

Mechatronic Hardware Tools for External Chest Compression in Cardiopulmonary Resuscitation

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Abstract

Every year in Russia circa 300,000 people die of cardiac arrest. Modern effective cardiopulmonary resuscitation (CPR) facilitates preserving the blood circulation and breathing functions to the degree, required for the patient's survival in cardiac arrest. CPR includes the patient's chest compression at a specific frequency rate and the execution of the induced ventilation of lungs. The review considers the unassisted (manual) CPR methods; the existing devices for CPR are discussed, their advantages and disadvantages are described; the necessity to develop new complex smart mechatronic devices for external chest compression, drastically different from the existing systems, is justified.

Keywords: Adaptive, Anatomic, Cardiac Compressor, Cardiac Massage, Cardiopulmonary Resuscitation, Mechatronic

1. Introduction

Sudden cardiac mortality accounts for 15–20% of all non-violent deaths among the population in the developed countries. Even a person in absolutely good health with no symptoms of cardiovascular disease may be a victim. Up to now there is no exhaustive answer to the question about the causes of this phenomenon. Close to 75% of sudden deaths from cardiac arrest take place at home, at work, at pleasure resorts, and only 25% of cases occur in hospitals. When no first aid is rendered, nearly 91% of cardiac arrest victims die before they are delivered to a hospital¹.

Cardiopulmonary resuscitation (CPR) is a medical procedure, executed on the patients, for supporting the blood circulation and breathing functions at a definite level in cases, when blood circulation and breathing are either restricted or not functioning at all. Usually CPR includes the patient's chest compression at a specific frequency rate and executing the induced ventilation of lungs (IVL). To execute CPR to a proper quality the compression should be done in a way as follows²:

- At the required frequency rate and to the required depth of chest depression,

- With full decompression of chest upon each compression move,
- With minimum interval between the compression moves,
- With no redundant ventilation of lungs.

To conform to the required parameters of closed-chest cardiac massage (CCCM) without recurring to the control means is difficult even for an experienced reanimation doctor. According to statistics, upon executing CPR only 5% of victims survive³. This is related to ineffective manual CPR execution, as the arterial pressure could not be sufficiently increased (up to 90 mm mercury column and higher). For the purposes of improving the effectiveness of the chest external compression the reanimation doctors were recommended to replace each other every 3 minutes, which, however, did not result in improving the survival rate³. According to one of the domestic investigations, when the training CPR has been practiced on a dummy by the experienced anesthetists/resuscitation experts (those with the record of service of not less than 4 years; the group of 46 people have been analyzed) only in less than 40% of cases the closed-chest massage was done correctly⁴. Given all mentioned above, it is of

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current importance to introduce technical means to the practice of CPR execution, which would control the actions performed in CCCM and facilitate correcting the compression-decompression process in real time mode.

2. Theoretical Basis and Literature Review

2.1 Contemporary State and History of the Mechanical Means for Closed-Chest Cardiac Massage

The official source for training and performing CPR in Russia is represented by the recommendations of European Resuscitation Council (ERC), which have been approved by Ministry of Health and by National Resuscitation Council of Russia. The latest ERC recommendations on CPR performance have been adopted and published in 2010⁵.

The most important task of CPR is restoring the heart's proper normal rhythm, which is done by means of applying external defibrillators⁶⁻⁸. Undoubtedly, future development of the chest external compression devices is associated with their integration with defibrillators, based on the adaptive algorithms of interaction. As an example, the evolution of BLS+AED technology can be presented (basic CPR + automated external defibrillator). A strategic line of the new practical recommendations for this protocol is securing the earliest possible electrical defibrillation⁹, which can be achieved by distributing the publicly accessible automated external defibrillators extensively^{10,11}.

Thus, it can be maintained that the unassisted CPR methods are well developed now and are applied on a routine basis in the practice of rendering emergency aid to the patients and victims both adults and infants¹². The universal character and the accessibility of this type of medical aid is the basis for recommending its wide application everywhere, for training not only medics but also the population in the protocols of its execution¹². Nevertheless, the unassisted CPR has one considerable disadvantage, which, according to many authors, degrades the results of its application, especially at the pre-hospital stage⁷⁻⁹. This disadvantage is that a resuscitation doctor cannot perform the chest compression-decompression effectively because of fatigue (efficient chest compression activity lasts for 3 min)¹³⁻¹⁶. Quick personnel replacement, in most of cases, cannot be done. Restrictions to applying manual chest compression include the problems occurring while transporting the patient or a victim. Therefore,

creating and producing the effective chest compression technical means by the domestic medical industry is now a very important technical and humanistic task.

Up to now, to optimize CPR process, the world practice has developed and is employing mechanical cardiac compressors, the devices which replace a man in executing manual manipulations. At the same time there is a need to create both inexpensive and efficient cardiac compressor, capable of controlling in automated mode the parameters of compression, depending on the patient's physiological indicators, because the existing devices do not deploy such sensory systems, and are, as a consequence, not sufficiently effective^{17,18}.

Over the 20th century different mechanical devices for performing chest compressions have been developed, the overwhelming majority of which have not been applied in the clinical practice due to a number of reasons, and the principle ones among them were as follows: cumbersome and ineffective power supply units, as well as the inconvenient and complicated control units, which resulted in losing the precious time at performing the resuscitation activities^{19,20}. In the Standards for CPR and Urgent Cardiac Aid, published in 1974, both manual and mechanical methods of resuscitation were commented, the later one being recommended for the highly trained and experienced personnel only²¹. Nevertheless, the 90-s were marked with the newly emerged interest in using devices for cardiac massage when one layman has successfully used a plumber's plunger to resuscitate one's own farther²². Thus, the improved blood circulation and lungs ventilation at active compression – decompression have been found. Similar mechanism had acquired different comments on its effectiveness and was put in use only in 1995, when its effectiveness (as compared with manual cardiopulmonary resuscitation) was proved²³.

3. Conceptual Basis

3.1 Description of the Commercially Available Mechanical Devices for Chest Compression at Cardiopulmonary Resuscitation

As of today, the automated devices for CPR chest compression are very poorly presented at the world market. In fact, there are 2 such devices: ZOLLAutoPulse (ZOLL Medical Corporation, USA) and LUCAS (Jolife AB/Physio-Control Lund, Sweden). Notwithstanding

different constructive specific features, power/energy supply units, each of those devices helps a resuscitation doctor significantly at executing the closed-chest cardiac massage, especially, when it is performed over a long period of time.

ZOLLAutoPulse is a system for performing the mechanical cardiac massage (Figure 1). The rhythmic, sparing compression of thorax is effected by two big soft-stuffed pads, attached to one compression belt on the right and on the left side. Compression belt is fixed on a dowel, connected with the drive shaft, situated at the lower surface of the platform. The belt rolls along this shaft (with frequency of 80 per minute), thus performing the compression of the chest. The pads are fixed on the patient's body by means of sticking patches.

A set of belts for the chest compression is called Life Band. The application of this device secures the continuous compression moves improving the blood circulation of heart and brain at cardiac arrest.

The advantages of ZOLLAutoPulse system are as follows²⁴⁻⁷:

- Uninterrupted compression within a long time period or compression in mode 30:2 at CPR;

- Under any conditions a stable high quality compression is secured, user mistakes are excluded;
- Possibility to continue compression while executing other resuscitating activities or during transportation;
- There is no need to interrupt CPR to perform defibrillation;
- There is no need to interrupt CPR during catheterization on the left ventricles of heart;
- Smooth continuous CPR for the patients with highly expressed hypothermia until restoring the normal body temperature;
- Smooth continuous CPR is ensured until achieving the positive results of thrombolysis (injecting special medications for coronary artery thrombus resorption);
- Smooth continuous CPR is ensured for intoxicated patients until detoxication is achieved;
- As compared to manual CRP, better blood flux to brain and heart is achieved.

Coronary perfusion pressure improves by 33% at implementing ZOLLAutoPulse due to optimized pressure distribution technology²⁵. A set of Life Band belts ensures smooth, rhythmical and highly effective compression, distributing pressure on the patient's thorax. Besides, during pauses at the moment of decompression the coronary perfusion gets to maximum²¹.

At the same time, ZOLL AutoPulse system has its drawbacks as well. In the first place, one should mention the insufficiently high frequency of the chest compression moves: 80 per minute, which does not meet the modern requirements to CPR⁵. Besides, Life Band set covers almost all the front surface of the chest of an adult man, which creates considerable predicaments for implementing the external defibrillator, while performing defibrillation within the shortest possible time is one of the basic requirements to modern CPR. Also, the practicability, effectiveness and safety of applying ZOLL AutoPulse system have not been studied in catheterization laboratories²⁸.

Chest compression system LUCAS (Figure 2.) is intended for securing uninterrupted compression of thorax with constant frequency and depth of chest depression.

Cardiac compressors LUCAS are manufactured in two options: pneumatic LUCAS and electric LUCAS 2. Initially LUCAS system has been developed which is fed by the portable air compressor. Such pneumatic compressor

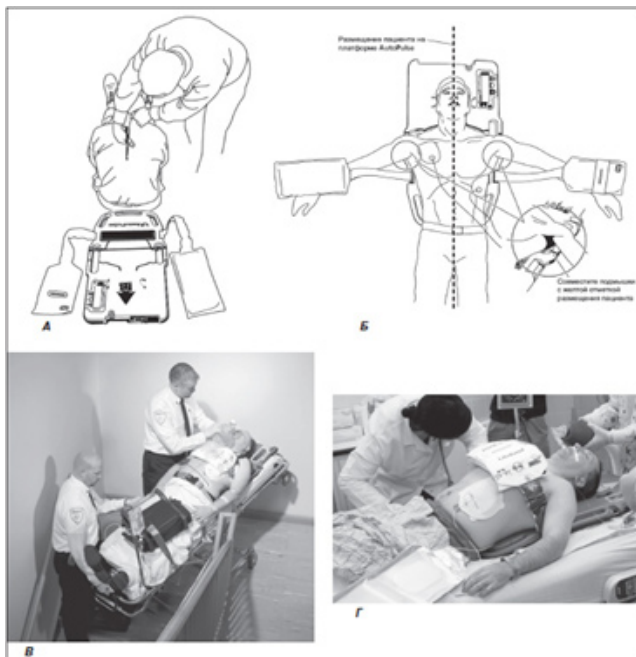


Figure 1. AutoPulse resuscitation system. A – placing the patient on the platform. B – correct position of the patient on the platform and fixing the belts. C – transferring the patient. D – possibility to perform defibrillation without interrupting the chest compression²⁴.



Figure 2. Cardiac compressor LUCAS in operational position²⁹.

is quite heavy and inconvenient in transportation. More modern cardiac compressor LUCAS 2 operates using the built-in modular accumulating battery, which can be removed from the cardiac compressor and can be charged independently.

In a number of investigations^{29,30} LUCAS system proved to be effective and safe almost to the degree of manual closed-chest cardiac massage. Constructive specific features of LUCAS system do not impede performing the life supporting activities on the patient at executing CPR: defibrillation and IVL. LUCAS system is penetrable for X-rays (except the casing and the shaft included in the system). Consequently, LUCAS system can be applied in catheterization laboratories, if there is any necessity to perform CPR during the procedures.

It is quite difficult to carry out high quality random investigations with patients who suffered from sudden heart arrest, as undertaking such studies is limited by a number of reasons of both methodological and ethical character. Nevertheless, there are some studies, proving the effectiveness and safety of the mechanical chest compression assisted by LUCAS system, as compared to the manual closed-chest cardiac massage. In a two-centre randomized pilot investigation of CPR assisted by LUCAS system, as compared to manual CPR, with the patients who suffered from out-of-hospital cardiac arrest, carried out by S. Rubertsson and the co-authors²⁹, no meaningful differences were discovered in the rate of rehabilitating the independent blood circulation (30 (43.5%) and 22 (31.9%) patients accordingly ($p = 0.22$)), among the patients who were hospitalized alive (18 (26.1%) and 15 (21.7%) patients accordingly ($p = 0.69$)), and also among

the patients, discharged from hospital alive (6 (8.7%) and 7 (10.1%) patients accordingly ($p > 0.05$)). However a trend for improving the early resuscitation rate when using LUCAS system was identified.

Y. Maule³¹ analyzed the data obtained at performing CPR with the help of LUCAS ($n = 123$) and performing manual CPR ($n = 27$) with 150 out-of-hospital cardiac arrest patients in sequence. The rate of rehabilitating spontaneous blood circulation when using LUCAS (57.7%) was more than two times better than the result of the group where manual CPR (25.9%) was performed. Moreover, LUCAS device provided the possibility to transport the patient while implementing CPR effectively and to focus the reanimation doctors' attention on other live saving problems.

LUCAS system affords continuing the procedure, securing the uninterrupted chest compression and, consequently, enabling blood circulation and the oxygen flow to the vitals. Besides, this system facilitates supporting the blood pressure, when the planned hypodermic coronary intervention and catheterization are performed at the same time. Medical personnel can perform catheterization procedures with no effect on the compression, which helps decreasing stress and facilitates the decision making. LUCAS device is transparent for X-rays (excluding the casing and the shaft), which makes it possible to execute roentgenoscopy in most of projections (left front oblique - cranial/caudal oblique, right front oblique - cranial/caudal oblique, straight caudal, straight lateral and straight cranial) with no need to remove the device. Thus, it is no longer necessary for the personnel to perform CPR within the X-rays affected area⁸.

In a number of published studies the safety of applying LUCAS system for closed-chest cardiac massage at CPR is highlighted^{1,32,33}. In the investigation, undertaken by D. Smekal³⁴ and the co-authors, the results were obtained, which enabled the conclusion that, that LUCAS system implementation is correlated with the same number and the same type of damages, as when implementing manual CPR (prospective controlled investigation with 85 patients, who did not survive the cardiac arrest). The majority of patients suffered from the pre-hospital cardiac arrest. The patients were randomized in groups: CPR assisted by LUCAS ($n = 38$) and manual CPR ($n = 47$). In the post-mortem examination no damages were found in 42.1% patients in LUCAS group and 55.3% patients in manual CPR group ($p = 0.28$). The occurrence rate and the types of damages as a result of CPR in different groups

were not significantly different, and none of the damages resulting from CPR was considered to be life threatening. Multiple rib fractures (more than three) were discovered in 17/38 (44.7%) of patients in LUCAS group and 13/47 (27.7%) patients in manual CPR group ($p = 0.12$). The breast bone fractures were found in 29.0% patients of LUCAS group and in 21.3% of patients in manual CPR group ($p = 0.46$).

Thus, LUCAS system has several advantages as compared to manual chest compression²⁶:

- The factor of a resuscitating doctor's fatigue becomes nil,
- There is a possibility to engage lesser medical personnel for CPR (while LUCAS system is in operation the personnel is busy with other aspects of CPR: installing the defibrillator, executing IVL),
- The risk of potentially traumatizing the resuscitating doctor, while performing chest compression, becomes much lower,
- When the investigations are carried out in the catheterization laboratories (simultaneously with CPR) the personnel is protected from X-ray radiation.

As a disadvantage of LUCAS system, the lack of the force-torque system can be mentioned. This is an important factor, as it is necessary to prevent rib fractures while performing CPR. Less obvious, but a considerable disadvantage of LUCAS device is a strict requirement to the high precision of the piston positioning on the chest. Just a little deviation of the piston from its correct position on the chest deteriorates CPR quality and can result in the chest traumas. The piston should be positioned along the central axis of the chest with no possible displacements either to the right or to the left³⁵.

4. Results

The submitted data and the considered technical means for performing CPR enable the conclusion that up to now the level of technical equipment, state-of-the-art developments and innovative technologies provide the basis for creating medical robot-assisted technical complexes for performing CPR. The development and the creation of such devices will help improving the effectiveness of this procedure, because the factor of the resuscitating doctor's fatigue will become nil, the quality of CPR will become better. Obviously, the existing devices require updating in terms of equipping them with different sensor systems,

which will result in more perfect operation algorithms, namely, adaptive algorithms.

5. Discussion

The key problem in manual CPR is the lack of control of the compression rate stability and the depth of depression. Is it convenient when the resuscitating doctor is assisted by an instructor at his back, evaluating the results of CPR and giving directions on how to optimize the procedure? This is impractical, but this is exactly the case when practicing on manikins. The rational way to solve this technical and humanistic issue is creating an inexpensive domestic cardiac compressor based on modern mechatronic technologies, satisfactorily meeting the dimensional, weight and energy consumption requirements with the function of manual regulation and with smart electronics elements. Smart electronics in this case means hard/software command solutions to the tasks of controlling the actuating device. The decision on performing the actions (moves) should be made by an expert system, this being a constructive part of the device. Modern electronics basis and the software make it possible to create a compact, portable device with low energy consumption. The most advanced means of information transfer, storage and processing, when realized constructively within such complex, will make CPR process smart, the knowledge base stored within the device memory will be used for expert evaluation.

6. Conclusion

Today the mechanical devices for chest compression have been developed and put in operation. They, in contrast to a human, do not get tired from continuous work and do support the parameters of the compression stable. An obstacle to their propagation is not only the lack of any statements within the modern recommendations, stipulating the obligatory use of these devices at performing the resuscitation activities, but also the high price of such items. Nevertheless, the relevance of developing the mechanical devices for optimizing CPR process acquires urgency as the time goes. A specialist, performing CPR, should have skills to evaluate both the adequacy of the patient's or of the victim's clinical status and the timeliness and adequacy of the CPR activities performed, and, at the same time, he has to do a very hard physical work. Under conditions when the number of patients or victims is high, these activities become difficult, and, sometimes,

impossible. The solution to this technical and humanistic problem is creating principally new, completely integrated hardware for CPR based on modern achievements in cybernetics and mechatronics.

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