9. The blood flow in the left internal carotide artery during the first hour after ROSC. Mean value±S.E.M., $n = 5$.

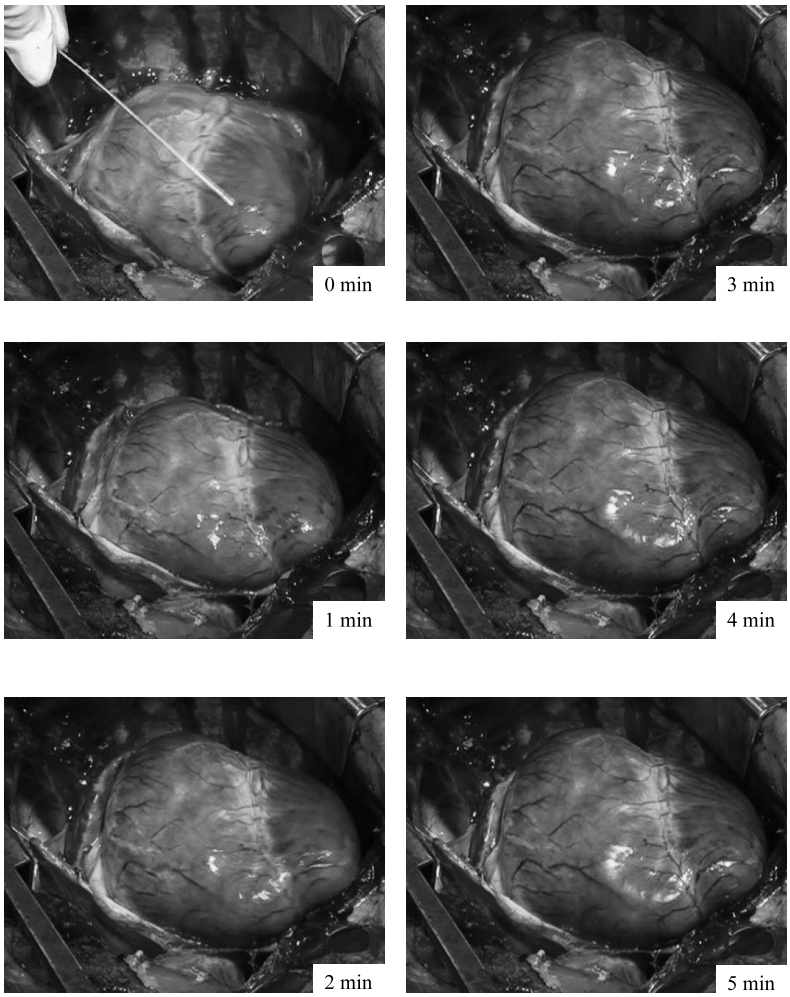

Fig. 10. Frozen pictures from the video uptake after induction of ventricular fibrillation.

ventricle was seen to contract without coronary perfusion pressure. It seems important, therefore, in the treatment of prolonged VF, to give chest compressions before attempting defibrillation, otherwise the physiological requisites for ROSC are absent.

In the absence of immediate restoration of an effective heart beat there is another reason why immediate chest compressions are vitally important for full functional recovery. By the time rescue efforts are under way, the brain has already been subjected to minutes of hypoxia and some flow must be restored as quickly as possible. The initial period of compressions serves two purposes: preservation of brain function during a period of continuing vulnerability, and priming of the heart for successful restoration of the heart beat.

As seen in Fig. 2, one min of compressions (i.e. 100 adequate compressions) was needed to bring the coronary perfusion pressure back to zero, and a further 30 s (50 compressions) to produce a coronary perfusion pressure of 15 mmHg, i.e. the minimum pressure needed for a predictable ROSC [4,7]. Wik et al. recently presented the results from a randomized clinical study

of witnessed out-of-hospital cardiac arrest in about 200 patients [2]. In cases in which CPR was not initiated until 5 min or more after the onset of VF, 3 min of external manual chest compressions before the first defibrillation attempt increased the 1-year survival rate to 20%. This compared with 4% survival in the group treated according to current guidelines with defibrillation as the first-step strategy. Thus, the suggestions of Cobb et al. [1] and Wik et al. [2], to perform chest compressions for 1.5 or 3 min before the first defibrillation attempt, is supported by the findings of the present study.

Interrupting chest compressions reduces the chance of successful ROSC due to the immediate loss of an adequate coronary perfusion pressure. As can be seen in Fig. 7, 30 s of compressions (= 50 compressions) between defibrillation attempts were not enough to create a positive coronary perfusion pressure, although the carotid flow increased to acceptable values (Fig. 5). Even the interruption of chest compressions for rescue breathing during CPR has been reported to give adverse haemodynamic effects [8,9]. It seems, therefore, that defibrillation should be attempted during and not after a period of chest compression. This would clearly not be feasible, or safe, during manual chest compression. It would be possible to reduce to a minimum the interval between stopping compressions and applying a manual defibrillator. On the other hand, automated external defibrillators (AEDs) currently require a significant 'hands off' period whilst analysis of the ECG rhythm takes place. Using mechanical chest compression (mCPR) is one way in which defibrillation can be safely and efficiently carried out during on-going chest compression.

To conclude, a fibrillating, distended heart should be treated by continuous chest compressions for at least for 90 s prior to defibrillation which should, ideally, be carried out during on-going compressions.

Acknowledgements

We want to thank Professor Douglas Chamberlain and Dr. Tony Handley for constructive criticism and great help with the writing of this manuscript. The Study was supported by grants from the University Hospital of Lund, the Swedish Heart Lung Foundation, and the Swedish Medical Research Council (project no. K2002-71X-12648-05C).

References

[1] Cobb LA, Fahrenbuch CE, Walsh TR, et al. Influence of cardiopulmonary resuscitation prior to defibrillation in patients with out-of-hospital ventricular fibrillation. J Am Med Assoc 1999;281:1182–8.
[2] Wik L, Boye Hansen T, Fylling F, et al. Delaying defibrillation to give basic cardiopulmonary resuscitation to patients with out-of-hospital ventricular fibrillation. A randomized trial. J Am Med Assoc 2003;289:1389–95.
[3] Idris AH, Becker LB, Ornato JP, et al. Utstein-style guidelines for uniform reporting of laboratory CPR research. Resuscitation 1996;33:69–84.
[4] Steen S, Liao Q, Pierre L, Paskevicius A, Sjöberg T. Evaluation of LUCAS, a new device for automatic mechanical compression and active decompression resuscitation. Resuscitation 2002;55:285–99.
[5] The Hypothermia After Cardiac Arrest Study Group. Mild therapeutic hypothermia to improve the neurologic outcome after cardiac arrest. N Engl J Med 2002;346:549–56.
[6] Curfman GD. Hypothermia to protect the brain. Perspective. N Engl J Med 2002;346:546.
[7] Paradis NA, Martin GB, Rivers EP, et al. Coronary perfusion pressure and the return of spontaneous circulation in human cardiopulmonary resuscitation. J Am Med Assoc 1990;263:1106–13.
[8] Berg RA, Sanders AB, Kern KB, Hilwig RW, Heidenreich JW, Porter ME, Ewy GA. Adverse hemodynamic effects of interrupting chest compressions for rescue breathing during cardiopulmonary resuscitation for ventricular fibrillation cardiac arrest. Circulation 2001;104:2465–70.
[9] Kern KB, Hilwig RW, Berg RA, Sanders AB, Ewy GA. Importance of continuous chest compressions during cardiopulmonary resuscitation. Improved outcome during a simulated single lay-rescuer scenario. Circulation 2002;105:645–9.

III

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RESEARCH ARTICLE Open Access

Manual versus mechanical cardiopulmonary resuscitation. An experimental study in pigs

Qiuming Liao, Trygve Sjöberg, Audrius Paskevicius, Björn Wohlfart, Stig Steen*

Abstract

Background: Optimal manual closed chest compressions are difficult to give. A mechanical compression/decompression device, named LUCAS, is programmed to give compression according to the latest international guidelines (2005) for cardiopulmonary resuscitation (CPR). The aim of the present study was to compare manual CPR with LUCAS-CPR.

Methods: 30 kg pigs were anesthetized and intubated. After a base-line period and five minutes of ventricular fibrillation, manual CPR (n = 8) or LUCAS-CPR (n = 8) was started and run for 20 minutes. Professional paramedics gave manual chest compression's alternating in 2-minute periods. Ventilation, one breath for each 10 compressions, was given to all animals. Defibrillation and, if needed, adrenaline were given to obtain a return of spontaneous circulation (ROSC).

Results: The mean coronary perfusion pressure was significantly ($p < 0.01$) higher in the mechanical group, around 20 mmHg, compared to around 5 mmHg in the manual group. In the manual group 54 rib fractures occurred compared to 33 in the LUCAS group ($p < 0.01$). In the manual group one severe liver injury and one pressure pneumothorax were also seen. All 8 pigs in the mechanical group achieved ROSC, as compared with 3 pigs in the manual group.

Conclusions: LUCAS-CPR gave significantly higher coronary perfusion pressure and significantly fewer rib fractures than manual CPR in this porcine model.

Background

Studies of cardiopulmonary resuscitation (CPR) events have shown how difficult it is to give optimal chest compressions manually [1-11]. These studies have identified many factors that make manual CPR suboptimal, e.g. rescuer fatigue within 2 minutes, too shallow or too deep chest compressions, too high or too low compression and ventilation rates, too small body size of the rescuer, CPR during transport, especially in stairs or in ambulances, too long pre- and post-shock pauses and too many interruptions in the chest compressions.

In the latest guidelines for CPR from 2005, recommendations to improve the delivery of chest compressions were given [12,13]. To give effective chest compressions, rescuers are advised to "push hard and push fast", at a rate of about 100 compressions per minute. The chest should be allowed to recoil freely after each compression, approximately equal compression and relaxation times should be used, and interruptions in chest compressions should be minimized.

LUCAS™ (LUCAS V2US; Jolife AB, Lund, Sweden) is a CPR device providing automatic 5 cm deep compressions and active decompressions back to normal position with a frequency of 100 per minute, and a duty cycle (compression time) of 50%, i.e., LUCAS is adjusted to give chest compressions according to the latest guidelines. LUCAS was introduced in clinical practice in Sweden by Steen and coworkers in the year 2000, and the first scientific report on its properties, based on 100 pigs and 20 patients, was published in 2002 [14]. Since then several experimental and clinical studies on LUCAS have been published, which confirms its efficacy in supporting quality chest compressions [14-18].

No comparison between mechanical and manual compression performed according to the 2005 guidelines has been made in an experimental study. Our hypothesis is that mechanical compression/decompression will give

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higher coronary perfusion pressure in a model with prolonged CPR, simulating ventricular fibrillation resistant to defibrillation. It is well known that external chest compressions are associated with rib fractures. LUCAS CPR gives a standardized compression depth of maximum 5 cm, whereas with manual CPR there is no control regarding the compression depth. Therefore a second hypothesis was that less rib fractures would occur in the LUCAS-CPR group.

Methods

We have described in detail our pig model for CPR research elsewhere [14]. The design of the experiment is shown in Figure 1. Swedish domestic pigs were stratified into one manual CPR group (n = 8, mean weight 31 kg, range 29-33 kg) and one LUCAS-CPR group (n = 8, mean weight 31 kg, range 28-32 kg). The chest compressions were performed with the pigs in a supine position. All pigs received humane care in compliance with the European Convention for the Protection of Vertebrate Animals used for Experimental and Other Scientific Purposes (1986) and the 'Guide for the Care and Use of Laboratory Animals' published by the National Institutes of Health (NIH Publication 85-23, revised 1985). The study was approved by the ethics committee for animal experiments at Lund University, Sweden.

Anesthesia and ventilation

Anesthesia was induced with an intramuscular injection of ketamine (30 mg/kg) and xylasin (4 mg/kg). Sodium thiopental (5-8 mg/kg) and atropine (0.015 mg/kg) were given intravenously before tracheotomy. Anesthesia and muscular paralysis were maintained with a continuous infusion of 10 ml/h of a NaCl (0.9%) solution containing ketamine (16 mg/ml) and pancuronium (0.6 mg/ml).

A Boussignac ET tube for cardiac arrest (Laboratories Pharmaceutiques VYGON, Ecouen, France, 7 mm internal diameter) was used as an ordinary endotracheal tube. Intratracheal pressure was measured through one of the distal lines incorporated in the wall of the Boussignac ET

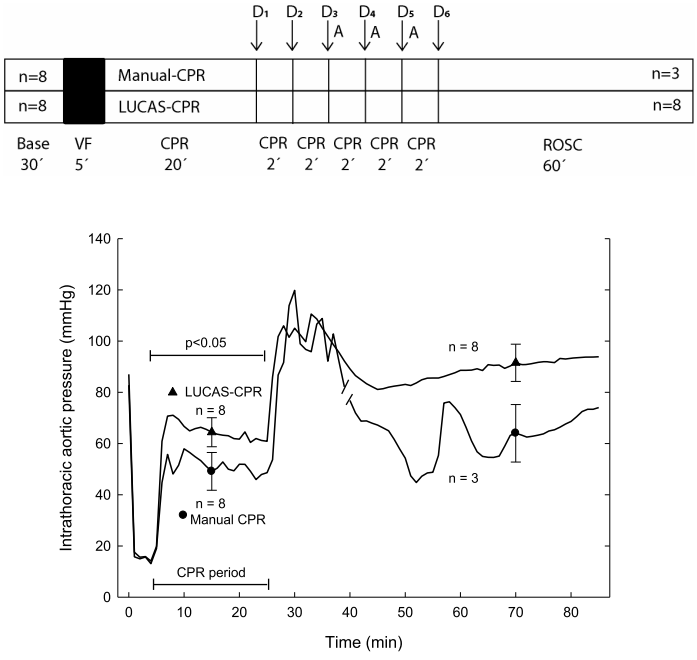

Figure 1 The design of the study (upper panel). The number of pigs with return of spontaneous circulation (ROSC) is indicated within the ROSC rectangle. VF: ventricular fibrillation; CPR: cardiopulmonary resuscitation; D_1-D_6: defibrillations; A: adrenaline 0.01 mg/kg given intravenously. The lower panel shows the mean systolic pressure and during CPR the compression pressure, in the intrathoracic aorta during the experiment. The CPR period is marked. The break in the manual CPR curve marks where n is changed from 8 to 3 individuals. Mean ± SEM is included in 2 places in each curve; n = 8, except for the ROSC period for manual CPR, where n = 3.

tube. The tube was connected to a Servo Ventilator 300 (Servo Ventilator 300, Siemens, Solna, Sweden) using pressure-regulated (max 30 cmH_2O = 23 mmHg) and volume-controlled intermittent positive pressure ventilation (IPPV). Normo-ventilation (end-tidal CO_2 around 5.3 kPa = 40 mmHg) was obtained by using a tidal volume of 8 ml/kg body weight, 20 breaths/min, a PEEP of 5 cmH_2O and a FiO_2 of 0.21.

During CPR ventilation was given, without interruption of chest compressions, by means of a Ruben bag in both the manual CPR and the LUCAS-CPR group. Ventilation was given with 100% oxygen, the frequency was 1 ventilation after every 10th compression (= 10 ventilations/min) in both groups. After return of spontaneous circulation (ROSC) the animals in both groups were given baseline ventilation by the Servo Ventilator 300 with a FiO_2 of 1.0.

Preparation and monitoring

Four catheters for blood pressure measurements and blood sampling were introduced into the right carotid artery and the right internal jugular vein. The catheters were inserted into the ascending aorta and into the right atrium, respectively. An ultrasonic flow probe connected to a MediStim flowmeter apparatus (CM-4000, MediStim ASA, Oslo, Norway) was placed on the left internal carotid artery. A temperature probe was inserted into the esophagus. Three-lead electrocardiogram (ECG) were obtained by electrodes corresponding to R,L,F and ground were adhered to the skin.

Chest compressions

VF was induced with a 5-20 mA and 6-14 Hz square formed wave current delivered to the epicardial surface via a needle electrode puncture through the upper abdomen. CPR was started 5 minutes after induction of VF.

In the manual CPR experiments, 16 paramedics and ambulance nurses from Lund Ambulance Station, 10 men and 8 women (mean length 175 cm, range 162-188 cm, mean weight 76 kg, range 55-95 kg) were responsible for the chest compressions and ventilations. Two paramedics carried out the compressions at each manual CPR experiment and they shifted between doing chest compressions and ventilation every second minute. A sound indicator was used to keep the frequency of the manual compressions at 100/min. Within 14 days before the experiments were done, all rescuers had to undergo manual CPR training on a mannequin and were instructed to give chest compressions according the international guidelines from 2005. The exact spot for delivery of the manual chest compressions were decided by placing of LUCAS on all pigs in both groups and mark the optimal compressions spot by drawing an ink line around the suction cup. During the 5 minutes with VF, LUCAS was placed in correct position so that the compressions could start at scheduled time. The compressions were given on sternum between the inferior 1/3 and superior 2/3 of sternum. The marked place was used for both manual and mechanical chest compressions. The anterior-posterior diameter of the thorax was measured by means of a ruler before and after CPR.

LUCAS (V2US; Jolife AB), also used in humans, was used to deliver the mechanical chest compressions. According to an international agreement (Utstein-style guidelines for uniform reporting of laboratory CPR research. Resuscitation 1996;33:69-84) 20-25 kg pigs are recommended to use as they have similar anterior-posterior diameter as adult humans.

Return of spontaneous circulation

Defibrillations, if indicated, were done externally using biphasic shocks (Lifepak 12, Medtronic, Minneapolis, MN, USA), using 360 J energy through pads (see Figure 1). Between each shock, chest compressions for 2 minutes were to be given. At manual CPR there was to be minimal delay (around 2 seconds) between chest compression and defibrillation. With LUCAS-CPR, defibrillation was given during ongoing CPR. The research leader judged whether ROSC had been obtained after each defibrillation (systolic arterial pressure above 60 mmHg for 1 minute). How to give defibrillation and adrenaline was adjusted to the experimental situation. If ROSC was not obtained after 3 defibrillations, adrenaline 0.01 mg/kg was given in the central venous catheter 3 times, with 2-minute intervals of chest compressions between each dose. After the third dose of adrenaline, CPR was continued for 2 minutes and then terminated. If ROSC was obtained, measurements continued for 1 hour.

Autopsy

After terminating each experiment an autopsy was performed. For obvious reasons (suction marks on the skin) could the autopsy not be made blinded. The position of catheters and the presence of any fractures in ribs or sternum, or injuries on lungs, heart and abdominal organs were noted.

Calculation of the coronary perfusion pressure

The coronary perfusion pressure (CPP) was computed as the difference between the intrathoracic aortic and the right atrial pressure in the end-decompression phase. The beginning of each compression cycle was defined as the maximal pressure rise ratio (see Figure 2). The end-decompression phase was measured in a window between 0.1 to 0.05 seconds before the compression. The mean of the sampled values during that window of 0.05 seconds (10 values, i.e., 200 Hz) was calculated.

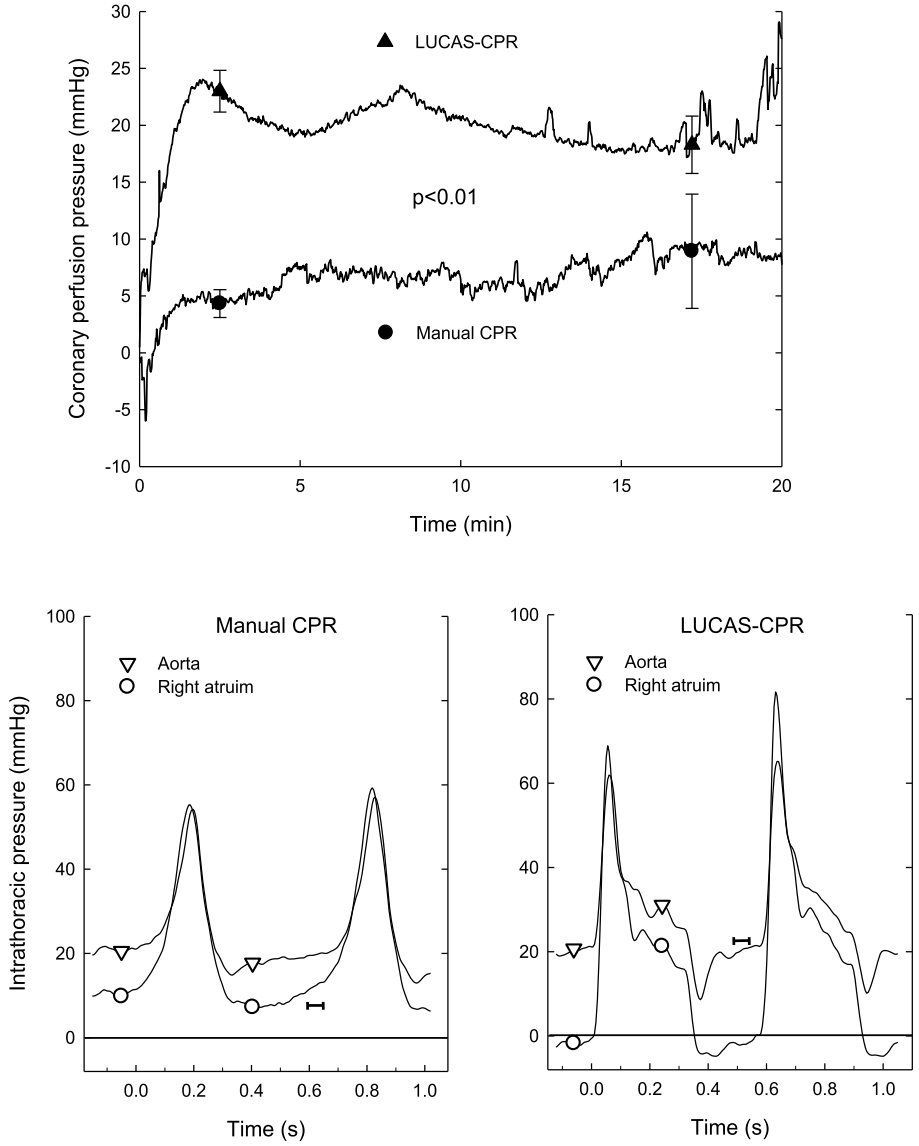

Figure 2 The coronary perfusion pressure in the two groups (upper panel). The lower panels show typical pressure curves in the intrathoracic aorta (triangles) and the right atrium (circles) during two cycles of CPR in the manual CPR (left) and LUCAS-CPR (right) groups just after a ventilation. A bar (|–|) is inserted before one compression in both panels. The 0.05-second long bar shows where in the cycle CPP is calculated (as the difference between the pressure in aorta and right atrium). The level of the bar shows the CPP in this registration; 7 mmHg in the manual group and 22 mmHg in the LUCAS group.

Statistics

A sample size of 8 in each group was used. By use of the following parameters sample size calculation showed that n had to be at least n = 7 in each group. 1: A standard deviation of 4.9 mmHg for the measurement of CPP during manual compressions as found in an earlier study [14]. 2: A difference of 7 mmHg between groups. 3: A significance level of 5%.

Global interpretation of data was done by means of the area under curve comparing different variables between the two groups during the CPR period. Student's t-test for unpaired observations was used. Data obtained during the first 90 seconds of the CPR period was excluded from the statistical calculations because this is the time required to reach plateau. Fisher's Exact Test was used for autopsy findings. A p-value <0.05 was regarded as indicative of a statistically significant difference between the groups.

Results

ROSC

In the manual group five pigs did not achieve ROSC. One pig obtained ROSC after 1 defibrillation, 1 pig obtained ROSC after 1 defibrillation followed by 2 minutes of manual CPR and 1 pig obtained ROSC after 1 defibrillation followed by 10 minutes of manual CPR and intravenous adrenaline 0.01 mg/kg 3 times at 2-minute intervals, according to the protocol (Figure 1).

In the LUCAS group all 8 animals obtained ROSC. In 5 pigs, ROSC was obtained after the first defibrillation. In 2 pigs ROSC was obtained after one defibrillation followed by 2 minutes of LUCAS-CPR. In 1 pig, ROSC was obtained after 1 defibrillation, 4 minutes of LUCAS-CPR and the first dose of 0.01 mg/kg of intravenous adrenaline according to the protocol (Figure 1).

Number of compressions given during the 20-minute CPR-period

About two thousand compressions were given to each animal in the LUCAS group. The mean time for the paramedics to change between compression and ventilation was 4 ± 1 seconds, i.e., each pig received about 60 compressions less in the manual group.

Aortic pressure during compression phase

The aortic compression pressure in the LUCAS-group was around 65 mmHg, and in the manual group around 55 mmHg during the CPR period ($p < 0.05$)(Figure 1).

Intrathoracic aortic and right atrial pressures during decompression phase

The intrathoracic aortic pressure during the decompression phase varied between 5 and 15 mmHg in the manual group and was significantly higher in the LUCAS group where it varied between 10 and 25 mmHg ($p < 0.05$). The right atrial pressure during the decompression phase was between 5 and 10 mmHg in the manual group whereas it was significantly lower in the LUCAS group, where it varied between -5 and 5 mmHg ($p < 0.01$).

Coronary perfusion pressure

The coronary perfusion pressure was between 20 and 25 mmHg in the LUCAS group during CPR which was significantly ($p < 0.01$) higher than in the manual group where it was between 5 and 10 mmHg (Figure 2). There was no overlap of CPP between the two groups.

Left carotid artery flow

The mean flow at baseline was 176 ± 17 ml/min in the manual group and 212 ± 33 ml/min in the LUCAS group (not significant). During CPR, the flow was significantly higher ($p < 0.05$) in the LUCAS-CPR group during the first 10 minutes (Figure 3).

Electrocardiogram

All ECG recordings just before initiation of ventricular fibrillation showed sinus rhythm with a mean rate of 95/min (n = 16).

In the LUCAS group there was no sign of ischemia 1 hour after ROSC; in the 3 animals with ROSC in the manual group, ECG was also normal, except in one pig where negative T-waves were seen.

End-tidal CO_2

The $ETCO_2$-values were around 3.4 kPa in the LUCAS group and around 2.2 kPa in the manual group; this difference was statistically significant ($p < 0.05$).

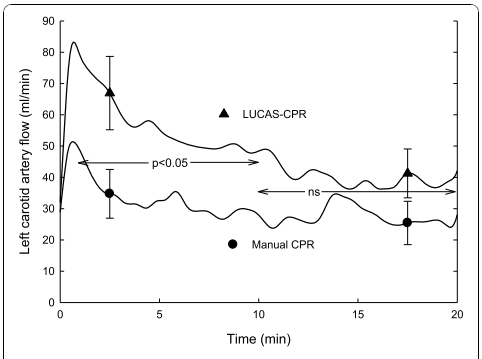

Figure 3 Left carotid artery blood flow in the manual CPR and LUCAS-CPR groups during the CPR period. Statistically significant differences between the groups are shown. Mean ± SEM, n = 8 in both groups.

Peak airway pressure

The peak airway pressure varied between 15 to 25 mmHg, and there was no statistically significant difference between the groups.

Blood gases

There were no significant differences in blood gases (Table 1). The arterial oxygenation was excellent in both groups. The animals in both groups had subnormal $PaCO_2$-values during CPR, i.e., the animals were slightly hyperventilated (Table 1).

Flattening of thorax after CPR

The anterior-posterior diameter decreased by 25 ± 2 mm in the manual group and by 20 ± 2 mm in the LUCAS group, a difference of 5 mm (p = 0.14)

Autopsy

In the 5 pigs that did not achieve ROSC in the manual group, the hearts were in ischemic contracture (stone heart) with no lumen seen on cross section of the left ventricle. In the manual group there was significantly (p < 0.01) more rib fractures; manual group left side 33, right side 21, and LUCAS group left side 30, right side 3. Two serious injuries were seen in the manual group, one right-sided pressure pneumothorax (air escaping when the right pleura was opened, right lung collapsed), and one vertical deep liver rupture (500 ml blood could be sucked out from the abdomen, which is about 20% of the blood volume of a pig this size).

Discussion

In the porcine model used in the present study, LUCAS-CPR was more efficient and caused less trauma than manual CPR. The shape of the pig thorax is different from the human thorax [14] and therefore the results obtained in the manual group should be interpreted with caution. The human thorax in the supine position is like an egg laying on its side whereas in the same position the pig thorax is like an egg standing on its end. In pigs, the ventricles are positioned in the center of the thoracic cavity, surrounded by lung tissue on all sides. In humans, the right ventricle is positioned just under the sternum. This anatomic difference makes it more difficult to get a compression effect on the heart in pigs where the compressions affect the heart only by 'the thoracic pump mechanism', e.g., a chest compression increases the intrathoracic pressure which in turn affects the heart. In humans not only 'the thoracic pump mechanism' but also a 'heart pump mechanism' works, i.e. a direct compression of the heart by a chest compression. Patients with chronic obstructive pulmonary disease (COPD) have a thorax that is more like the porcine thorax with lungs surrounding the heart on all sides.

Table 1 Blood gases at baseline, during CPR, and during ROSC in the manual group and the LUCAS group

	Baseline	20 min CPR	60 min ROSC
Temperature (°C)			
Manual	37.1 ± 0.4	36.8 ± 0.3	35.8 ± 0.5
LUCAS	37.5 ± 0.2	36.6 ± 0.3	36.4 ± 0.3
Hbv (g/l)			
Manual	111 ± 2	127 ± 3	109 ± 6
LUCAS	109 ± 2	120 ± 2	110 ± 2
Hctv (%)			
Manual	34 ± 1	39 ± 1	33 ± 2
LUCAS	34 ± 1	37 ± 1	34 ± 1
SaO_2 (%)			
Manual	92 ± 0	95 ± 1	95 ± 1
LUCAS	91 ± 0	94 ± 0	95 ± 0
SvO_2 (%)			
Manual	66 ± 3	26 ± 3	50 ± 9
LUCAS	66 ± 2	24 ± 2	61 ± 5
PaO_2 (kPa)			
Manual	13.4 ± 0.3	53.5 ± 4.5	71.1 ± 3.3
LUCAS	12.6 ± 0.3	54.6 ± 2.7	62.4 ± 2.7
PvO_2 (kPa)			
Manual	6.0 ± 0.3	2.9 ± 0.2	5.0 ± 0.3
LUCAS	5.9 ± 0.2	3.3 ± 0.6	5.7 ± 3.3
$PaCO_2$ (kPa)			
Manual	5.5 ± 0.3	3.1 ± 0.4	5.6 ± 0.9
LUCAS	5.6 ± 0.3	4.0 ± 0.4	5.6 ± 0.3
$PvCO_2$ (kPa)			
Manual	6.6 ± 0.4	8.0 ± 0.6	8.8 ± 1.6
LUCAS	6.5 ± 0.3	8.1 ± 0.5	7.7 ± 0.6
pHa			
Manual	7.48 ± 0.01	7.47 ± 0.03	7.38 ± 0.06
LUCAS	7.47 ± 0.01	7.42 ± 0.02	7.42 ± 0.02
pHv			
Manual	7.42 ± 0.01	7.27 ± 0.02	7.24 ± 0.07
LUCAS	7.43 ± 0.01	7.25 ± 0.01	7.32 ± 0.03
Base excess a (mmol/l)			
Manual	6.2 ± 0.7	-5.5 ± 0.7	-0.4 ± 3.6
LUCAS	6.4 ± 0.7	-4.4 ± 0.8	2.4 ± 1.1
Base excess v (mmol/l)			
Manual	6.5 ± 0.8	-1.4 ± 0.6	-0.9 ± 3.7
LUCAS	6.5 ± 0.7	-2.2 ± 0.7	2.1 ± 1.2

Table 1 Blood gases at baseline, during CPR, and during ROSC in the manual group and the LUCAS group *(Continued)*

Lactate v (mmol/l)			
Manual	1.5 ± 0.2	6.1 ± 0.2	6.6 ± 1.9
LUCAS	1.5 ± 0.2	6.3 ± 0.2	4.3 ± 0.5
Glucose v (mmol/l)			
Manual	5.6 ± 0.4	15.0 ± 1.5	11.8 ± 3.1
LUCAS	5.9 ± 0.4	14.7 ± 0.7	11.6 ± 1.3

N = 8, except at 60 min ROSC in the manual group were n = 3.

Hbv = hemoglobin in venous blood; Hctv = hematocrite in venous blood; SaO_2 and SvO_2 = oxygen saturation in arterial and venous blood, respectively; PaO_2 and PvO_2 = partial oxygen pressure in arterial and venous blood, respectively; $PaCO_2$ and $PvCO_2$ = partial carbon dioxide pressure in arterial and venous blood, respectively; pHa and pHv = pH in arterial and venous blood, respectively; base excess a and base excess v = base excess in arterial and venous blood, respectively; lactate v and glucose v = lactate and glucose in venous blood. Blood gases are given at temperature-corrected values.

The animals in the LUCAS-group received continuous compressions without a need to stop due to rescuer fatigue, or for rescuer safety during defibrillation attempts. Therefore the animals in the manual group received about 60 compressions less than those in the LUCAS-group. For each change between ventilation and compression, the animals were without CPR for about 4 seconds, during which time the coronary perfusion pressure dropped to zero, and when the compressions were started again, it took about 10 seconds to regain the CPP that had been obtained during the previous 2-minute period of continuous manual CPR.

Studies have shown the difficulty in giving optimal manual compressions consistently without fail, many compressions are either too shallow [6] or too deep [4]. Too deep compressions may cause severe injuries, as was seen in one pig in the manual group. There were significantly more rib fractures in the manual group; typically, in the manual group there were rib fractures on both sides, whereas in the LUCAS-group there were fractures only on one side. After the experiment, the thorax recoiled better in the LUCAS-group, because most ribs were intact on one side. The anterior-posterior diameter of the chest at the point where the compressions were given was on average 5 mm less in the manual group based on measurements before and after compressions. This difference between groups was not statistically significant, but co-incided with a visibly flatter appearance of the anterior part of the chest in some of the animals in the manual group. In a clinical CPR study comparing LUCAS with manual chest compressions, Smekal et. al. showed no increased rate of injuries in deceased victims in the LUCAS CPR group [19]. Though, patients allotted to a mechanical chest compression group get manual chest compression initially before mounting the device. This makes it impossible to compare the true difference between mechanical and manual chest compression in clinical studies.

The suction cup of the LUCAS device provides active decompression of the chest. This resulted in a negative pressure in the right atrium during the initial part of decompression phase (Figure 2). The right atrial pressure during the decompression phase was between 5 and 10 mmHg in the manual group whereas in the LUCAS group it was between -5 and 5 mmHg, i.e., it was significantly lower in the LUCAS group. This, together with a significantly higher intrathoracic aortic pressure during the end-decompression phase in the LUCAS group, explains the significantly higher CPP in that group. Paradise and co-workers found that only patients with a coronary perfusion pressure of 15 mmHg or higher got ROSC [20]. In an earlier study we have found the same for pigs [14]. A CPP of only 5 mmHg, as seen in the manual group, probably explains the lower ROSC rate. Another possible explanation for the higher ROSC rate in the LUCAS CPR group was that they were defibrillated during ongoing compressions [15]. However, in the present study the delay between compressions and defibrillation was only 2 seconds, which is too short for a significant drop in CPP. Therefore, we think that the lower ROSC rate in the manual group was caused by the low CPP in this model with prolonged CPR.

Rubertsson and Karlsten [16] used a device (Cardiopress) for standardized manual chest compressions and compared it with LUCAS in a porcine model. During CPR mean cortical cerebral blood flow in the group treated with LUCAS compressions reached a level of approximately 65% of baseline blood flow that was stable throughout the whole CPR period. In the manual group the mean cortical cerebral blood flow was statistically significantly lower, around 40%.

If the ventilation is standardized during CPR, as in the present study, end tidal CO_2 can be used as an index of the blood flow through the lungs [21]. End tidal CO_2 was significantly higher in the LUCAS group, indicating a higher blood flow in that group.

Conclusions

LUCAS-CPR is significantly more efficient and gives less injury than manual CPR in this porcine model.

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Authors' contributions
All authors participated in the design of the study and performed the experiments. QL, TS and SS drafted the manuscript. All authors read and approved the final manuscript.

Competing interests
Jolife AB has given economical support for the research in cardiopulmonary resuscitation done by Stig Steen. There are no other competing financial or non-financial interests.

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References

1. Hightower D, Thomas SH, Stone CK, Dunn K, March JA: **Decay in quality of closed-chest compressions over time.** *Ann Emerg Med* 1995, **26**:300-303.
2. Sunde L, Wik K, Steen PA: **Quality of mechanical, manual standard and active compression-decompression CPR on the arrest site and during transport in a manikin model.** *Resuscitation* 1997, **34**:235-242.
3. Ocha FJ, Ramalle-Gómara E, Lisa V, Saralegui I: **The effect of rescuer fatigue on the quality of chest compressions.** *Resuscitation* 1998, **37**:149-152.
4. Thorén AB, Axelsson A, Holmberg S, Herlitz J: **Measurement of skills in cardiopulmonary resuscitation - do professionals follow given guidelines?** *Eur J Emerg Med* 2001, **8**:169-176.
5. Ashton A, McCluskey A, Gwinnutt CL, Keenan AM: **Effect of rescuer fatigue on performance of continuous external chest compressions over 3 min.** *Resuscitation* 2002, **55**:151-155.
6. Wik L, Kramer-Johansen J Myklebust H, Sørebø H, Svensson L, Fellows B, Steen PA: **Quality of cardiopulmonary resuscitation during out-of-hospital cardiac arrest.** *JAMA* 2005, **293**:299-304.
7. Heidenreich JW, Berg RA, Higdon TA, Ewy GA, Kern KB, Sanders AB: **Rescuer fatigue: standard versus continuous chest-compression cardiopulmonary resuscitation.** *Acad Emerg Med* 2006, **13**:1020-1026.
8. Aufderheide TP, Pirrallo RG, Yannopoulos D, Klein JP, von C, Sparks CW, Deja KA, Kitscha DJ, Provo TA, Lurie KG: **Incomplete chest wall decompression: a clinical evaluation of CPR performance by trained laypersons and an assessment of alternative manual chest compression-decompression techniques.** *Resuscitation* 2006, **71**:341-351.
9. Kim JA, Vogel D, Guimond G, Hostler D, Wang HE, Menegazzi JJ: **A randomized, controlled comparison of cardiopulmonary resuscitation performed on the floor and on a moving ambulance stretcher.** *Prehosp Emerg Care* 2006, **10**:68-70.
10. Edelson DP, Abella BS, Kramer-Johansen J, Wik L, Myklebust H, Barry AM, Merchant RM, Hoek TL, Steen PA, Becker LB: **Effect of compression depth and pre-shock pauses predict defibrillation failure during cardiac arrest.** *Resuscitation* 2006, **71**:137-145.
11. Olasveegen TM, Tomlison AE, Wik L, Sunde K, Steen PA, Myklbust H, Kramer-Johansen J: **A failed attempt to improve quality of out-of-hospital CPR through performance evaluation.** *Prehosp Emerg Care* 2007, **11**:427-433.
12. European Resuscitation Council: **Guidelines 2005.** *Resuscitation* 2005, 67S1.
13. **2005 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care.** *Circ* 2005, 112.
14. Steen S, Liao Q, Pierre L, Paskevicius A, Sjöberg T: **Evaluation of LUCAS, a new device for automatic mechanical compression and decompression resuscitation.** *Resuscitation* 2002, **55**:285-299.
15. Steen S, Liao Q, Pierre L, Paskevicius A, Sjöberg T: **The critical importance of minimal delay between chest compressions and subsequent defibrillation: a haemodynamic explantation.** *Resuscitation* 2003, **58**:249-258.
16. Rubertsson S, Karlsten R: **Increased cortical cerebral blood flow with LUCAS, a new device for mechanical chest compressions compared to standard external compressions during experimental cardiopulmonary resuscitation.** *Resuscitation* 2005, **65**:357-363.
17. Steen S, Sjöberg T, Olsson P, Young M: **Treatment of out-of-hospital cardiac arrest with LUCAS, a new device for automatic mechanical compression and active decompression resuscitation.** *Resuscitation* 2005, **67**:25-30.
18. Nielsen N, Sandhall L, Scherstén F, Friberg H, Olsson SE: **Successful resuscitation with mechanical CPR, therapeutic hypothermia and coronary intervention during manual CPR after out-of-hospital cardiac arrest.** *Resuscitation* 2005, **65**:111-3.
19. Smekal D, Johansson J, Huzrvka T, Rubertsson S: **No difference in autopsy detected injuries in cardiac arrest patients treated with manual chest compared with mechanical compressions with the LUCAS TM device - A pilot study.** *Resuscitation* 2009, **80**:1104-7.
20. Paradis NA, Martin GB, Rivers EP, *et al*: **Coronary perfusion pressure and the return of spontaneous circulation in human cardiopulmonary resuscitation.** *JAMA* 1990, **263**:1106-1113.
21. Levine RL, Wayne MA, Miller CC: **End-tidal carbon dioxide and outcome of out-of-hospital cardiac arrest.** *N Engl J Med* 1997, **337**:301-306.

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