Study of central hemodynamic parameters in pediatric burn shock patients using the method of the heart cycle phase analysis

Vladimir A. Vecherkin\textsuperscript{1*}, Victor A. Ptitsin\textsuperscript{1}, Olga K. Voronova\textsuperscript{2}

\textsuperscript{1} Voronezh State Medical Academy Named after Bourdenko, 394036, Voronezh, Student str. 10
\textsuperscript{2} Russian New University, 105005, Russia, Moscow, Radio str. 22

* Corresponding author: Phone: +7 (473) 237-28-32. E-mail: vecherkinva@mail.ru


Aims

This paper deals with a study of central hemodynamics in 363 pediatric patients with burn shock as compared with a reference healthy children group in order to establish clinical value of the hemodynamic parameters for burn shock diagnostics and therapy.

Materials and methods

There is a new method applied to examine the functional status of the cardiovascular system with use of the medical equipment Cardiocode that is based on the method of the heart cycle phase analysis and capable of measuring parameters such as a stroke volume (SV), a circulation minute volume (CMV), systolic parameters (both a rapid ejection volume Vr.e. and a slow ejection volume Vs.e.), diastolic parameters (an early diastole volume Ve.d. and an atrial systole volume Va.s.), including a volumetric parameter characterizing the actual tonus of the ascending aorta (Va.a.).

Results

Age-related trends in the above volumetric parameters have been established herein. Specific features of the hemodynamic parameters in pediatric patients with burn shock have been identified.

Conclusion

Diagnostics of changes in the central hemodynamics in pediatric burn patients at their hospital admission provides reliable prediction tools for detecting shock well in advance and starting with an adequate intensive therapy.

Keywords

Pediatric patients • Burn shock • Hemodynamics • Stroke volume • Minute volume • Cardiac output • Cardiocode • Heart cycle phase analysis

Imprint

Introduction

Treatment of children with thermal burns complicated by a shock is a very critical issue in pediatrics surgery. Even with use of most advanced technologies in treatment of severely burned pediatric patients, sometimes we have to deal with rather significant mortality and disability rates [1]. The clinical studies show the presence of considerable disturbances in the central hemodynamics and oxygen supply to tissues in the above shock-trauma patients [2,3,4]. Therefore, our study of the central hemodynamic parameters conducted in the said patient population should be of great interest to pediatricians and pediatric surgeons.

Until the present time, there has been no complete picture for perfect understanding of laws of the performance of the heart and its associated blood vessels. This is because one of the open issues in blood circulation physiology is to properly realize the fluid mechanics of the cardiovascular system as a single system and, on this basis, acquire knowledge of its design and management laws [5]. The blood flow system is a giant hierarchical structure integrating a great number of systems and subsystems with some common and specific features, the functioning of which is aimed at one thing only: to maintain an adequate blood flow in all organs and tissues in our organism according to the principle of biological optimization making every biological system as efficient as possible.

At present, the condition of the pumping function of the heart is assessed according to some conventional significant parameters of the central hemodynamics, among which are the stroke volume, the minute volume that is known as the cardiac output (CO) and the total peripheral resistance that is referred to as the systemic vascular resistance (SVR). Both the stroke volume (SV) and the circulation minute volume (CMV, or CO) are measured by direct (invasive) or indirect (noninvasive) methods while the SVR is calculated from the fluid dynamics Poiseuille’s equation. As a rule, for measuring of SV and CMV parameters in pediatric practice used are noninvasive methods [6]. It is generally believed that both conventional invasive and noninvasive methods for measuring central hemodynamic parameters are based on assumptions that blood plasma and formed elements circulate with the same velocity. But new evidence demonstrates [7,8,9,10] that erythrocytes move in the pulsating blood flow due to static pressure gradients, generated transverse to the blood vessel axis, forming in such a manner a specific dynamic radial ring pattern, that facilitates the much more faster movement of the erythrocytes as compared with plasma.

At the same time, it should be noted that there is no rigorous relationship between the stroke volume and the systemic vascular resistance. The reason is that it is customary to assume that the blood circulation in our organism is maintained in a flow mode according to
the Poiseuille’s law. But this assumption is inconsistent with the principle of optimization in biological systems according to which all processes in the biological systems are managed in the most perfect manner (to maximize their efficiency).

Over forty years ago, it was established that blood circulation is managed not under the Poiseuille’s law, but by meeting the most efficient “third-type” flow conditions [9, 10]. This innovative blood flow concept laid the foundations for development of a new noninvasive method for measuring parameters of the central hemodynamics that was based on actual times of every heart cycle phase, and it is just the method that is used in our study described herein (i.e., the method by Poyedintsev – Voronova) [8,9].

The study of the central hemodynamic parameters in pediatric patients with burn shock was aimed at establishing clinical value of the said parameters.

Materials and methods

97 healthy patients aged 1 to 14 years from preschool and school institutions as reference groups were studied by us. In the pediatric clinics, 363 children with burn shock were enrolled into the study of the central hemodynamic parameters using the medical equipment Cardiocode (produced by the Scientific-Technical Company CARCDIOCODE, Taganrog, Russia). At the hospital admission, in pediatric patients the standard parameters of hemodynamics were taken as follows: HR, AP, CVD, Hb, Ht complete with their ECGs. With use of Cardiocode, by the Poyedintsev – Voronova method, we measured the following heart performance data:

SV (ml) – stroke volume;
CMV (l) - circulation minute volume, or cardiac output;
Ve.d. (ml) is a volume of blood entering the left ventricle in the slow filling phase due to venous inflow and suction function of the ventricle (early diastole);
Va.s. (ml) is a volume of blood, entering the left ventricle in the atrial systole that features the left atrium myocardial contractility, and, in addition, phase-related diastolic volumetric parameters Ve.d. and Va.s. featuring the preload level;
Vr.e.(ml) is a volume of blood ejected by the left ventricle in the rapid ejection phase;
Vs.e.(ml) is a volume of blood ejected by the left ventricle in the slow ejection phase;
the systolic phase-related volumetric parameters Vr.e. and Vs.e. are strong markers of the myocardial contractility of the left ventricle;
Va.a. (ml) is a volume of blood pumped by the ascending aorta as peristaltic pump (in the phase of slow ejection), reducing by this means the post-load of the left ventricle. Besides, this volume is a strong marker of the ascending aorta tonus.
The measurements of the central hemodynamic variables in burn-shock patients were performed with Cardiocode according to the schedule as follows: on hospital day 1, day 2, day 5, day 10, day 20, and day 45 post-burn.

It should be noted that the results obtained therein are assessed not only in absolute units of measure but also by evaluating the deviations of the hemodynamic parameters from their top and bottom limits, considering heart rate (HR), sex and age of every child.

The statistics was processed with application of the Software STATISTICA employing both parametric and non-parametric criteria.

In order to assess variation rows of quantitative data, calculated were the following values: the mean value of the variables observed (M), the standard error of the estimated mean (m) and the mean square of the error ( & ). All tables and pictures herein exhibit the respective group-related data as the mean values ± the standard error of the estimated mean (M±m).

To test the hypothesis of difference in sample means, the paired two sample Student’s t-Test is applied by us. In this case, it is assumed that there are unequal dispersions of the general populations from which our samples are drawn. The paired t-Test is usually conducted when natural pairs of observations in sampling occur, for example, when a general population is tested two times.

For all surveys, representativeness of the obtained results is assessed.

In testing the statistics hypotheses, it is assumed that p-values <0,05 to <0,001 are statistically significant.

A correlation analysis is carried out to determine the probability that the correlation is a real one and not a chance. This analysis makes possible to sample matters, which have the most significant influence on the resulting attribute, and identify previously unknown relationships between variables. It should be employed for quantitative assessment of cross-relations between two data sets represented dimensionless. Following this way, the sample correlation coefficient is the covariance of two data sets that is obtained by dividing by the product of their standard deviations.

**Results and discussion**

The parameters of the central hemodynamics (CH) were studied by us first in three reference groups of healthy children: group 1– infants and children aged 1 to 4 years, group 2 – children aged 4 to 7 years, and group 3 – children aged 7 to 14 years (s. Table 1 below).

Phase-related volumetric parameters of CH in healthy children.
### Table 1. Phase-related volumetric parameters of central hemodynamics in healthy children.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ - standard deviation</td>
<td>σ - standard deviation</td>
<td>σ - standard deviation</td>
</tr>
<tr>
<td>Specific SV(ml/cm²)</td>
<td>19,2±1,16</td>
<td>21,8±1,11</td>
<td>24,1±0,98</td>
</tr>
<tr>
<td></td>
<td>5,58</td>
<td>6,22</td>
<td>5,10</td>
</tr>
<tr>
<td>Specific CMV (l/cm²)</td>
<td>2,1±0,11</td>
<td>1,95±0,09</td>
<td>2,07±0,08</td>
</tr>
<tr>
<td></td>
<td>0,55</td>
<td>0,54</td>
<td>0,39</td>
</tr>
<tr>
<td>SV (ml)</td>
<td>22 ± 1,35</td>
<td>2,66±1,74</td>
<td>51,1±2,7</td>
</tr>
<tr>
<td></td>
<td>6,45</td>
<td>9,85</td>
<td>14,15</td>
</tr>
<tr>
<td>CMV (l)</td>
<td>2,43±0,13</td>
<td>2,96±0,15</td>
<td>4,37±0,19</td>
</tr>
<tr>
<td></td>
<td>0,62</td>
<td>0,84</td>
<td>1,00</td>
</tr>
<tr>
<td>Ve.d. (ml)</td>
<td>15,44±0,03</td>
<td>24,81±0,02</td>
<td>39,43±0,04</td>
</tr>
<tr>
<td></td>
<td>0,61</td>
<td>0,63</td>
<td>1,09</td>
</tr>
<tr>
<td>Va.s. (ml)</td>
<td>6,56±0,03</td>
<td>8,03±0,02</td>
<td>11,68±0,04</td>
</tr>
<tr>
<td></td>
<td>0,61</td>
<td>0,65</td>
<td>1,09</td>
</tr>
<tr>
<td>Vr.e.(ml)</td>
<td>17,67±0,01</td>
<td>26,07±0,01</td>
<td>42,31±0,02</td>
</tr>
<tr>
<td></td>
<td>0,30</td>
<td>0,23</td>
<td>0,47</td>
</tr>
<tr>
<td>Vs.e. (ml)</td>
<td>4,33±0,01</td>
<td>6,74±0,01</td>
<td>8,8±0,02</td>
</tr>
<tr>
<td></td>
<td>0,30</td>
<td>0,34</td>
<td>0,47</td>
</tr>
<tr>
<td>Va.a.</td>
<td>6,89±0,02</td>
<td>10,85±0,01</td>
<td>16,3±0,02</td>
</tr>
<tr>
<td></td>
<td>0,36</td>
<td>0,39</td>
<td>0,50</td>
</tr>
<tr>
<td>Ve.d.(% of SV)</td>
<td>70,17±1,96</td>
<td>75,97±1,14</td>
<td>77,15±1,48</td>
</tr>
<tr>
<td></td>
<td>9,39</td>
<td>6,44</td>
<td>7,69</td>
</tr>
<tr>
<td>Va.s.(% of SV)</td>
<td>29,83±1,96</td>
<td>24,59±1,17</td>
<td>22,85±1,48</td>
</tr>
<tr>
<td></td>
<td>9,39</td>
<td>6,61</td>
<td>7,69</td>
</tr>
<tr>
<td>Vr.e.(% of SV)</td>
<td>80,30±0,96</td>
<td>79,84±0,41</td>
<td>82,78±0,63</td>
</tr>
<tr>
<td></td>
<td>4,60</td>
<td>2,32</td>
<td>3,30</td>
</tr>
<tr>
<td>Vs.e.(% of SV)</td>
<td>19,7±0,96</td>
<td>20,63±0,62</td>
<td>17,22±0,63</td>
</tr>
<tr>
<td></td>
<td>4,60</td>
<td>3,50</td>
<td>3,30</td>
</tr>
<tr>
<td>Va.a.(% of SV)</td>
<td>31,3±1,17</td>
<td>33,2±0,69</td>
<td>31,89±0,68</td>
</tr>
<tr>
<td></td>
<td>5,60</td>
<td>3,92</td>
<td>3,54</td>
</tr>
<tr>
<td>HR</td>
<td>112,91±2,64</td>
<td>90,94±1,27</td>
<td>86,22±1,98</td>
</tr>
<tr>
<td></td>
<td>12,68</td>
<td>7,21</td>
<td>10,29</td>
</tr>
</tbody>
</table>

Notes: M is a mean value; m - standard error of the estimated mean; σ - standard deviation.

Considering the data given in the above table, when evaluating the pumping function of the heart in the healthy children, it should be noted that the specific stroke volume tends to increase with age (by 1,25 times): from 19,22 ± 1,16 (ml/cm²) in group one to 21,81 ± 1,10 (ml/cm²) in group two, and the school-aged children demonstrate an increase therein to 24,13 ± 0,98 (ml/cm²). The same tendency is observed when we treat such data as the stroke volume (an increase is noted from 22,00 ml in group 1 to 32,66 ml in group 2 with further growing up to 51,11 ml in school-aged children, i.e., we deal with an increase by 2,3 times), and when we analyze the circulation minute volume, or cardiac output (reported is an increase from 2,43 l ± 0,13 in group 1 to 2,96 l±0,15 in group 2 with further rising to 4,37±0,19 in children in group 3, i.e., by 1,8 times).

When evaluating the diastolic data of the above reference groups, we can conclude that both absolute and relative values of the early diastole show their tendency to grow with age (starting with 15,44 ± 0,03 ml in group 1, then reaching 24,81 ± 0,02 ml in group 2 and growing up to 39,43 ± 0,04 ml in group 3, respectively, i.e., showing a growth by 2,5 times; or it can be illustrated as follows: beginning from the level of 70,17 ± 1,96 % of the stroke volume in group 1, reaching 75,97 ± 1,14 % in group 2 and ranging up to 77,15 ± 1,48 % in children of group 3, i.e., an increase by 1,1 times is reported). The absolute values of the atrial systole demonstrate their age-group dependent growth, too (from 6,56 ± 0,03 ml in the first group to 8,03 ± 0,02 ml in the second group, reaching 11,68 ± 0,04 ml in the third group, i.e., recorded is an increase by 1,8 times), while the corresponding relative values of the parameter...
show their reducing (to illustrate this, we have 29.83 ± 1.96 % of the stroke volume in group 1, then, 24.58 ± 1.17 % in group 2 and up to 22.85 ± 1.48 % in children in group 3, respectively, i.e., a decrease by 1.3 times is reported).

There is an evident age-related trend detected when the absolute systolic values of the rapid and slow ejection phases grow considerably (the volume of blood ejected by the left ventricle in the phase of the rapid ejection increases from 17.67 ± 0.01 ml to 42.31 ± 0.02 ml, i.e., by 2.4 times, and the volume of blood ejected in the slow ejection phase demonstrates an increase from 4.33 ± 0.01 to 8.8 ± 0.02 ml, i.e., by 2 times, respectively). The relative values of the systolic parameters in the rapid ejection phase in healthy children in all reference groups do not show any significant differences and are reported to be 80.3 ± 0.96 %, 79.84 ± 0.41 % and 82.78 ± 0.63 % of the stroke volume, respectively. The relative systolic parameters in the slow ejection phase of the healthy children in groups 1 and 2 are approximately at the same level with their measurements of 19.70 % and 20.63 % of the stroke volume, respectively. The school-aged children show a tendency to a slight decrease in this value to 17.22 % of the stroke volume.

Upon an analysis of the absolute parameters featuring the aorta performance as peristaltic pump (in the phase of rapid ejection), it should be stated that there is a significant increase in these values revealed that is age-related, too (from 6.89 ± 0.02 ml in children in group 1 to 16.3 ± 0.02 ml in school-aged children, i.e., by 2.4 times). The respective relative values in the first, second and third groups do not differ essentially from each other and are reported to be 31.30 %, 31.89 % and 33.22 % of the stroke volume, accordingly.

To provide a clear picture of the CH parameters in children with burn shock, we used in our study a list of most important hemodynamic parameters as follows: SV, CMV, Ve.d., Va.s., Vr.e., Vs.e. and Va.a..

Upon treating the central hemodynamic parameters in pediatric patients with burns of the first to three degrees, we found that the said patients had at the time of their admission to the hospital a lowered SV that was 5 -25% below the normal level, depending on the shock degree, while their CMV reached 110 %.

In such cases, of particular value are the hemodynamic data pertaining to the early diastole (Ve.d.), since it is precisely these parameters that are strong markers of hypovolemia caused by circulation stagnation and loss of plasma through burn wounds. So, the early diastole parameters on day 1 post-burn decreased to 75% of the norm for the first-degree burn cases, to 65% for the shock cases with the second-degree burns and to a level under 65% for shock cases of the third-degree burn patients. Later, despite the therapy received, the early diastole
parameters could not be recovered in full up to the end of the hospital treatment (on hospital day 45 post-burn).

Moreover, it was reported that the left ventricular myocardial function in the pediatric patients with burn shock is badly affected (Vr.e. and Vs.e.). So, in children with the first-degree burn shock a Vr.e. fall (up to 80%) on day 1 post-burn was recorded only, while the same patients had their Vs.e. at the normal levels, but in cases of the burn shock of the second or third degree the said parameters were lowered (up to 56 % on hospital day 5 post-burn).

It was also fixed that the markers of the tonus of the ascending aorta (Va.a.) were reduced to 82% in pediatric patients of the first and second burn shock degrees, and the same parameters were reduced to 68% of the normal value in third-degree burn shock patients. This substantiates our conclusion that we deal in such cases with a considerable fall in capacity of the aorta operating as peristaltic pump. Most pronounced changes in the CH parameters are found in children with unfavorable outcome.

For critically ill patients of that category, the following data were typical: a drastic decrease in the SV by 35-45%, in the CMV by 40 – 50 %, in the early diastole volume (Ve.a.) by 64-57%, in the ascending-aorta tonus volume (Va.a.) by 68-56%, and in the volumes Vr.e. and Vs.e. by 58-67%. At the same time, recorded was a sharp increase in the systolic parameter (Va.s.) up to 187 – 203 % that might be treated as a compensatory reaction of the cardiovascular system. Besides, a distinguishing characteristic of these patients was that despite intensive therapy measures their early diastole parameters (Ve.a.) were recorded at a level of 40 – 50 % of the norm, and it was impossible to bring them to the proper level up to the lethal outcome, so that the said parameters can be treated as strong markers of a dramatic drop in blood volume circulation.

Conclusions

1. The new method of assessment of the functional status of the cardiovascular system delivers data of high informative value, is noninvasive and can considerably expand the ECG capabilities; it is appropriate for measuring the CH parameters in pediatric patients.

2. An application of this method to treatment of burn children provides for more precise diagnostics tools for revealing pathologic abnormalities in the CH parameters, it allows detecting the burn shock degree during the first hours upon admission to a surgery hospital.

3. The CH systolic and diastolic parameters measured by the above mentioned Povedintsev – Voronova method can be successfully used to decide on an adequate basic infusion therapy and starting with the required treatment.
4. The early diastole data (Ve.d.) are most important CH parameters, and they are treated to be strong markers of drop in volumes in circulating blood. A decrease in this blood volume to 30-40% of the norm should be considered as an unfavorable outcome predictor.

**Abbreviations**

SV – stroke volume  
CMV – circulation minute volume or cardiac output  
Vr.e. – systolic parameter of rapid ejection of blood from ventricle  
Vs.e. – systolic parameter of slow ejection of blood from ventricle  
Ve.d. – diastolic parameter: early diastole of atrium  
Va.s. – diastolic parameter: atrial systole  
Va.a. – tonus of ascending aorta  
SVR – systematic vascular resistance  
EP – efficiency of performance  
HR – heat rate  
AP – arterial pressure  
CVP – central vein pressure  
Hb - hemoglobin  
Ht - hematocrit  
ECG – electrocardiography  
M – mean value;  
m - standard error of the mean;  
σ – standard deviation  
CH – central hemodynamics  
CBV – circulating blood volume

**Acknowledgments**

The authors of this paper thank the Administration of Voronezh State Medical Academy Named after N.N.Bourdenko and Voronezh Regional Pediatric Clinical Hospital No.2, especially I.E. Yessaulenko, Professor, Pediatric Surgery Chair, S.N. Gissak, Professor, Pediatric Surgery Chair, and Avdeyev S.A., Head Doctor of State Pediatric Hospital No.2, for their kind support and assistance in clinical trials conducted in children.
Author contributions
All authors contributed equally to the work presented in this paper. V.A.V. read and met the ICMJE criteria for authorship. All authors read and approved the final manuscript.

Conflict of interest
None declared.

Statement on ethical issues
Research involving people and/or animals is in full compliance with current national and international ethical standards.

References