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Development of Algorithms for the External Cardiac Compressor of Original Design

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Abstract

Manual chest compression method as a part of Cardiopulmonary Resuscitation (CPR) is a common, but not necessarily effective method of emergency in cases of the sudden cardiac arrest. In turn, the efficiency of methods using special apparatus for CPR depends on how a particular automatic system is simple to set up, operate and maintain. The article presents the data on the Russian External Cardiac Compressor (ECC) of original design for efficient chest compression and maintaining patient's blood pressure at the required level. The algorithms of automatic operation of the ECC and the results of experimental measurements, confirming the efficiency of the proposed algorithms are described. This is the first publication on the new Russian ECC and methods of its operation.

Keywords: Cardiopulmonary Resuscitation, External Cardiac Compressor, Mathematical Modeling, Operating Algorithms

1. Introduction

The number of people dying every year in Russia from sudden cardiac arrest is compared with the population of a large city and makes about 300,000 cases[1]. According to the official statistics, in Europe and the United States in 1-5 cases per thousand hospitalized patients it is necessary to provide measures of Cardiopulmonary Resuscitation (CPR)[2]. CPR typically is not a procedure which restarts the circulatory and respiratory functions. CPR may be effective for saving circulatory and respiratory functions in the quantity necessary for the survival of patient until his own circulatory and respiratory function are not reestablished. Non-apparatus CPR techniques are now well developed and routinely used in emergency practice in sick and injured adults and children[3]. A significant disadvantage of these techniques is the inability to perform CPR chest compressions effectively due to the rapid fatigue of the resuscitator (time of effective chest compressions is about 3 min)[4–7]. Quick change of personnel in most cases is impossible. Another limitation in the applicability of manual chest compressions is the difficulty arising when transporting of a patient is required. So the development of automated system with External Cardiac Compressor (ECC) is a matter of interest not only to replace a human during CPR, but also to be able to control the compression parameters depending on the physiological characteristics of the patient.

2. Concept Headings

In the Russian State Scientific Center for Robotics and Technical Cybernetics (Saint-Petersburg, Russia) mechatronic cardiac compressor has been developed and successfully tested. This cardiac compressor will be the main component of the automated ECC. All parts of the ECC are under the software control and are listed below:

- Electric drive with the transmission, converting the rotary motion of the motor into the linear motion of the loading platform of the cardiac compressor;

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- Driver of electric drive;
- A set of sensors for monitoring the patient's condition, the compression process control and management (invasive pressure sensor, a non-invasive pressure sensor, a load on the chest compression sensor, values of chest compression sensor);
- Microcontroller control system with a set of interfaces, including ones for additional sensors and systems;
- Additional sensors and systems: Doppler flow velocity meter, cardiograph, pulse oximetry sensor, body temperature, respiratory rate detection system, etc. (up to four at a time);
- Indication and displaying device;
- An input device;
- Pager;
- A secondary power supply for generating power to the components of the system;
- A system consisting of a set of compression sleeves for limbs with electronically controlled pneumatic pump unit and pressure sensors measuring pressure (oscillographic method);
- Autonomous power supply.

2.1 The Operation of the Automated External Cardiac Compressor

Management and correction of control parameters is made in accordance with the data from all of the sensors using the preset algorithms. The correction algorithm is based on the theoretical calculations to determine additional blood pressure (as a result of the restored cardiac activity) due to pressure fluctuations as a result of the ECC functioning. The proposed algorithm consists of two reduced versions of computational algorithms running simultaneously. The following three values are calculated in parallel:

- The difference of the measured pressures in the two neighboring cycles of compression pointwise, at equivalent points with the timing of the compression start (the position of the loading platform is at the top) and the sum of absolute deviations;
- The period of occurrence of an additional signal maximum to synchronize with the cardiac compressor operation;
- The change in the integral over the period of the compression pressure in the neighboring cycles.

The calculated values are compared with the established threshold and the law of load changes in the direction of decreasing the compression and reducing the frequency of exposure. At this stage, the amount of change is set empirically, and cannot be adjusted quickly. Simultaneously, the icon of restored cardiac activity (availability of the patient's own pulse) appears in the display and periodic beep is set.

To refine the algorithm to the specific values of the optimal compression parameters as well as techniques of changing the settings according to the obtained data of the patient's condition, a set of statistics is required, as the analogues of the developed device do not exist. The development of the algorithms is based on the American Heart Association Guidelines[8].

2.2 The Variables and Parameters of the Automated External Cardiac Compressor Operation

The list of program variables in the basic mode of operation is shown in Table 1.

2.3 The Structure of the Operating Control Algorithms of the Automated External Cardiac Compressor

The general operating control algorithms of ECC subsystems include:

- Self-test algorithm;
- Control algorithm by the amount of force (tracking the trajectory of the loading by the applied force controlling the output of the displacement beyond the maximum set value);
- Control algorithm by the compression value (tracing the path of the movement controlling restrictions on the force applied);
- Correction algorithm of compression parameters according to the sensor readings (this implementation provides correction mode by the integrated pressure value);
- Registration algorithm of abrupt changes in the trajectory (the applied force at a given amount of compression or the amount of compression for a given amount of force), which may be associated with fractured ribs or recovery of respiratory functions;
- Interruption algorithm for pause for artificial respiration.

Table 1. The parameters and constants of the basic mode

No	Parameter	Units	Min/Max	Pitch measurement	Description
1	Frequency of compression	1/min	30/120	10(5*)	The frequency of repetition cycles of compression / decompression
2	Basic frequency	1/min	80	–	Constant
3	Compression/ decompression	%	10/90	10	The ratio of compression / decompression time
4	Force	kgF	0/60	5(2*)	The maximum force determined by the force value
5	Depth of compression	mm	0/60	5(2*)	The magnitude of chest compressions from the contact point of the sternum that is controlled by the amount of compression
6	Basic depth	mm	35	–	Constant
7	Maximal force	kgF	0/60	5(2*)	Restriction on the used force by the largest compression value
8	Maximal compression	mm	0/60	5(2*)	Restrictions on the compression value by the force
9	Pause period	unit compression cycles	1/50	1	The number of cycles of compression before pausing for ventilation
10	Pause duration	sec	0/20	5(1*)	Pause duration
11	Control	logically	Compression	choosing	Selection of control based on the force or the compression value
12	Trajectory	–	0/9	1	Choice of one of the preset load laws

*Accurate set; Min – minimal value, Max – maximal value.

2.4 Development of Algorithms for Processing Information about an Integrated Blood Pressure

The development of the algorithm for processing information about integrated blood pressure is aimed at controlling the process of compression. Blood pressure is measured continuously invasively, by recording the original measuring system of volume arterial waveform. It is a well-known fact that the rhythmic activity of the heart leads to a pulse – periodic oscillations of blood supply and blood pressure in the blood vessels. Blood pressure sensor connected to the patient's artery shows the pressure as a continuous signal which can be digitized. Thus obtained waveform has the general characteristic pattern and consists of individual pulse waves or oscillations[9].

We shall assume that the measured circulation process can qualitatively be in one of four possible states:

- The normal functioning of the heart, characterized by a batch process, as discussed above.
- Extracorporeal circulation generated by ECC. This is characterized by a batch process similar to the natural one. Fibrillations may overlap this process, but they are in the nature of the noise component and do not affect the overall picture quality.
- Overlay of two processes. In practice this means that in the course of cardiopulmonary bypass the heart muscle begins to function in a natural mode, so that the body's natural blood flow is observed. The main objective of the algorithm of controlling blood pressure since the start is to establish the start of natural circulation in order to change the operating mode of ECC.
- The absence of both natural and artificial blood circulation. This state corresponds to the beginning of resuscitation.

Thus, as part of the algorithm, there is the problem of describing a batch process by the measured waveform. Let us consider periodic digital signal type: $x(0), x(1), x(2), \ldots x(n), \ldots$. Here $x(n)$ are counts corresponding to the values of arterial pressure. We pose the problem of predicting the value of *x(n)* from the previously measured values:

$$x(n-1), x(n-2), x(n-3), \; \ldots x(n-p)$$

To do this we form a linear combination:

$$\bar{x}(n) = a(1)\, x(n-1) + a(2)\, x(n-2) + \ldots + a(p)\, x(n-p) \quad (1)$$

Here $\bar{x}(n)$ is a predicted value, $a(1), a(2), \ldots a(p)$ are linear prediction coefficients.

The prediction error is: $e(n) = x(n) - \bar{x}(n)$.

For the mean square prediction error N of the successive pulses $x(n), \ldots x(n+N-1)$ we can write:

$$E_N = \sum_{k=0}^{N-1} (e(n+k))^2 = \sum_{k=0}^{N-1} ((x(n+k) - \bar{x}(n+k))^2)^2 \quad (2)$$

The values of linear prediction coefficients will be obtained from the minimum conditions of expression (2) by $a(1), a(2), \ldots a(p)$:

$$\sigma_N^2 = \min_{a(1)-a(p)} E_N \quad (3)$$

The value of the reached minimum σ_N^2 characterizes the quality of the signal prediction. Linear prediction coefficients can be converted to cepstral coefficients or reflection coefficients. The calculation of these values is also possible using fast Fourier transform. In the description of the process of controlling blood pressure it is important that for the batch values of linear prediction coefficients (as well as other associated features) calculated at different points of the discrete time should remain constant. The latter allows looking at the values of the coefficients of linear prediction as at the values of the random variable corresponding to a particular general population.

Let us now consider the time of the natural circulation launch while continuous chest compressions are performed. From the viewpoint of pressure measurement, this means that a detectable periodic process is added by the new batch process. For the linear prediction coefficients, this means that the last value calculated after the start of the natural circulation already belongs to another general population. Thus, by storing a set of linear prediction coefficients calculated at various successive time points, we obtain sampled values of a vector random variable, which is uniform only in the event of cardiopulmonary bypass system functioning only. Therefore blood pressure control is possible using a statistical criterion for testing the homogeneity of the sample.

Here is a scheme to test the hypothesis of homogeneity of the sample using the Smirnov criterion in the case of one-dimensional random variable. σ_N^2 can be taken as the latter from the formula (3).

Suppose there are two independent samples $(x_1', x_2', \ldots, x_m')$ and $(x_1'', x_2'', \ldots, x_n'')$. We need to verify that both samples are taken from the same continuous general population (in other words that the sample is homogenous). Using these samples we form two empirical distribution functions $F_{1m}(x)$ and $F_{2n}(x)$. If the two samples belong to the same population, the empirical distribution function will be close to the population distribution function, and therefore they are close to each other.

Consider the statistics

$$D_{mn} \sup_{x II \square |F1_{1m}(x) - F_{2n}(x)| \square} \quad (4)$$

There is a statement that if the empirical distribution function is constructed from samples of the same population, than

$$P(\mathrm{D}_{mn} / \sqrt{1/m + 1/n} < x) \to K(x) = \begin{cases} \sum_{k=-\infty}^{+\infty} (-1)^{k_e - 2k^2 x^2} & x > 0 \\ 0 & x \le 0 \end{cases} \quad (5)$$

with $n \to \infty, m \to \infty; m/n \to \rho > 0$.

Thus, the verification procedure is to implement the following:

- Choose the level of significance α.
- Find the root $K_{1-\alpha}$ of the equation $K(x) = 1 - \alpha$
- Determine the sample value *DB* of the statistics D_{mn}.
- Check the inequality $D_B / \sqrt{1/m + 1/n} < K_{1-\alpha}$. If this inequality is satisfied, the hypothesis of homogeneity is accepted at significance level α. Otherwise, the hypothesis is rejected, which means the appearance of the natural circulation.

Figure 1 shows the output to the optimum frequency mode compressions of ECC 80 beats/min at a depth of compressions 35 mm. In this mode, all the parameters were changed under the direction of the control program.

Study of ECC at various compression rates showed the presence of minute maximum flow rate and stroke volume at the compression rate of 80 beats/min, which

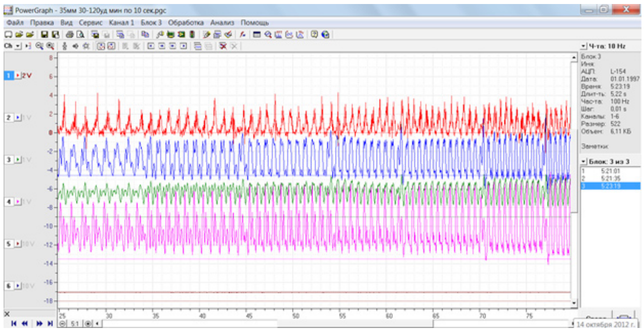

Figure 1. The sensor signals of flow and pressure in the test bench, registered during operation of external cardiac compressor in 'adaptive' mode in a phase of 'coarse' adaptation – selection of the optimal compression rates.

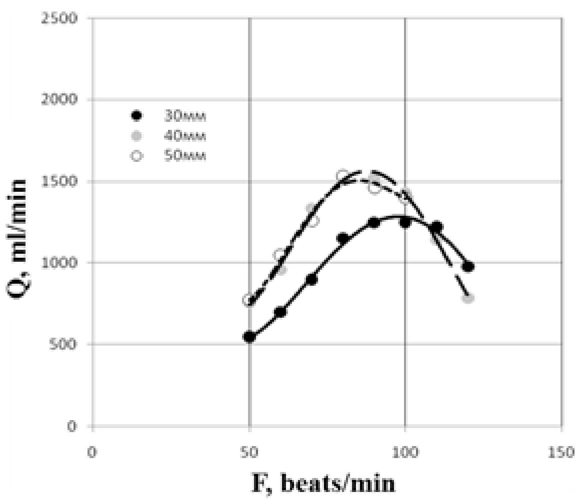

Figure 2. Relation between the minute rate in the experimental stand and the compression rate of the external cardiac compressor in the 'Neutral' mode with a depth of compressions 30-50 mm and a mean arterial pressure of 80 mmHg.

corresponds to the current guidelines for the cardiopulmonary resuscitation (Figure 2).

3. Discussion

Based on the results of the experimental studies we have determined that the developed operating control algorithms of the automated external cardiac compressor are fully functional, the software has no faults, sensor interfacing and control systems provide the correct automatic control of ECC in all modes. The studied adaptation algorithms are sufficiently effective and require no further optimization. The procedure of 'coarse' and 'fine' adjustment of compression parameters in the 'adaptive' mode of ECC operation provides maximum values of blood pressure because of the non-linear dependence of the minute flow rate and stroke volume on chest compression frequency with a pronounced maximum.

4. Conclusion

Since the value of blood pressure is a critical parameter determining the effectiveness of cardiopulmonary resuscitation, closed-chest cardiac massage in particular, it is very important to develop data processing algorithms for an integral blood pressure to control the compression process using automated ECC. Operating algorithms of the ECC of the original design developed by the authors have confirmed their performance on the actual measurements in the experimental stand for different values of the depth of compressions.

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7. References

1. Aman AA. Biophysical basis of measurement of blood pressure. Saint-Petersburg: Meditsina; 1983.
2. Bokeria LA, Revishvili AS, Neminushy NM. Sudden cardiac death. Moscow: GEOTAR; 2011.
3. Chugh SS, Jui J, Gunson K et al. Current burden of sudden cardiac death: multiple source surveillance versus retrospective death certificate-based review in a large U.S. community. J Am Coll Cardiol. 2004; 44:1268–75.

4. Cohen TJ, Goldner B, Maccaro P et al. A comparison of active compression-decompression cardiopulmonary resuscitation with standard cardiopulmonary resuscitation for cardiac arrests occurring in the hospital. N Engl J Med. 1993; 329:1918–21.
5. Cohen TJ, Tucker KJ, Lurie KG et al. Active compression-decompression. A new method of cardiopulmonary resuscitation. Cardiopulmonary Resuscitation Working Group. JAMA. 1992; 267:2916–23.
6. Field JM, Hazinski MF, Sayre MR, et al. Part 1: Executive summary: 2010 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care. Circulation. 2010; 122(Supp 18):640–56.
7. Kouwenhoven WB, Jude JR, Knickerbocker GG. Closed-chest cardiac massage. J Am Med Assoc. 1960; 173:1064–7.
8. Levine RL, Wayne MA, Miller CC. End-tidal carbon dioxide and outcome of out-of-hospital cardiac arrest. N Engl J Med. 1997; 337:301–6.
9. Wigginton JG, Miller AH, Fernando L, et al. Mechanical devices for cardiopulmonary resuscitation. Curr Opin Crit Care. 2005; 11:219–23.