

Original Research Paper

Development of New External Chest Compression Robotic System for Cardiopulmonary Resuscitation Using the Principles of Theranostics

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Article history

Received: 09-11-2015

Revised: 13-11-2015

Accepted: 05-03-2016

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Abstract: The article deals with theoretical approaches to the design of the experimental samples of robotic outer chest compression system for Cardiopulmonary Resuscitation (CPR) functioning in accordance with principles of theranostics. The required number of components and their characteristics has been determined and justified in order to realize the mentioned principles in the robotic system. The software to control the operation of the experimental sample of the robotic system has been developed. This article presents the first data on the development of the new external cardiac compressor working in the adaptive mode and describes electronics used in this compressor.

Keywords: Cardiopulmonary Resuscitation (CPR), External Cardiac Compressor (ECC), Robotic System, Theranostics

Introduction

Fast evolution of electronics, computer technologies, physical element base, introduction of new materials with unique properties, increase in computer power has made it possible to create a new class of medical robotic systems incorporating diagnostic and therapeutic capabilities. A new scientific field combining the processes of diagnostics and therapy has been developed which is called theranostics. This article presents an example of practical application of theranostics principles creating a new medical device with functional feedback to perform Cardiopulmonary Resuscitation (CPR)- the External Cardiac Compressor (ECC).

Theoretical Background and Literature Review

CPR is a medical procedure performed in patients for maintaining blood circulation and respiratory function at a certain level when a patient's circulatory and respiratory functions are limited or do not exist at all. According to the statistics, only 5% of patients survive after CPR which is mainly due to low efficacy of manual chest compressions not allowing to improve patient's blood pressure (up to 90 mmHg) (Plaisance *et al.*, 1999). To increase the CPR effectiveness special devices are used, such as defibrillators (increasing the effectiveness of CPR during manual chest compressions) and

automatic devices for pneumatic auxiliary compression. Intellectual mechatronic feedback ECC were developed over the past 10-15 years. The main patent holders in this area are such companies as ZOLL (USA) and PhysioControl (USA) (Ong *et al.*, 2006; Zheng *et al.*, 2001; Becker *et al.*, 1993; Eisenberg *et al.*, 1990; Ornato *et al.*, 2003; Rubertsson *et al.*, 2007).

Clinical experience of application of existing cardiac compressors has revealed the need for improving their functional characteristics (Rubertsson *et al.*, 2014; Steen *et al.*, 2003; Sato *et al.*, 1997; Paradis *et al.*, 1990; Eftestøl *et al.*, 2002; Rubertsson *et al.*, 1995; Smekal *et al.*, 2009; Wagner *et al.*, 2010; Webb *et al.*, 2002; Noc *et al.*, 2007; Steen *et al.*, 2002; Rubertsson and Karlsten, 2005), particularly with regard to the adaptive parameters changings depending on the value of the blood pressure, which is an integral index of the degree of blood circulation in patient during CPR (Malzer *et al.*, 1996; Rich *et al.*, 1981; Smith *et al.*, 1990).

New mechatronic automated ECC has been developed and successfully tested in the Russian State Scientific Center for Robotics and Technical Cybernetics (Saint-Petersburg, Russia). This ECC has a feedback from the force applied to the chest and the striker position (which is in direct contact with the

patient's chest). There are also algorithmically supposed feedbacks from blood pressure sensors with following changes in compression parameters, which enables automatic diagnostics of cardiovascular system functioning and the adjustment of ECC functional modes, i.e., allows applying principles of theranostics in practice.

Methods and Tools

Software for the Automated External Cardiac Compressor

The software for ECC is designed to ensure that the component parts of the device are operating according to the preset algorithm.

The ECC includes:

- Electric drive with transmission, which converts the rotary motion of the motor into linear motion of the loading platform of the cardiac compressor
- Set of sensors to monitor the patient's condition, compression process and to operate the ECC (invasive pressure sensor, noninvasive pressure sensor, sensor of the force applied to the chest, sensor of the value of compression);

- Microcontroller control system with a set of interfaces, including one for additional sensors and systems. Connection interface (protocol converter) for additional equipment provided with galvanic isolation
- Additional sensors and systems: Doppler flow velocity meter, cardiograph, pulse oximetry sensor, body temperature sensor, respiratory rate detection system, etc. (up to four sensors simultaneously) to monitor the patient's condition with the possibility to include these sensors in the process of the ECC monitoring and operation (additional equipment must provide their own primary power)
- Indication device (graphic display)
- Input device (keyboard)
- Warning device (buzzer, light-emitting diode)
- A secondary power supply for generating power to the system components
- System consisting of a set of compression sleeves for limbs with electronically controlled pneumatic pump unit and pressure sensors, carrying out the measurement of pressure oscillographically
- Autonomous power supply (lithium battery)

The developed ECC is presented on Fig. 1.

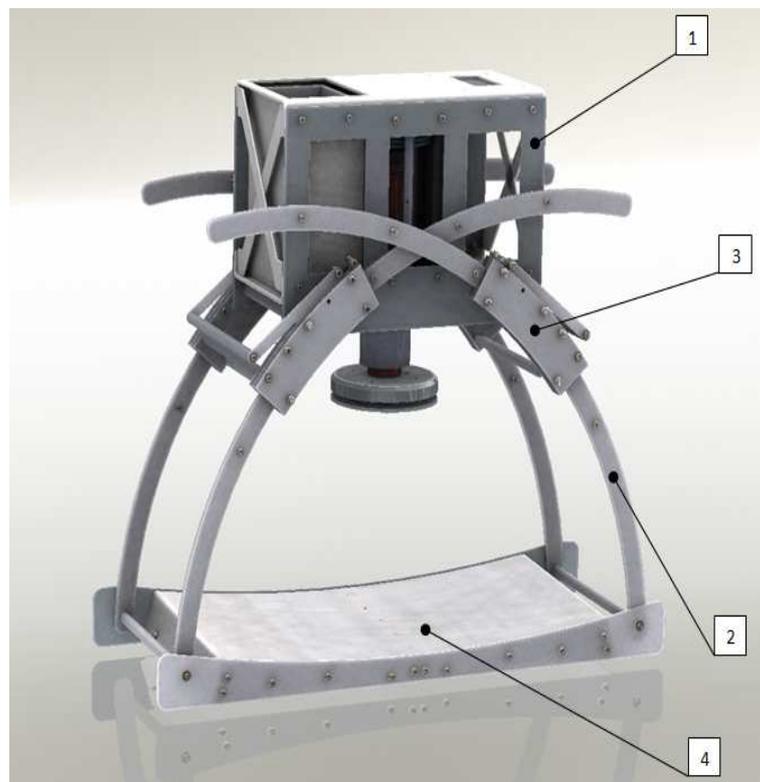


Fig. 1. General appearance of external cardiac compressor: mechatronic drive (1), rod attachment (2), position control mechanism for the actuator depending on the size of the patient's thorax (3), dorsal plate (bottom) (4)

Both construction of the device and the software should firstly provide extremely fast connecting of the ECC to the patient in all kinds of situations with minimal time lag in resuscitation as well as the diagnostics of major cardiovascular system parameters of the patient. That is why all the preparatory operations (setup, calibration, parameter setting, etc.) must be carried out prior to install the device on the patient. Adjustment of the parameters and ECC modes switching must be carried out with minimal manipulation. Adjusting the optimum rate and depth of compression is very important, as these values have individual features and exert a strong influence on the performance of the compression process. It is known that the compression rate has a greater impact than the amount of the chest deformation (the depth of compression).

As long as ECC can be equipped with many diagnostic devices it can also be used to monitor vital parameters of the patient without performing compression cycles. Such division implies four major operation modes of ECC:

- “Diagnostics”- determining the patient's vital signs without performing chest compressions
- “Set-up”- pre-setting and operational testing prior to application
- “Operation”- the intended use

The latter mode in its turn includes the following modes:

- “Basic”-working with pre-configured parameters recommended by the internal sensors
- “Advanced”- work with the built-in connection system and additional sensors according to pre-tested algorithms. This mode should be expanded with the experience of the device operation gained

The ergonomics of the ECC electronic part must also comply with the functions it performs, which defines such basic requirements as:

- The fastest as possible positioning of ECC on the patient's chest to minimize the time lag in resuscitation and ‘one-touch’ actuation with the preset parameters and the minimal number of sensors and systems
- The possibility of subsequent ‘hot’ connection of sensors and systems in the working process with a serial input of them into the process of monitoring and control
- A convenient top location and good protection of the device controls for fast setting and adjusting the compression parameters

- convenient top position of the display, ergonomic screens corresponding with the current mode of operation and containing only the necessary information and, where possible, instructions (tips)
- multistage control of overshoots options with distinct alarm (light and sound)

Since ECC is not a precision instrument, the requirements for measurement accuracy can thus be reduced. Based on the above requirements, it is possible to determine an adequate set of system components and their basic characteristics, which in turn determines the type and number of software interfaces and control routines for data collection.

Selection of the Components Ensuring Functioning of the Automated External Cardiac Compressor as a Therapeutic Device

The ECC includes the following sensors:

- A basic movement sensor for detecting the loading platform position (mm, accuracy of ± 1 mm)
- An acceleration sensor located at the loading platform for the secondary motion control (the loading platform position, mm, accuracy of ± 3 mm) and for the compression process dynamics record. Zero points are given for a zero acceleration of the platform that is detected by the acceleration sensor
- A pressure sensor in the loading platform to record the load on the chest by a drive (in kgf, accuracy ± 1 kgf)
- An invasive blood pressure sensor for the further control of ECC functioning and operative control of the patient's condition (in mmHg, accuracy of ± 5 mmHg). This sensor can also be used for automatic tuning parameters impact on the patient's chest (the depth of compression force) with the changes in his status
- A non-invasive blood pressure sensor is connected to a system of controlled pneumatic cuffs with periodic measurement of the blood pressure parameters (in mmHg, accuracy of ± 10 mmHg, measurement frequency of 1 min.) and checking the presence of pressure pulsations in the cuff. To squeeze the limbs and pulsation measurements the sensor is connected permanently and the pressure is measured only when the additional sensor is connected through the interface

It is necessary to emphasize a special importance of applying the electrocardiograph during resuscitation, which makes it possible not only to reliably determine the restoration of cardiac activity, but, if necessary, to

synchronize the operation of the ECC with the restored heart rhythm.

Selection of the Power Supply

Lithium iron phosphate battery was selected as a source of autonomous power. This type of battery was created by NASA program specifically to work in difficult conditions (Nishimura *et al.*, 2010). For the ECC two series-connected batteries 4S (12 V+12 V) with a capacity of 4.2 A-h each are used. The batteries have two connectors- for charging and energizing, enabling to use them with enough power charger as an uninterruptible power supply. In the standalone mode, the batteries provide the ECC systems with an average power consumption of 80 W per 1 h.

Functional Scheme of the Automated External Cardiac Compressor and its Interface Built in Accordance with the Theranostics Principles

Out of the entire functional scheme a subsystem for the compression parameters correction in accordance with the measured integral blood pressure can be singled out. Actuation of this subsystem converts the executive mechanism into both medical and diagnostic (theranostic) apparatus. The system (subsystem) of compression control according to the

integral pressure includes invasive and noninvasive (with a set of cuffs and a pneumatic pump unit) pressure sensors, hardware and software for controlling the measurement of current pressure values and calculating the integral pressure control parameters for a given criterion. The functional scheme of the subsystem is presented in Fig. 2.

The subsystem also includes warning system receiving signals from additional external sensors. The elements not included in the system are represented by a dotted line. The integral pressure is understood by the authors as:

- The average pressure in 4 cuffs imposed on a limb: These measurements are carried out at 1 min intervals using oscillographic method
- The average pressure over the period of compression or a heartbeat in case of restored cardiac activity: Fast measurements using invasive pressure sensor with the sampling frequency of the sensor in the range of 1-10 kHz

The average pressure characterizes the energy of directed blood motion and is calculated as a sum of the diastolic (lower) and 1/3 pulse pressure.

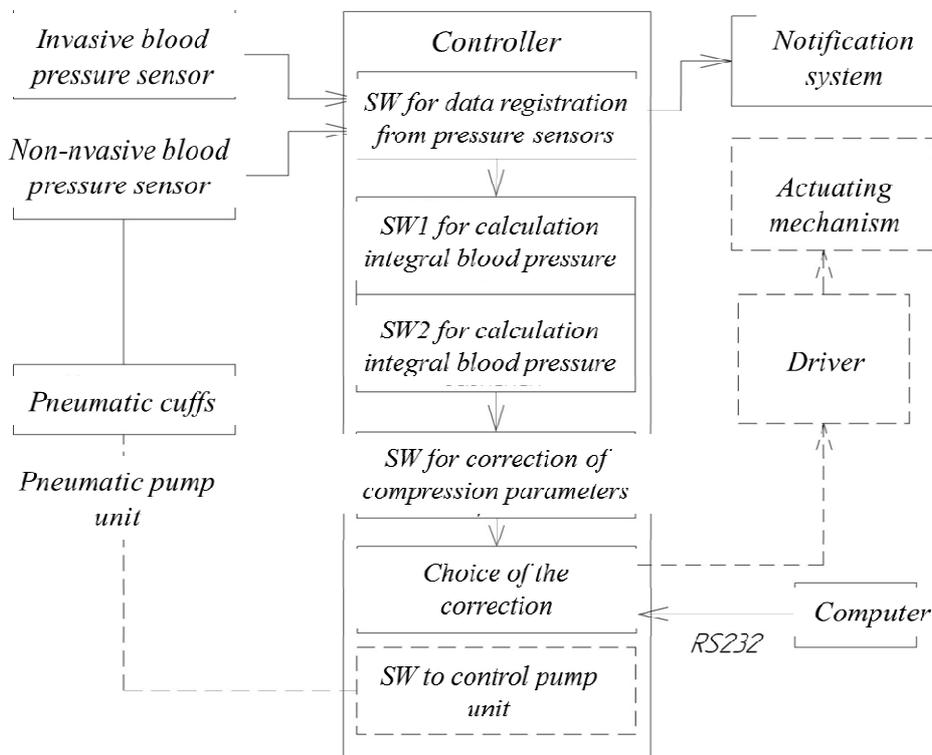


Fig. 2. System of compression control in accordance with the values of integral blood pressure

Pulse pressure, in turn, represents the difference between the systolic (the top number) and diastolic (the bottom number) pressures. Also the presence of additional low pressure pulsations in the limbs pinched with cuffs (indirect check availability rate) is recorded.

Results

As a result of research the choice of components for the implementation of the principles theranostics was defined and justified. 3D model of external cardiac compressor was developed. On the basis of the data an experimental prototype robotic system has been assembled and software has been developed. The external cardiac compressor has a force feedback to control the process. This provides additional information for the doctor. In addition, the device has a feedback of arterial pressure, which suggests an adaptive mode of operation. This enables automated diagnostics of the cardiovascular system functioning, which allows applying principles of theranostics in practice.

Discussion

This article presents data on the development of a new external ECC. It has a blood pressure measurement system to adjust the pump unit. This system allows accelerating the process of data processing with regard to the state of the cardiovascular system, to make this information more accessible and optimize the setup algorithm. It allows realizing an adaptive mode. We suppose that it will improve the outcomes of patients after the cardiopulmonary resuscitation procedure. However, further clinical trials are essential to implement this ECC in healthcare organizations.

Conclusion and Further Research

The effectiveness of the integration of the automated external cardiac compressor built on the principles of theranostics into the modern medical process can be achieved by incorporating it as a part of a more complex system, but in this case theranostic features of this larger system should be considered.

Acknowledgement

The authors would like to express their gratitude to the management of the Central Research Institute of Robotics and Cybernetics for their support.

Funding Information

This article was prepared with financial support from the Ministry of Education and Science of Russian Federation for the research under the Agreement of

17.06.2014, grant 14.575.21.0014 (unique identifier RFMEFI57514X0014) for the implementation of the federal target program "Research and development on priority directions of scientific-technological complex of Russia for 2014-2020 years".

Author's Contributions

Nikolai A. Gryaznov: Organized the study, information checking and manuscript writing

Konstantin Yu. Senchik: He was engaged in the results analysis, drafting of article.

Vyacheslav V. Kharlamov: He was responsible for data collecting and analysis of the results.

Galina S. Kireeva: Contributed in data collecting, writing and editing of the manuscript.

Ethics

The authors have no conflicts of interest in the development of the research and publication of this article.

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