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Automatic and manual devices for cardiopulmonary resuscitation: A review

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Abstract
Rate of survival without any neurological consequence after cardiac arrest is driven not only by early recognition but also by high-quality cardiopulmonary resuscitation. Because the effectiveness of the manual cardiopulmonary resuscitation is usually impaired by rescuers' fatigue, devices have been devised to improve it by appliances or ergonomic solutions. However, some devices are thought to replace the manual resuscitation altogether, either mimicking its action or generating hemodynamic effects with working principles which are entirely different. This article reviews such devices, both manual and automatic. They are mainly classified by actuation method, applied force, working space, and positioning time. Most of the trials and meta-analyses have not demonstrated that chest compressions given with automatic devices are more effective than those given manually. However, advances in clinical research and technology, with an improved understanding of the organizational implications of their use, are constantly improving the effectiveness of such devices.

Keywords
Cardiac arrest, cardiopulmonary resuscitation, automatic devices, interposed abdominal compression.

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Introduction

Cardiac arrest is a sudden diminution of heart activity which impairs the effective pumping of blood. More than 420,000 people suffer an out-of-hospital cardiac arrest in the United States every year, and the American Heart Association (AHA) estimates that this number will increase in the next years.[1] In the last 50 years, research has steadily improved cardiopulmonary resuscitation (CPR), but there is still much to do, since survival rates remain low. The effectiveness of the CPR depends on many factors, where the promptness and the quality of the resuscitation procedure are the most important. All the optimal parameters of such procedure, like execution timing, chest compression rate, and chest compression frequency are stated in the AHA guidelines.[2]

Automatic CPR devices have been devised to solve some problems that reduce the effectiveness of the manual CPR. The first of these problems, probably the most important, is the fatigue that rescuers experience during CPR. In fact, the human chest has a viscous damping that dissipates part of the energy applied during the massage, so that energy has to be continuously supplied by the rescuer.[3–5] Over time, fatigue sets in and

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lowers the effectiveness of the massage.[6–9] Therefore, rescuers need to change frequently, interrupting the massage and consequently reducing still further the effectiveness of the resuscitation.[10,11] On the other hand, automatic devices do not suffer fatigue at all and can also continue to massage during defibrillation or other complementary operations.[12] In addition, if a rigid stretcher is used during the transportation of the patient from the scene to the ambulance, the massage can continue uninterrupted all the time.

However, because no evidence has been shown that automatic devices improve the outcome of CPR, the AHA does not recommend their routine use. Nevertheless, such devices are a viable alternative when high-quality manual compressions are challenging or dangerous by the provider.[2] This article reviews the devices for CPR, which can be just adjuncts to manual CPR, for example providing prompts to the rescuer or improving the effect of the chest compressions, or devices aimed at replacing completely the manual CPR. After a brief description of each device, their technical features will be summarized and compared. Then, their effectiveness will be evaluated confronting the results of meta-analyses, trials, and smaller studies, considering not only clinical outcomes but also the ability to perform high-quality CPR in specific situations, such as during patient transportation, percutaneous coronary intervention, or diagnostic imaging. Finally, more specific issues will be addressed in the section "Discussion." Most of these issues are technical, but we will consider features and properties that influence the three main requirements that, in our opinion, an automatic device for CPR should have: effectiveness, fast positioning, and versatility.

CPR devices

The main categorization of CPR devices consists of the design approach. Previous and current versions follow two types of concepts: manual and automatic. Figure 1 shows examples of one manual—(a) CPR PRO Cradle—and three automatic devices—(b) EM-CPR, (c) LifeStat, and (d) LUCAS.

Manual devices are auxiliary components with the purpose to drive the rescuers on a step-by-step procedure in order to perform a more effective CPR massage by acoustic and visual signals. In some devices, a further scope is to reduce the fatigue of the rescuer with a mechanical advantage or a more efficient application of the compressing force. On the contrary, the automatic devices are able to provide autonomously the chest compression with well-defined depth and rate. CPR devices may be also categorized into the following:

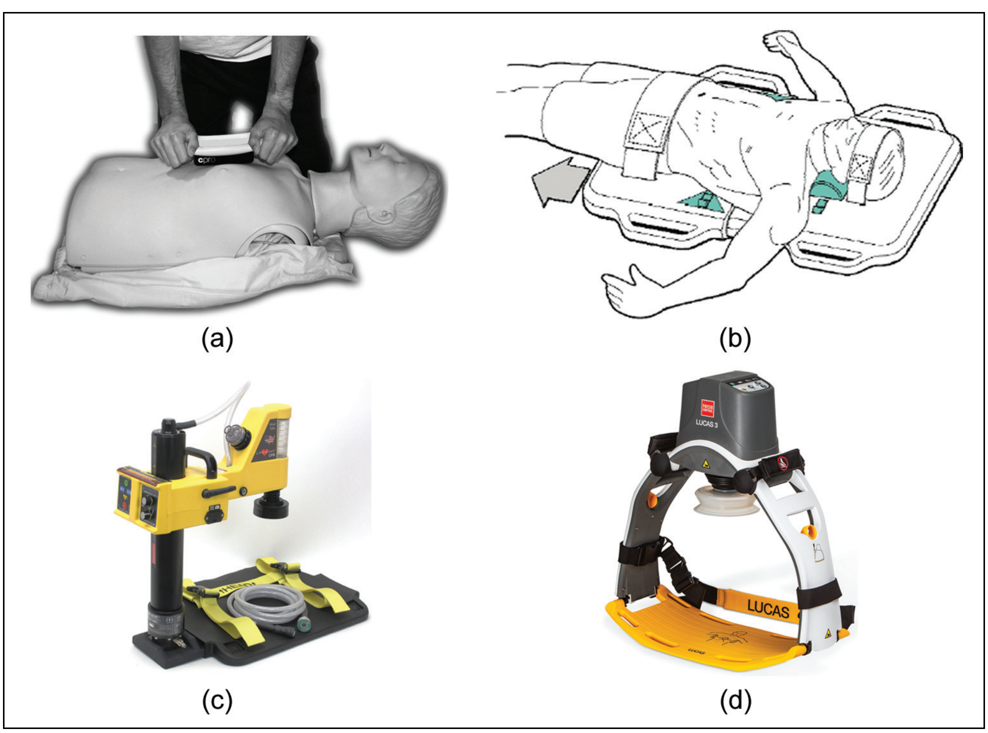

Figure 1. Examples of cardiopulmonary resuscitation devices: (a) CPR PRO Cradle, (b) EM-CPR, (c) LifeStat, and (d) LUCAS (courtesy of Ivor Medical, Politecnico di Milano, Michigan Instruments, Physio-Control, Inc., respectively).

- chest massage action—compression/decompression;
- actuation type—electric, pneumatic, and magnetic.

Further classifications may be based on the specific features of the devices as shown in Table 1.

Most of the devices are designed to be light and compact for out-of-hospital CPR, while the EM-CPR,[13–15] the parallel manipulator,[16] and the pGz[17–20] are intended for in-hospital CPR only (Table 2). All the devices, but the CardioPump and the LUCAS, perform exclusively chest compression. On the contrary, the CardioPump and the LUCAS alternate compression with active decompression by a suction cup that forces the thorax back to its uncompressed volume. Active decompression increases the venous return by decreasing the intrathoracic pressure, and consequently increases the overall flow, especially if coupled with an impedance threshold device (ITD).[21,22] However, comparing the effectiveness of active compression–decompression cardiopulmonary resuscitation (ACD-CPR) delivered by the CardioPump to manual CPR, Günaydın et al.[23] found no statistical differences in return of spontaneous circulation (ROSC), discharge rates, and survival rates in the outcome of 181 out-of-hospital and in-hospital events.

The LifeStick acts quite differently from the other devices because it performs an interposed abdominal compression–cardiopulmonary resuscitation (IAC-CPR), that is, abdominal compressions alternated to chest compressions. The cyclic alternation of chest and abdominal compressions doubles the flow,[24–26] allowing to decrease the depth of compression, and therefore the danger of ribs and sternum injuries. However, compressions have to be less vigorous to prevent injuries to vital organs because the abdomen is softer than the thorax. CardioPump, CPR PRO, CPR RsQ Assist, and LifeStick are manual tools that concentrate on the sternum the energy provided by the rescuer, while Animax, Cardiac Responder, corpuls cpr, Heartsaver, LifeStat, LifeBelt, Lifeline ARM, LUCAS, Thumper, Weil Mini, Weil SCC, and the parallel manipulator act with a piston or a compressing pad. The AutoPulse and the hydraulic–pneumatic[27] band compress the chest on a wider area by a wrapping band, while the vest[28] does the same with a device analogous to a large blood pressure cuff. The Weil Mini and the Weil SCC act on the sternum with a compressing piston and, simultaneously, on the whole chest cavity with a torso restraint placed around the patient. On the contrary, the EM-CPR and the pGz do not exert any force on the thorax. The EM-CPR stimulates the contraction of both the diaphragm and the abdominal muscles by magnetic impulses generated by coils, and such a rhythmic contraction of the abdominal muscles pumps blood from the abdomen, which contains about 20%–25% of the total blood of the body. In addition, it provides a negative pressure ventilation which aids rather than impedes circulatory output. Therefore, ventilation and circulation result from a single intervention. The pGz device generates hemodynamic effects in a completely different way because it is the periodic acceleration along the spinal axis that moves the blood in the cardiovascular and pulmonary systems. Furthermore, the inertia forces acting in the abdominal area compress and dilate the diaphragm to reproduce natural breathing.[29] The CardioPump, the CPR PRO, and the CPR RsQ Assist are the lightest and most compact devices because they have no moving parts. The CardioPump has two components: a handle with a gauge that measures the force applied to the thorax, and a suction cup for active decompression. The CPR RsQ Assist is similar, but it has no gauge. The CPR PRO is intended for compression only. The LifeBelt and the LifeStick are manual device too, but they are slightly heavier than the previous ones. Animax is different because it is powered manually, but it has moving parts. Therefore, it is heavier than the other manual devices. Dimensions and weight of the EM-CPR, the pGz, the parallel manipulator, the vest, and the hydraulic–pneumatic band are not defined because their development is still in progress. Being designed for in-hospital use only (save the hydraulic–pneumatic band), they do not have the dimensional constraints that portable devices have to comply with. All the other devices (AutoPulse, Cardiac Responder, corpuls cpr, Heartsaver, LifeStat, Lifeline ARM, LUCAS, Thumper) have similar weight, except Weil Mini and Weil SCC, which are comparable to the manual devices.

In order to be approved, devices must comply with the AHA and the European Resuscitation Council guidelines for CPR, above all to compress with a rate of at least 100 compressions per minute with a depth of 50 mm. Table 2 shows not only the compression rate and the compression depth, but also the time needed to position and start the device, as well as other noteworthy features. Manual tools do not have technical data of this sort because the effective rate and depth of compression are attained by the rescuer who uses them. However, the LifeStick requires a lower compression rate than the CardioPump and the CPR RsQ Assist because of its double pumping effect and the danger to injure the abdomen. Cardiac Responder, Heartsaver, LifeStat, and Thumper compress with a rate of 100 compressions per minute, while Weil Mini has a rate slightly higher. The corpuls cpr is more versatile because it can adjust the rate in a range of 40 compressions per minute, from a minimum of 80 to maximum of 120. On the contrary, the AutoPulse has a fixed rate of only 80 compressions per minute because it has a greater effect on hemodynamics at lower rates, as the vest, which compresses at 60 compressions per minute. Before starting, Thumper calculates the

Table 1. High-level characteristics of manual and automatic devices for CPR.

Device	Manufacturer	Description	Action	Actuation mode	Main features
Animax	AAT Alber Antriebstechnik GmbH	Piston operated by a lever. Frame adjustable in height and width to fit the patient's size.	Compression	Manual	30:2 ventilation, 2:1 advantage lever
CardioPump	Advanced Circulatory Systems	Handheld device. Piston with a suction cup to stick to the chest. The rescuer operates the device by a handle.	Compression + decompression	Manual	Force gauge, metronome
CPR RsQ Assist	CPR RsQ Assist	Handheld device. The rescuer operates the device by a toroidal handle.	Compression	Manual	Voice prompts, metronome
CPR PRO Cradle	Ivor Medical	Handheld device. Ergonomic design.	Compression	Manual	Slot for smartphone
LifeBelt	Deca-Medics	Leverage pushed against the chest.	Compression	Manual	2:1 advantage
LifeStick	Datascope Corporation	Dual-handled rigid bar with two short pistons with adhesive pads. The larger pad is placed over the abdomen and the smaller over the chest.	Thoracic + abdominal	Manual	Force gauges
Autopulse	ZOLL Circulation	A load-distributing band and a backboard. The band is placed around the chest, and tightened and loosened by a motor.	Compression	Electric	Band
corpuls cpr	GS Elektromedizinische Geräte GmbH	Piston mounted on a swivel arm.	Compression	Electric	Piston
Lifeline ARM	Defibtech	Piston mounted on a removable frame placed around the chest. The frame is fixed to a rigid backboard.	Compression	Electric	Piston
LUCAS	Physio-Control, Inc./Jolife AB	Piston mounted on a removable frame placed around the chest. The frame is fixed to a rigid backboard.	Compression + decompression	Electric	Piston
EM-CPR	Polytechnic of Milan (Italy)	Electrical or magnetic device placed on or in a blackboard.	Expulsive maneuver	Electric	Magnetic coils
pGz	–	Table oscillating along the longitudinal axis.	Oscillating motion	Electric	Motor
Parallel manipulator	KL University (India)	Translating parallel manipulator mounted on a movable base with supporting columns.	Compression	Electric	Parallel manipulator
Cardiac Responder	Brunswick Biomedical Technologies	Piston tied to the chest by straps.	Compression	Pneumatic	Piston
Thumper	Michigan Instruments	Piston mounted on an arm fixed to a supporting column. Rigid backboard.	Compression	Pneumatic	Piston
Weil Mini	Resuscitation International	Piston secured by a torso restraint placed underneath and around the back of the patient.	Compression	Pneumatic	Piston
Weil SCC	SunLife Science	Piston secured by a torso restraint placed underneath and around the back of the patient.	Compression	Pneumatic	Piston
Heartsaver	Brunswick Biomedical Technologies	Piston mounted on an arc. The supporting arm is placed on the device that drives the piston.	Compression	Pneumatic	Piston
LifeStat	Michigan Instruments	Piston mounted on an arm fixed to a supporting column. Rigid backboard.	Compression	Pneumatic	Piston
Vest CPR	Johns Hopkins University	Vest placed around the patient's chest. The vest is cyclically inflated and deflated.	Compression	Pneumatic	Vest
Hydraulic–pneumatic band	Johns Hopkins University	Circumferential band tightened and loosened by a pneumatic piston. A hydraulic cushion (a water-containing bladder) placed between the band and the chest applies a pressure to the chest when the band is tightened.	Compression	Pneumatic	Pressure generated by the movement of a piston

CPR: cardiopulmonary resuscitation.

Table 2. Detailed technical characteristics of CPR devices.

Device	Actuation type	Hospital	Active decompression	Abdominal compression	Force	Weight (kgf)	Dimensions (mm)	Actuator system	Actuator power	Compression rate (1/min)	Compression depth (mm)	Positioning time (s)
CardioPump	Manual	I/O	Yes	No	Pointed	0.58	–	Piston	Manual	–	–	–
CPR PRO	Manual	I/O	No	No	Pointed	–	–	Piston	Manual	–	–	–
CPR RsQ Assist	Manual	I/O	No	No	Pointed	–	–	Piston	Manual	–	–	–
LifeStick	Manual	I/O	No	Yes	Pointed	–	–	Piston	Manual	–	–	–
Animax	Manual	I/O	No	No	Pointed	9.8	3830 × 530 × 180	Piston	Manual	–	40–50	20
LifeBelt	Manual	I/O	No	No	Pointed	2.26	–	Piston	Manual	–	–	15
AutoPulse	Automatic	I/O	No	No	Distributed	101	84 × 462 × 825	Motor	Electric	80	6.3/−112.6	30
Cardiac Responder HLR 601	Automatic	I/O	No	No	Pointed	6.8	127 × 508 × 431	Piston	Pneumatic	100	–	–
corpuls cpr	Automatic	I/O	No	No	Pointed	5.52	450 × 430 × 90	Piston	Electric	80–120	20–60	–
EM-CPR	Automatic	I	–	–	Train of magnetic stimulation	–	–	–	Magnetic coils	20	–	–
Heartsaver 100	Automatic	I/O	No	No	Pointed	7.25	609 × 457 × 102	Piston	Pneumatic	100	–	–
Hydraulic–pneumatic band	Automatic	I/O	No	No	Distributed	10		Piston	Pneumatic	–	–	–
Lifeline ARM	Automatic	I/O	No	No	Pointed	7.1	597 × 527 × 229	Piston	Electric	101 ± 1	53 ± 3	–
LifeStat	Automatic	I/O	No	No	Pointed	8.85	572 × 194 × 464	Piston	Pneumatic	100	80.76/−50.5	15
LUCAS	Automatic	I/O	Yes	No	Pointed	7.8	570 × 520 × 240	Piston	Electric	102	53 ± 24	20
Parallel manipulator	Automatic	I	–	–	Pointed	–	–	Motor	Electric	Up to 120	38–51	–
pGz	Automatic	I	–	–	Cyclic accel.	–	–	Motor	Electric	–	–	–
Thumper	Automatic	I/O	No	No	Pointed	8.85	572 × 194 × 464	Piston	Pneumatic	100	80.76/−50.5	15
Vest	Automatic	I	No	No	Distributed	50		Inflatable vest	Pneumatic	60	–	–
Weil Mini	Automatic	I/O	No	No	Pointed + distributed	2.5	162.6 × 139.7 × 193	Piston	Pneumatic	110 (± 22)	38–63.5	10
Weil SCC	Automatic	I/O	No	No	Concentrated + distributed	2	–	Piston	Pneumatic	–	–	–

CPR: cardiopulmonary resuscitation.

anterior–posterior chest diameter to deliver the right sternum deflection. Similarly, the AutoPulse adjusts automatically the band to the patient's chest and, measuring its circumference, calibrates the compression depth. Therefore, the depth at which the two devices compress is relative to the dimension of the patient. All the other devices compress with an absolute depth that can often be adjusted to the dimension of the chest.

An essential requirement for a successful device is the positioning time because CPR has to start as early as possible to be effective: according to the manufacturers, this time varies from a minimum of 10 s (Weil Mini) to a maximum of 30 s (AutoPulse).

The effectiveness of the automatic devices

Devices are used when they are effective. Therefore, there are two main questions to be answered about the devices for CPR. The first is: are they at least as effective as the manual CPR? Whatever the answer, the next question is: what are the factors that influence their performance? Answering to the first question is necessary to decide if such devices are useful, in general or in specific situations, while answering to the latter question is a prerequisite condition to devise solutions that increase their effectiveness, even if the performance is already satisfactory. The following sections summarize the findings of published studies that are useful to answer the two previous questions.

Is the automatic CPR effective?

Despite automatic devices deliver high-quality chest compressions, there is no consensus whether they improve the outcome of CPR. To compare AutoPulse CPR with manual CPR in out-of-hospital cardiac arrests, Hallstrom et al.[30] carried out a multicenter, randomized trial, with 554 patients in the treatment group and 517 patients in the control group. They found no difference in survival to 4 h after the emergency call, but mechanical CPR was associated with worse performance than manual CPR both in survival to hospital discharge (5.8% vs 9.9%, $p = 0.06$ after adjustment for covariates and clustering) and neurological outcomes (3.1% vs 7.5%, $p = 0.006$). The Circulation Improving Resuscitation Care (CIRC) trial in the study of Wik et al.[31] was a randomized, unblended, controlled group sequential trial, where AutoPulse CPR was administrated to 2099 patients and manual CPR to 2132 patients. Comparing mechanical CPR to manual CPR, sustained ROSC was 28.6% versus 32.3%, 24-h survival was 21.8% versus 25.0%, and hospital discharge was 9.4% versus 11.0%. The LINC trial of Rubertsson et al.[32] was a multicenter randomized clinical trial aimed to determine whether defibrillation during ongoing mechanical compressions would improve 4-h survival compared with manual CPR. A total of 1300 patients received mechanical chest compressions with LUCAS combined with defibrillation during ongoing compressions, while 1289 patients received manual CPR according to the guidelines. There was no significant difference in 4-h survival, and almost all the survivors in both groups (99% mechanical vs 94% manual) had good neurological outcomes by 6 months (8.5% mechanical vs 7.6% manual). PARAMEDIC[33,34] was another large trial. It was a pragmatic, cluster-randomized open-label trial, enrolling adults with out-of-hospital cardiac arrest as the previous trials. A total of 985 out of 1652 patients received mechanical CPR with LUCAS, while 2819 received manual CPR. The findings showed that 30-day survival was similar in the two groups: 6% LUCAS versus 7% manual.

All these studies showed that chest compression delivered by automatic devices is as effective as that delivered by high-quality manual CPR, but meta-analyses and reviews did not find sufficient evidence that mechanical devices are so beneficial to recommend their widespread use. Gates et al.[35] reviewed randomized controlled trials and cluster-randomized trials that compared mechanical CPR (LUCAS and AutoPulse) with manual CPR in out-of-hospital cardiac arrests. They included in their meta-analysis five trials which enrolled over 10,000 patients.[30–33,36] Differences between the studies may have introduced heterogeneity into the meta-analysis, but the randomization methods appeared to be adequate in all the studies. The results did not show advantages in using mechanical devices for survival, both to discharge and with good neurological outcome. The same was true for ROSC, but the effects of the two devices seemed different. Westfall et al.[37] conducted another meta-analysis, but concentrating on ROSC. They selected 12 investigations (reported in 6 journal articles[30,36,38–41] and 6 abstracts) enrolling 6538 patients. The ROSC events were 1824. Like the previous meta-analysis, they found that LUCAS and AutoPulse had different effectiveness: LUCAS had an effect similar to manual CPR, while AutoPulse had significantly greater odds of ROSC. Therefore, unlike the previous meta-analysis, they concluded that both mechanical devices had, together, higher odds of ROSC compared to manual CPR. The updated review of Brooks et al.[42] analyzed six trials with a total of 1166 patients. Despite such studies lacked clinical homogeneity and overall quality, the authors concluded that there was no evidence that mechanical CPR is more beneficial or harmful than manual CPR. Bonnes et al.[43] reached a similar conclusion after having analyzed 20 studies, 5 randomized controlled trials, and 15 studies with non-randomized design, for a total of 21,363 patients. Couper et al.[44] carried out a review and meta-analysis to ascertain the effectiveness of automated devices during in-hospital

CPR. They included nine studies in their analysis, for a total of 689 patients. The use of automated devices appeared to be useful (30-day survival, short-term survival, and physiological outcomes), but the quality of the evidence was very low.

The time factors

Given the importance of providing blood to the organs, the immediate loss of coronary perfusion pressure at each interruption, and the time needed to restore it, interruptions should be infrequent and brief.[45] Estock et al.[46] compared the time required to apply, adjust, and remove the LUCAS and the AutoPulse in a manikin scenario simulating CPR in an intensive care unit. The AutoPulse required to interrupt the massage for shorter periods of time than the LUCAS during the application and the removal of the device (application: 31.6 ± 8.44 s vs 39.1 ± 11.20 s, $p = 0.001$; removal: 6.5 ± 3.65 s vs 10.1 ± 3.97 s, $p = 0.002$), while the time required to adjust the device to the patient was substantially the same (14.3 ± 5.24 s vs 12.5 ± 3.89 s; $p = 0.162$). However, the authors noted that such interruptions were much longer than those the AHA recommends as acceptable. Ong et al.[47] carried out a phased, before–after cohort evaluation of 26 manual and 41 mechanical (AutoPulse) resuscitations. The median no-flow time (the sum of all pauses which are longer than 1.5 s) during the first 5 min was 85 s for the manual CPR and 104 s for the mechanical CPR, for a mean no-flow ratio (the no-flow time divided by the segment length) of 0.28 and 0.40, respectively. However, during the following 5 min, the median no-flow time was 85 s for the manual CPR and 52 s for the mechanical CPR, for a mean no-flow ratio of 0.34 and 0.21. The time to apply the band was 152 s on average.

The safety factors

Most of the injuries ascribed to mechanical devices are similar to those caused by manual CPR. However, because mechanical devices are usually applied after some duration of manual CPR, it is difficult to attribute specific injuries to the mechanical device when its use has been preceded by manual compressions.[48] Smekal et al.[49] carried out a prospective multicentre trial on CPR-related injuries. Autopsies were conducted on 222 victims of unsuccessful resuscitation (83 manual, 139 mechanical). In total, 75.9% of the patients in the manual group displayed at least one injury, against 91.4% of those in the mechanical group ($p = 0.002$). The incidence of sternal fractures was the same for both methods, but the mechanical CPR caused more rib fractures. In any case, no fracture was fatal. Pinto et al.[50] compared patterns of trauma associated with manual and mechanical CPR (AutoPulse) on 175 victims of unsuccessful resuscitation (87 manual, 88 mechanical). Manual CPR caused more frequent anterior rib fractures, sternal fractures, and midline chest abrasions along the sternum, whereas AutoPulse CPR caused more frequent posterior rib fractures, skin abrasions located along the anterolateral chest and shoulder, vertebral fractures, and a few cases of visceral injuries. Unlike manual-only CPR, in which the fractures are close to the point where the force is exerted, the compressive band around the torso results in fractures distributed through the entire rib cage. According to the authors, the vertebral fractures of the lower thoracic and upper lumbar spine in the AutoPulse group were likely the result of pressing the thorax on the uneven surface of the stabilizing board (a horizontal plane followed by an inclined one). Not all the injuries have to be regarded as negative side effects. Frascone et al.[21] carried out a secondary analysis of data from a randomized, prospective, multicenter, intention-to-treat clinical trial with 2738 patients enrolled during a period of almost 4 years (ACD + ITD = 1403, standard CPR = 1335). Despite the major adverse events exhibited a similar overall rate of occurrence, pulmonary edema was more frequent with ACD + ITD (11.3% vs 7.9%, $p = 0.002$). However, the survival rate of the patients with pulmonary edema in both treatment groups was higher than that of the patients without pulmonary edema. Bonnemeier et al.[51] reported the mechanical compression of the chest could fragment the thrombus in patients with pulmonary embolism that could not be treated with standard therapy.

The situational factors

Mechanical chest compression devices are not currently recommended as an alternative to manual CPR.[2] However, their use is valuable when manual CPR is difficult or impossible to perform effectively, such as during a percutaneous coronary intervention,[52–56] an extracorporeal membrane oxygenation,[57] diagnostic imaging, or organ transplantations.[58–60] Preethi et al.[61] reviewed the use of mechanical devices during transportation to and in catheterization laboratory. To support the conclusion that the unique features of mechanical devices are useful in such a context, the authors cited the works of Wagner et al.,[62,63] who reported their successful experience with LUCAS over a period spanning from 2004 to 2013.

When the base plate or the backboard of a device is partially radiolucent, CPR can be continued during diagnostic imaging.[52,55,56] AutoPulse, corpuls cpr, and LUCAS are partly radiolucent.

The use of computed tomography (CT) scanning during resuscitation has been limited by the physical constraints placed on manual CPR by the scan tunnel. Wirth et al.[64] demonstrated the feasibility of CT imaging during mechanical CPR with AutoPulse and LUCAS. Besides, mechanical devices are useful for maintaining effective circulation after confirmation of cardiac death, allowing organ donation.

Transportation of patients in CPR in and out the hospital is a frequent contingency. Ventzke et al.[65] compared the performance of Animax, LUCAS 2, AutoPulse, and manual CPR during the transportation of a manikin from the fifth floor to the basement of the same hospital. Unfortunately, they did not give information about the training of the staff involved in the trial. However, chest compressions were interrupted to set up the device for 10.7 s with Animax, 15.3 s with LUCAS 2, and 23.5 s with AutoPulse. The mechanical devices reduced the transport time from 144.5 s required with the manual compressions, to 126.8 s of Animax, 111.1 s of LUCAS 2, and 98.5 s of AutoPulse ($p < 0.05$). During the transfer to the laboratory gurney, the massage had to be interrupted for 3.3 s with the manual compressions, 10.3 s with Animax, 0.8 s with LUCAS 2, while AutoPulse required no interruption at all. Gyory et al.[66] carried out a similar study, with similar results, although the focus was on the prehospital phase of the intervention. They simulated the transportation of a patient from the second floor of a building to the hospital, providing manual or mechanical CPR all the time. The mechanical device (LUCAS) provided a lower hands-off time (15% vs 20%, $p < 0.005$) and a higher percentage of adequate compressions (rate: 71% vs 40%, $p < 0.002$; depth: 52% vs 36%, $p < 0.007$).

When the cause of an out-of-hospital cardiac arrest has to be treated in hospital, as a cardiac arrest secondary to hypothermia or a refractory ventricular fibrillation to deal with a percutaneous coronary intervention,[54,67] CPR has to be administrated during transportation. However, unrestrained rescuers may not only sustain injuries when the vehicle is moving[68] but also suffer back strain injuries as a consequence of performing their task in cramped conditions.[69,70] In addition, it is difficult to perform effective chest compressions when the ambulance is in motion.[71,72] In this situation, automatic devices allow uninterrupted CPR. Forti et al.[73] reported the case of a patient transferred to a catheterization laboratory facility by helicopter. According to the authors, the patient would have been declared dead at the scene if an automatic device had not been available, because not only would standard CPR in the helicopter have been impossible to perform effectively, but also the transportation to the catheterization laboratory by ambulance would have needed another 30 min.

Omori et al.[74] carried out a retrospective study on the effectiveness of AutoPulse CPR in flying helicopters. A total of 92 patients were enrolled. They found that ROSC and survival to hospital discharge were significantly more frequent in the AutoPulse group than in the manual group (ROSC: 30.6% vs 7.0%; survival to hospital discharge: 6.1% vs 2.3%). Putzer et al.[75] carried out a similar study. In total, 25 life support–certified paramedics were enrolled for a prospective, randomized, crossover manikin study. The flight was 8-min long, the average transport time in the Eastern European Alps. Mechanical compressions were more frequently correct than manual compressions (99% vs 59%, $p < 0.001$), caused a shorter hands-off time (46 s vs 130 s, $p < 0.001$), but a longer time until first defibrillation (112 s vs 49 s, $p < 0.001$). Gässler et al.[76] obtained similar results in a simulation study which compared the quality of manual CPR to the quality of CPR delivered by three mechanical devices, two automated (LUCAS and AutoPulse), and one manual (Animax mono). In particular, they considered that the automated devices should be especially useful during the rescue of casualties in military operations, because helicopters operate in hostile areas where the threat posed to them makes impossible to treat the patient during the flight.

The economic factors

About the economic implications, Marti et al.[77] enrolled 4471 patients to assess if the automated devices are cost-effective when used in out-of-hospital CPR. In their analysis, they took into account the cost of the intervention and the cost of the services delivered during and after hospitalization. According to the data collected within the trial and those extrapolated over a lifetime horizon, the worse neurological outcomes and lower survival provided by the automated devices (LUCAS 2) imply a poorer health quality, and higher social and healthcare costs. Gates et al.[34] came to the same conclusion.

Discussion

Once the factors that influence the effectiveness of the devices have been assessed, the next step is to devise solutions that could enhance their effect when it is positive or mitigate it when it is negative, in order to improve the performance. Therefore, the aim of the discussion is to highlight a number of features that, in the authors' opinion, should be considered in the design of a successful.

Mechanical devices for CPR have to fulfill many requirements, but four of them are so important that it should be spared no effort to further improve them:

- Effectiveness;
- Fast positioning;
- Versatility;
- Reliability.

Effectiveness

A higher effectiveness means not only a higher percentage of ROSC and survival with a good neurological outcome, but also no injuries to the rib cage and the abdomen. Therefore, the massage has to be precise, continuous, and safe.

More accurate and sophisticated measuring systems and controllers might improve hemodynamics and safety during automated CPR. For example, Betz et al.[78] studied the effects on hemodynamics of a high-impulse mechanical massage (Thumper). A rapid down-stroke produces a high-impulse waveform that should speed the valve closure up and rise the arterial pressure, therefore maximizing the flow. In a porcine model of prolonged ventricular fibrillation, they compared the coronary perfusion pressure achieved by this method to those achieved by manual compression and standard mechanical compression. They found a greater increase (which was correlated with a higher rate of ROSC) during high-impulse compression (10/10 with high-impulse mechanical, 6/9 with standard mechanical, 4/9 with manual), suggesting that this method might be useful. Sundermann et al.[79] tested the feasibility to use biosignals to adapt automatically the rate and depth of mechanical compression until the biosignals satisfy a threshold or the two variables reach their maximum value. The mean arterial pressure and the quantitative electrocardiogram (qECG) metric median slope of the ventricular fibrillation waveform were used as biosignals in a swine experiment that confirmed the feasibility of the approach. Zhang et al.[80] developed a closed-loop controller that provides a trade-off between the benefit of improved blood perfusion and the risk of ribs fracture. Such trade-off was evaluated by comparing the closed-loop controlled massage to the standard massage. Although the study is based on simulations performed on a human circulation hardware model, nevertheless it demonstrates that the effect of chest compressions can be controlled to some extent.

Fast positioning

The fast positioning is relative to the time needed to assemble the device and to start the massage. This time has to be as short as possible because the chances of survival drop exponentially with any delay.[81,82] Furthermore, it is advisable that the devices, especially those for out-of-hospital CPR, should require no or little attendance during the massage, to free the rescuers to perform complementary tasks. However, how a device is deployed is just as important[83] and depends on factors that are not only technical but also organizational. According to Ong et al.,[47] the no-flow time in the initial 5 min is usually due to the time needed to apply the device, poor co-ordination, and hands-off time. In the following 5 min, it is usually due to other interruptions, such as pulse check, intubation, analysis of cardiac rhythm, and defibrillation. Therefore, they maintained that, to improve the quality of mechanical CPR, the crew has to be trained in a coordinated protocol, like a "pit-crew" protocol, where each member is drilled in a specific role at a specific place. Moreover, they found that despite rigorous training, the actual application of a device is amply variable because habits and mindsets probably are difficult to change. Spiro et al.[84] assessed the efficiency of using mechanical devices in a cardiac arrest scenario. After a prior training from an industry representative, 40 participants (cardiologists, cardiology nurses, auxiliary healthcare workers) were led individually, without warning, to a training room and instructed to position a device on a mannequin, start compressions, and then switch from 30:2 to continuous mode. At baseline, the positioning time was high (mean 59 ± 24 s), with 57% of the participants being unable to switch mode. After re-training, the positioning time reduced significantly (28 ± 9 s, $p < 0.01$ vs baseline), with 95% of the participants being able to switch mode. After the trial, the authors have opted to follow not only a program of re-education using mannequin-based training but also the "pit-crew" protocol. In addition, they noted that there is a learning curve to negotiate, and the performance of a resuscitation team improves over time.

Versatility

The third fundamental requirement is versatility, which means the device could be adapted not only to any chest size but to also its stiffness, the etiology of cardiac arrest, and the response to drug treatment as well.[85] Therefore, to enhance the probability of a successful outcome, the automatic devices should be able to discriminate how the thorax responds to the massage. In addition, versatility may concern the ability to adjust the massage to the Electrocardiogram (ECG) reading, which monitors the hemodynamic parameters.

Reliability

Good clinical outcomes depend largely on the reliability of the device, because the use of automated devices might be impaired not only by the inexperience of the staff, but also by battery failure, device failure, and limited battery life.[86] Automatic devices can occasionally fail even if they are proved to be effective and reliable and are used by experienced crews.[84]

Advantages and limits of CPR devices

In order to improve existing devices or to develop new ones, it is necessary to evaluate advantages and disadvantages of each solution.

The manual devices are usually equipped with sensors and appliances to assist rescuers during the massage, such as a metronome to give the rhythm of compression, an accelerometer to measure the compression depth, or a load cell to measure the force applied to the chest. It is important to note that accelerometers used as sternum-displacement transducers overestimate the compression depth when the patient is on a soft surface. However, manual devices have negligible contribution on the main issue of manual CPR, that is, the rescuers fatigue. In this regard, the CardioPump worsens the problem because, as a result of the active decompression, rescuers get tired sooner for having to act twice, applying a pushing force in compression and a pulling force in decompression. Therefore, an improved effect on the hemodynamics may compromise the overall effectiveness of the CPR if rescuers do not alternate frequently enough.

ACD-CPR devices increase the hemodynamics with an effect similar to the natural pumping of the heart,[87] but they cause a higher percentage of chest injuries.[88] Distributed force devices should theoretically reduce ribs fractures and other injuries because they apply a lower pressure to the thorax, but there is no clinical evidence to confirm this beneficial effect. Furthermore, they should be easier to be applied because a concentrated force has to push at the right point on the sternum, whereas a distributed force compresses a wider area of the thorax.[89,90] The pGz and the EM-CPR are innovative solutions that generate a blood flow by mechanical oscillations or by electrical stimulation of the abdominal circulatory pump. Therefore, they obviate many drawbacks of conventional CPR: no chest or abdominal injuries due to mechanical manipulation, suitability to be used on patients with chest operations, and no limitations based on the chest dimension.[17–20]

Although a manual massage is prone to repeatability errors because the rescuer's performance decreases over time, an automated massage is affected by systematic errors when the device is wrongly positioned (point and direction of compression). Furthermore, an incorrect placement might not only impair the effectiveness of CPR but also increase the risk of injury. Automatic devices compress by means of an actuator, either electrical or pneumatic. When reliability is concerned, an electric actuator has a motion more regular and responsive to commands, whereas a pneumatic actuator has inertia and friction forces that dampen the motion and may lead to a jerky rhythm of compression. However, the damped push of a pneumatic actuator is beneficial as well because it decreases the stress in the rib cage at the beginning of each compression, unlike the stiffer electrical actuator. This difference is confirmed by two studies. Comparing the frequency of ribs and sternum injuries, Smekal et al.[91] observed no difference between manual CPR and CPR delivered with the (older) gas-driven version of LUCAS, while Lardi et al.[92] found higher injuries with the electric-driven version of the same device.

Weight is an issue whose significance differs depending on whether the device is for in-hospital or out-of-hospital CPR. In-hospital devices have fewer limitations about size and weight than out-of-hospital devices; therefore, they can be equipped with more accessories and instruments and can also be based on working principles that require more powerful sources of energy, as the EM-CPR and the pGz. Besides, a continuous source of power ensures that the CPR can last for a time much longer than the 30–45 min usually allowed by portable batteries or gas tanks. In addition, an in-hospital device could be equipped with ECG sensor, which could be useful both to analyze the cardiac arrest parameters of the patient before starting the massage, in order to determine the best therapeutic solution, and to control vital parameters during the resuscitation itself. Another useful feature in automated resuscitation could be the ability to ascertain the stiffness of the chest. Such a measure could be useful for adapting the massage to the mechanical characteristics of the rib cage. It should be done by strain sensors applied to the thorax, thus enabling the device to calibrate the force of compression during the first compressions, and then to perceive warped or broken ribs, and inform the rescuers with a light or a ring tone.

The critical characteristics are summarized in Table 3 with the purpose of quantifying, albeit tentatively, the optimal device properties for future developments.

Conclusion

This article has presented a review of the CPR devices. The main conclusions could be the following:

- Manual devices are usually equipped with sensors and appliances to assist rescuers during the massage, such as metronomes, accelerometers, and load cells.
- Most of the automatic devices mimic the dynamics of the manual massage, while the Autopulse compresses a wider area of the chest. Weil Mini and Weil SCC are hybrid devices because a torso restraint squeezes the thorax, while a piston compresses the sternum. EM-

Table 3. Out-of-hospital cardiac arrest device performances.

CPR critical characteristic	Expected value direction
Dimensions	Less than 350 × 200 × 200 mm
Weight	Less than 3.00 kg
Setup procedure	Less than 20 s
Safety	In accordance to European regulations
Durability	20 years, without intervention
Chest compression depth	0.5 mm
Chest compression rate accuracy	0.1 compression per minute
Manual massage allowed during deployment	Yes
Massage types	Thoracic, abdominal, and thoracic and abdominal
Exerted force	Compression, decompression, and compression and decompression
Defibrillation without stopping massage	Yes
Sensors	Depth, rate, compression waveform
Ventilation	Yes
Signals	Acoustic, visual

CPR and pGz perform CPR exploiting working principles that do not require the direct, mechanical manipulation of the patient.

- Automatic devices deliver compressions with a more consistent rate and depth than manual compressions. Nevertheless, the AHA does not recommend the routine use of automatic devices because there is no evidence that they have a better outcome than manual massage.[93]
- Despite a better performance during the massage, the overall performance of automatic devices depends not only on technical factors but also on procedural and organizational factors.
- Automatic devices have to be applied to the patient, and this requires time, especially when the staff is not familiar with the device and not properly trained. There is a learning curve to negotiate, and the performance of a resuscitation team usually improves over time with practice and regular training.
- It is reasonable to assume that advances in technology and a better understanding of the hemodynamic and physiological response to chest compression will improve the effectiveness of automatic devices for CPR. Besides, more accurate and sophisticated measuring systems and controllers could adapt the massage to patients, for example, to the stiffness of their rib cage or his clinical condition, improving safety during automatic CPR.

Finally, the review of literature emphasized several scientific directions for CPR automatic devices that require further developments.

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References

1. Neumar RW, Otto CW, Link MS, et al. Part 8: adult advanced cardiovascular life support: 2010 American heart association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. *Circulation* 2010; 122: S729–167.
2. Kleinman ME, Brennan EE, Goldberger ZD, et al. Part 5: adult basic life support and cardiopulmonary resuscitation quality: 2015 American heart association guidelines update for cardiopulmonary resuscitation and emergency cardiovascular care. *Circulation* 2015; 132: S414–135.
3. Yu T, Weil MH, Tang W, et al. Adverse outcomes of interrupted precordial compression during automated defibrillation. *Circulation* 2002; 106: 368–372.
4. Hightower D, Thomas SH, Stone CK, et al. Decay in quality of closed-chest compressions over time. *Ann Emerg Med* 1995; 26: 300–303.
5. International Liaison Committee on Resuscitation. 2005 international consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations. Part 2: adult basic life support. *Resuscitation* 2005; 67: 187–201.
6. Abella BS, Sandbo N, Vassilatos P, et al. Chest compression rates during cardiopulmonary resuscitation are suboptimal: a prospective study during in-hospital cardiac arrest. *Circulation* 2005; 111: 428–434.
7. Ashton A, McCluskey A, Gwinnutt CL, et al. Effect of rescuer fatigue on performance of continuous external chest compressions over 3 min. *Resuscitation* 2002; 55: 151–155.
8. Ochoa FJ, Ramalle-Gómara E, Lisa V, et al. The effect of rescuer fatigue on the quality of chest compressions. *Resuscitation* 1998; 37: 149–152.

9. McDonald CH, Heggie J, Jones CM, et al. Rescuer fatigue under the 2010 ERC guidelines, and its effect on cardiopulmonary resuscitation (CPR) performance. *Emerg Med J* 2013; 30: 623–627.
10. Leary M and Abella BS. The challenge of CPR quality: improvement in the real world. *Resuscitation* 2008; 77: 1–3.
11. Eftestol T, Sunde K and Steen PA. Effects of interrupting precordial compressions on the calculated probability of defibrillation success during out-of-hospital cardiac arrest. *Circulation* 2002; 105: 2270–2273.
12. Libungan B, Dworeck C and Omerovic E. Successful percutaneous coronary intervention during cardiac arrest with use of an automated chest compression device: a case report. *Ther Clin Risk Manag* 2014; 10: 255–257.
13. Aliverti A, Bovio D, Fullin I, et al. The abdominal circulatory pump. *PLoS ONE* 2009; 4: e5550.
14. Aliverti A, Uva B, Laviola M, et al. Concomitant ventilatory and circulatory functions of the diaphragm and abdominal muscles. *J Appl Physiol* 2010; 109: 1432–1440.
15. Aliverti A, Macklem PT, Pedotti A, et al. *Abdominal circulatory pump device*. US20120016280-A1 Patent, 2012.
16. Yedukondalu G, Srinath A and Suresh Kumar J. Mechanical chest compression with a medical parallel manipulator for cardiopulmonary resuscitation. *Int J Med Robot Comp* 2014; 11: 448–457.
17. Adams JA, Wu DM, Bassuk J, et al. Cardiopulmonary resuscitation (CPR) using periodic acceleration (pGz) in an older porcine model of ventricular fibrillation. *Resuscitation* 2004; 60: 327–334.
18. Nava G, Adams JA, Bassuk J, et al. Echocardiographic comparison of cardiopulmonary resuscitation (CPR) using periodic acceleration (pGz) versus chest compression. *Resuscitation* 2005; 66: 91–97.
19. Adams JA, Uryash A, Wu H, et al. Microcirculatory and therapeutic effects of whole body periodic acceleration (pGz) applied after cardiac arrest in pigs. *Resuscitation* 2011; 82: 767–775.
20. Wu D, Bassuk J, Arias J, et al. Post-resuscitation reperfusion injury: comparison of periodic Gz acceleration versus Thumper CPR. *Resuscitation* 2006; 70: 454–462.
21. Frascone RJ, Wayne MA, Swor RA, et al. Treatment of non-traumatic out-of-hospital cardiac arrest with active compression decompression cardiopulmonary resuscitation plus an impedance threshold device. *Resuscitation* 2013; 84: 1214–1222.
22. Aufderheide TP, Frascone RJ, Wayne MA, et al. Standard cardiopulmonary resuscitation versus active compression-decompression cardiopulmonary resuscitation with augmentation of negative intrathoracic pressure for out-of-hospital cardiac arrest: a randomised trial. *Lancet* 2011; 377: 301–311.
23. Günaydın YK, Çekmen B, Akıllı NB, et al. Comparative effectiveness of standard CPR vs active compression-decompression CPR with CardioPump for treatment of cardiac arrest. *Am J Emerg Med* 2016; 34: 542–547.
24. Babbs CF. CPR techniques that combine chest and abdominal compression and decompression: hemodynamic insights from a spreadsheet model. *Circulation* 1999; 100: 2146–2152.
25. Havel C, Berzlanovich A, Sterz F, et al. Safety, feasibility, and hemodynamic and blood flow effects of active compression-decompression of thorax and abdomen in patients with cardiac arrest. *Crit Care Med* 2008; 36: 1832–1837.
26. Jung E, Lenhart S, Protopopescu V, et al. Optimal control applied to a thoraco-abdominal CPR model. *Math Med Biol* 2008; 25: 157–170.
27. Halperin H, Berger R, Chandra N, et al. Cardiopulmonary resuscitation with a hydraulic-pneumatic band. *Crit Care Med* 2000; 28: N203–N206.
28. Halperin HR, Tsitlik JE, Gelfand M, et al. A preliminary study of cardiopulmonary resuscitation by circumferential compression of the chest with use of a pneumatic vest. *N Engl J Med* 1993; 329: 762–768.
29. Babbs CF. Biophysics of cardiopulmonary resuscitation with periodic z-axis acceleration or abdominal compression at aortic resonant frequencies. *Resuscitation* 2006; 69: 455–469.
30. Hallstrom A, Sayre MR, Christenson J, et al. Manual chest compression vs use of an automated chest compression device during resuscitation following out-of-hospital cardiac arrest: a randomized trial. *JAMA* 2006; 295: 2620–2628.
31. Wik L, Olsen JA, Persse D, et al. Manual vs. integrated automatic load-distributing band CPR with equal survival after out of hospital cardiac arrest. The randomized CIRC trial. *Resuscitation* 2014; 85: 741–748.
32. Rubertsson S, Lindgren E, Smekal D, et al. Mechanical chest compressions and simultaneous defibrillation vs conventional cardiopulmonary resuscitation in out-of-hospital cardiac arrest: the LINC randomized trial. *JAMA* 2014; 311: 53–61.
33. Perkins GD, Lall R, Quinn T, et al. Mechanical versus manual chest compression for out-of-hospital cardiac arrest (PARAMEDIC): a pragmatic, cluster randomised controlled trial. *Lancet* 2015; 385: 947–955.
34. Gates S, Lall R, Quinn T, et al. Prehospital randomised assessment of a mechanical compression device in out-of-hospital cardiac arrest (PARAMEDIC): a pragmatic, cluster randomised trial and economic evaluation. *Health Technol Assess* 2017; 21: 1–176.
35. Gates S, Quinn T, Deakin CD, et al. Mechanical chest compression for out of hospital cardiac arrest: systematic review and meta-analysis. *Resuscitation* 2015; 94: 91–97.
36. Smekal D, Johansson J, Huzevka T, et al. A pilot study of mechanical chest compressions with the LUCAS^{TM} device in cardiopulmonary resuscitation. *Resuscitation* 2011; 82: 702–706.
37. Westfall M, Krantz S, Mullin C, et al. Mechanical versus manual chest compressions in out-of-hospital cardiac arrest: a meta-analysis. *Crit Care Med* 2013; 41: 1782–1789.
38. Axelsson C, Nestin J, Svensson L, et al. Clinical consequences of the introduction of mechanical chest compression in the EMS system for treatment of out-of-hospital cardiac arrest-a pilot study. *Resuscitation* 2006; 71: 47–55.
39. Casner M, Andersen D and Isaacs SM. The impact of a new CPR assist device on rate of return of spontaneous circulation in out-of-hospital cardiac arrest. *Prehosp Emerg Care* 2005; 9: 61–67.

40. Ong MEH, Ornato JP, Edwards DP, et al. Use of an automated, load-distributing band chest compression device for out-of-hospital cardiac arrest resuscitation. *JAMA* 2006; 295: 2629–2637.
41. Steinmetz J, Barnung S, Nielsen SL, et al. Improved survival after an out-of-hospital cardiac arrest using new guidelines. *Acta Anaesthesiol Scand* 2008; 52: 908–913.
42. Brooks SC, Hassan N, Bigham BL, et al. Mechanical versus manual chest compressions for cardiac arrest. *Cochrane Database Syst Rev* 2014; 2: CD007260.
43. Bonnes JL, Brouwer MA, Navarese EP, et al. Manual cardiopulmonary resuscitation versus CPR including a mechanical chest compression device in out-of-hospital cardiac arrest: a comprehensive meta-analysis from randomized and observational studies. *Ann Emerg Med* 2016; 67: 349–360.
44. Couper K, Yeung J, Nicholson T, et al. Mechanical chest compression devices at in-hospital cardiac arrest: a systematic review and meta-analysis. *Resuscitation* 2016; 103: 24–31.
45. Steen S, Liao QM, Pierre L, et al. The critical importance of minimal delay between chest compressions and subsequent defibrillation: a haemodynamic explanation. *Resuscitation* 2003; 58: 249–258.
46. Estock JL, Curinga HK and Li A. Comparison of chest compression interruption times across 2 automated devices: a randomized, crossover simulation study. *Am J Emerg Med* 2016; 34: 57–62.
47. Ong MEH, Annathurai A, Shahidah A, et al. Cardiopulmonary resuscitation interruptions with use of a load-distributing band device during emergency department cardiac arrest. *Ann Emerg Med* 2010; 56: 233–241.
48. Guyette FX, Reynolds JC and Frisch A. Cardiac arrest resuscitation. *Emerg Med Clin North Am* 2015; 33: 669–690.
49. Smekal D, Lindgren E, Sandler H, et al. CPR-related injuries after manual or mechanical chest compressions with the LUCAS^{TM} device: a multicentre study of victims after unsuccessful resuscitation. *Resuscitation* 2014; 85: 1708–1712.
50. Pinto DC, Haden-Pinneri K and Love JC. Manual and automated cardiopulmonary resuscitation (CPR): a comparison of associated injury patterns. *J Forensic Sci* 2013; 58: 904–909.
51. Bonnemeier H, Simonis G, Olivecrona G, et al. Continuous mechanical chest compression during in-hospital cardiopulmonary resuscitation of patients with pulseless electrical activity. *Resuscitation* 2011; 82: 155–159.
52. Protasiewicz M, Szymkiewicz P, Sciborski K, et al. Cardiac arrest during percutaneous coronary intervention in a patient "resistant" to clopidogrel—successful 50-minute mechanical chest compression. *Postepy Kardiol Interwencyjnej* 2013; 9: 394–396.
53. Larsen AI, Hjornevik AS, Ellingsen CL, et al. 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.
54. Zimmermann S, Rohde D, Marwan M, et al. Complete recovery after out-of-hospital cardiac arrest with prolonged (59 min) mechanical cardiopulmonary resuscitation, mild therapeutic hypothermia and complex percutaneous coronary intervention for ST-elevation myocardial infarction. *Heart Lung* 2014; 43: 62–65.
55. Zhang ZP, Su X, Liu CW, et al. Continuous mechanical chest compression-assisted percutaneous coronary intervention in a patient with cardiac arrest complicating acute myocardial infarction. *Chin Med J* 2015; 128: 846–848.
56. Agostoni P, Cornelis K and 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: 19–21.
57. Stub D, Bernard S, Pellegrino V, et al. Refractory cardiac arrest treated with mechanical CPR, hypothermia, ECMO and early reperfusion (the CHEER trial). *Resuscitation* 2015; 86: 88–94.
58. Morozumi J, Matsuno N, Sakurai E, et al. Application of an automated cardiopulmonary resuscitation device for kidney transplantation from uncontrolled donation after cardiac death donors in the emergency department. *Clin Transplant* 2010; 24: 620–625.
59. Fondevila C, Hessheimer AJ, Ruiz A, et al. Liver transplant using donors after unexpected cardiac death: novel preservation protocol and acceptance criteria. *Am J Transplant* 2007; 7: 1849–1855.
60. Morozumi J, Sakurai E, Matsuno N, et al. Successful kidney transplantation from donation after cardiac death using a load-distributing-band chest compression device during long warm ischemic time. *Resuscitation* 2009; 80: 278–280.
61. Preethi W, Rao P, Kanakadandi UB, et al. Mechanical cardiopulmonary resuscitation in and on the way to the cardiac catheterization laboratory. *Circ J* 2016; 80: 1292–1299.
62. Wagner H, Terkelsen CJ, Friberg H, et al. Cardiac arrest in the catheterisation laboratory: a 5-year experience of using mechanical chest compressions to facilitate PCI during prolonged resuscitation efforts. *Resuscitation* 2010; 81: 383–387.
63. Wagner H, Hardig BM, Rundgren M, et al. Mechanical chest compressions in the coronary catheterization laboratory to facilitate coronary intervention and survival in patients requiring prolonged resuscitation efforts. *Scand J Trauma Resusc Emerg Med* 2016; 24: 4.
64. Wirth S, Korner M, Treitl M, et al. Computed tomography during cardiopulmonary resuscitation using automated chest compression devices—an initial study. *Eur Radiol* 2009; 19: 1857–1866.
65. Ventzke MM, Gassler H, Lampl L, et al. Cardio pump reloaded: in-hospital resuscitation during transport. *Intern Emerg Med* 2013; 8: 621–626.
66. Gyory RA, Buchle SE, Rodgers D, et al. The efficacy of LUCAS in prehospital cardiac arrest scenarios: a crossover mannequin study. *West J Emerg Med* 2017; 18: 437–445.
67. Friberg H and Rundgren M. Submersion, accidental hypothermia and cardiac arrest, mechanical chest compressions as a bridge to final treatment: a case report. *Scand J Trauma Resusc Emerg Med* 2009; 17: 7.
68. Halperin H and Carver DJ. Mechanical CPR devices. *Signa Vitae* 2010; 5: 69–73.

69. Jones AY. Can cardiopulmonary resuscitation injure the back? *Resuscitation* 2004; 61: 63–67.
70. Tsou JY, Chi CH, Hsu RMF, et al. Mechanical loading of the low back during cardiopulmonary resuscitation. *Resuscitation* 2009; 80: 1181–1186.
71. Fox J, Fiechter R, Gerstl P, et al. Mechanical versus manual chest compression CPR under ground ambulance transport conditions. *Acute Card Care* 2013; 15: 1–6.
72. Olasveengen TM, Wik L and Steen PA. Quality of cardiopulmonary resuscitation before and during transport in out-of-hospital cardiac arrest. *Resuscitation* 2008; 76: 185–190.
73. Forti A, Zilio G, Zanatta P, et al. Full recovery after prolonged cardiac arrest and resuscitation with mechanical chest compression device during helicopter transportation and percutaneous coronary intervention. *J Emerg Med* 2014; 47: 632–634.
74. Omori K, Sato S, Sumi Y, et al. The analysis of efficacy for AutoPulse™ system in flying helicopter. *Resuscitation* 2013; 84: 1045–1050.
75. Putzer G, Braun P, Zimmermann A, et al. LUCAS compared to manual cardiopulmonary resuscitation is more effective during helicopter rescue-a prospective, randomized, cross-over manikin study. *Am J Emerg Med* 2013; 31: 384–389.
76. Gässler H, Kümmerle S, Ventzke M-M, et al. Mechanical chest compression: an alternative in helicopter emergency medical services? *Intern Emerg Med* 2015; 10: 715–720.
77. Marti J, Hulme C, Ferreira Z, et al. The cost-effectiveness of a mechanical compression device in out-of-hospital cardiac arrest. *Resuscitation* 2017; 117: 1–7.
78. Betz AE, Menegazzi JJ, Logue ES, et al. A randomized comparison of manual, mechanical and high-impulse chest compression in a porcine model of prolonged ventricular fibrillation. *Resuscitation* 2006; 69: 495–501.
79. Sundermann ML, Salcido DD, Koller AC, et al. Feasibility of biosignal-guided chest compression during cardiopulmonary resuscitation: a proof of concept. *Acad Emerg Med* 2016; 23: 93–97.
80. Zhang G, Wu TH, Song ZX, et al. A mechanical chest compressor closed-loop controller with an effective tradeoff between blood flow improvement and ribs fracture reduction. *Med Biol Eng Comput* 2015; 53: 487–497.
81. Truong HT, Low LS and Kern KB. Current approaches to cardiopulmonary resuscitation. *Curr Probl Cardiol* 2015; 40: 275–313.
82. Lin CK, Huang MC, Feng YT, et al. Effectiveness of mechanical chest compression for out-of-hospital cardiac arrest patients in an emergency department. *J Chin Med Assoc* 2015; 78: 360–363.
83. Ong ME, Quah JLJ, Annathurai A, et al. Improving the quality of cardiopulmonary resuscitation by training dedicated cardiac arrest teams incorporating a mechanical load-distributing device at the emergency department. *Resuscitation* 2013; 84: 508–514.
84. Spiro JR, White S, Quinn N, et al. Automated cardiopulmonary resuscitation using a load-distributing band external cardiac support device for in-hospital cardiac arrest: a single centre experience of AutoPulse-CPR. *Int J Cardiol* 2015; 180: 7–14.
85. Nysaether JB, Dorph E, Rafoss I, et al. Manikins with human-like chest properties—a new tool for chest compression research. *IEEE Trans Biomed Eng* 2008; 55: 2643–2650.
86. Ong MEH, Fook-Chong S, Annathurai A, et al. Improved neurologically intact survival with the use of an automated, load-distributing band chest compression device for cardiac arrest presenting to the emergency department. *Crit Care* 2012; 16: R144.
87. Wenzel V, Fuerst RS, Idris AH, et al. Automatic mechanical device to standardize active compression-decompression CPR. *Ann Emerg Med* 1995; 25: 386–389.
88. Wolcke BB, Mauer DK, Schoefmann MF, et al. Comparison of standard cardiopulmonary resuscitation versus the combination of active compression-decompression cardiopulmonary resuscitation and an inspiratory impedance threshold device for out-of-hospital cardiac arrest. *Circulation* 2003; 108: 2201–2205.
89. Timerman S, Cardoso LF, Ramires JAF, et al. Improved hemodynamic performance with a novel chest compression device during treatment of in-hospital cardiac arrest. *Resuscitation* 2004; 61: 273–280.
90. Krep H, Mamier M, Breil M, et al. Out-of-hospital cardiopulmonary resuscitation with the AutoPulse system: a prospective observational study with a new load-distributing band chest compression device. *Resuscitation* 2007; 73: 86–95.
91. Smekal D, Johansson J, Huzevka T, et al. 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.
92. Lardi C, Egger C, Larribau R, et al. Traumatic injuries after mechanical cardiopulmonary resuscitation (LUCAS2): a forensic autopsy study. *Int J Legal Med* 2015; 129: 1035–1042.
93. Brooks SC, Anderson ML, Bruder E, et al. Part 6: alternative techniques and ancillary devices for cardiopulmonary resuscitation: 2015 American heart association guidelines update for cardiopulmonary resuscitation and emergency cardiovascular care. *Circulation* 2015; 132: S436–S443.