Hemodynamic contribution to human ECG

Alexander V. Kramarenko[a,*], Gennady P. Kulemin[b], Alexander M. Savchuk[c]

[a]*TREDEX Company Ltd., PO box 11515, Kharkiv 61001, Ukraine*
[b]*O. Ya. Usikov Institute for Radiophysics and Electronics of the National Academy of Sciences of Ukraine, 12, Ac. Proskura st., Kharkiv 61085, Ukraine*
[c]*Kharkiv hospital for railways #1 of the branch "Health Center" Public Joint Stock Company "Ukrainian Railways", 5, Balakireva lane, Kharkiv 61103, Ukraine*

Abstract

The electrical and dynamic properties of intracardiac blood are not taken into account when considering the origin of the surface electrocardiogram, which leads to the idea that there are no electrical processes in the diastole that manifest on the surface of the body. Nevertheless in seven men (average age of 38 ± 2) having the aortic insufficiency low amplitude potentials has been revealed in diastole by signal-averaged electrocardiotopography method. These potentials was negative relative to the central Wilson terminal located in the left anterior thoracic region. The amplitude of the minimum was hundreds of microvolts and varied depending on the clinical condition of the patient. Since the phenomenon appeared to be quite distant from the moment of the possible manifestation of the U wave and was observed tens of milliseconds before the onset of atrial depolarization, we assumed that it was caused solely by hemodynamic factors.

In order to test our hypothesis experimentally we have used a differential amplifier having 1 GOhm input impedance (at zero frequency) to measure the difference of potentials between two points of an aqueous 0.9% sodium chloride solution at the moment of appearing of the jet inside it. The registered signal looked like a damped harmonic oscillation. A mathematical model of the process has been proposed in the form of the differential equation relating the charge bulk density in the solution of electrolyte, its viscosity and acceleration of the jet moving inside it. The results of the study show that intracavitary blood moving with acceleration has electrogenic properties since it is an electrolyte solution containing ions having different mobilities. The contribution of such properties should be taken into account when considering the mechanisms of formation of a surface ECG.

1. Introduction

The role of blood as an extracardiac factor in the mechanism of formation of surface electrocardiogram (ECG) has been studied in sufficient detail. So, the influence of the degree of filling of the ventricles with blood and changes in its electrical conductivity on the amplitude of the teeth of the QRS complex was established back in the 50s and was repeatedly confirmed later [1]. But in these studies intracavitary blood was considered only as a factor in the transfer of electrical processes, which are occurred in myocardium, to the surface at the time interval corresponding to the appearance of $PQRSTU$ waves on the ECG curve. Electric and dynamic properties of the blood filling the heart chamber in diastole have not been taken into consideration while interpretating ECG. It resulted in the concepts of the absence of electrical processes exhibited at the surface during diastole and, therefore, about its electric "silence".

However, in seven male patients (average age of 38 ± 2) having aortic insufficiency on isopotential map of signal averaged ECG (recorded with averaging relative to the central Wilson terminal) low-amplitude negative potentials are recorded during the slow filling phase in the lower third of the anterolateral torso on the left. There is a complex distribution of potentials on the surface; in most cases, the shape of the distribution approaches ellipsoidal. The equipotential structure of the region of negative potentials is represented by deformed ellipses, the larger radius of which is oriented in the craniocaudal direction, the zone of the minimum is in the form of an irregular circle is localized mainly in the lower anterior thoracic region on the left.

The amplitude of the minimum negative potential varies depending on the characteristics of the clinical condition of the patients and reaches to hundreds of microvolts. In figure 1 the zonal structure of the region of negative potentials in the phase of slow filling of the ventricles in a representative patient is shown. Time evolution of equipotential zones has a decreasing direction during diastole.

The phenomenon described is quite distant in time from the moment of the possible manifestation of the U wave, since it is observed 380-420 ms after the end of the T wave considering a cardiac cycle duration of 980-1200 ms. On the other hand it precedes (for 100-130 ms) the manifestation of atrial depolarization on the surface ECG and therefore cannot be due to the spike potential of the sinus node that occurs 20-25 ms before the appearance of wave R. Thus, low-amplitude negative potentials on the surface of the torso are recorded in the time interval when the electrical processes in the heart due to the previous excitation of its structures have already ended (according to existing ideas [2]) but ones which are due to the next cycle in excitement has not yet begun.

*Principal corresponding author
Email address: `tredexcompany37@gmail.com`
(Alexander V. Kramarenko)

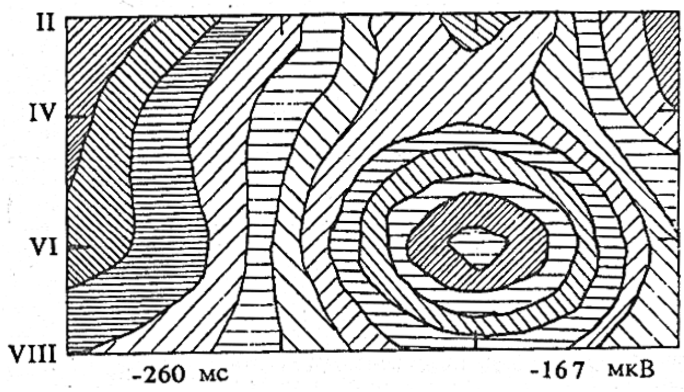

Figure 1: Isopotential map of signal averaged ECG at the moment which is 260 ms earlier than the peak of the $rU1$ wave in a 35-year-old man having aortic insufficiency. The rectangular ECG field corresponds here to the part of the torso which is bounded on the right and on the left by the right posterior axillary line and the left paravertebral line, respectively. The intermediate lines are the right sternum and the left front axillary. The upper boundary of the map is level II of the intercostal space, the lower boundary is the VIII intercostal space, the intermediate ones are the levels of IV and VI intercostal space. Therefore, right anterolateral, left anterior and left posterolateral regions are determined on the ECG map starting from right margin. More fine detailing of the isopotential map regions is possible using the anatomical landmarks. A zone of negative potentials is located in the lower third of the left anterior region with propagation to the lower left posterolateral sections of the torso 260 ms before the peak of the $rU1$ wave. The zone of the most negative peak value of the potential is localized in the lower left front region and reaches a value of $-167\ \mu$V

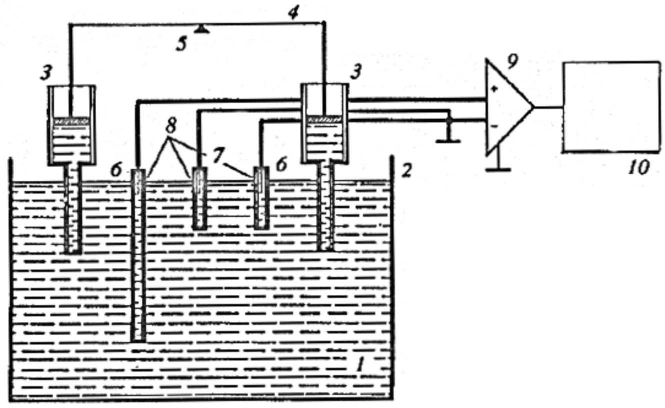

Figure 2: The experimental setup. Explanations in the text

In this regard, it can be assumed that the registered phenomenon is due to the peculiarities of intracavitary blood movement. Aortic insufficiency has a specific feature of central hemodynamics in the diastole. It is the presence of a retrograde blood stream because of the defect in the valve apparatus. This stream appears due to a high aortic-ventricular gradient of pressure. It has a significant acceleration that varies over time. In other words, in the diastole phase in the heart there is a retrograde flow of the solution of electrolytes which the blood is.

2. Experimental

In order to experimentally confirm the possibility of the occurrence of electrical phenomena in a liquid solution of electrolytes during the existence of a jet inside it, the potential difference between two points of the solution was recorded.

The appearance of the experimental setup is shown schematically in figure 2. Piston pumps *3* are immersed in an aqueous 0.9% sodium chloride solution *1* located in a glass cuvette *2*. They contain the same solution and interconnected by a beam *4* that rotates about the axis *5*. Pumps are designed to create a short-term jet inside a resting bulk solution and maintain its volume unchanged. Gold recording *6* and grounding *7* electrodes are placed in the solution. They are enclosed in polystyrene (DC resistance of at least 1 GOhm) tubes *8* of various lengths filled with the same solution. A differential chopper amplifier *9* is used to record the response signals. An amplifier we specially designed has an input DC resistance of more than 1 GOhm and 2×20 MOhm input impedance at 30 Hz frequency. Its passband (at the level of 0.7) is 0.3-30.0 Hz and it has a peak-to-peak input noise of 330 nV. From the output of the amplifier the signal is fed to a storage oscilloscope *10*.

In order to eliminate the polarization potential and electrochemical EMF (which could be caused by impurities in the solution) some preliminary steps were taken before the experiment. The polarization potential was controlled by an additional chopper amplifier (which is not shown in the diagram) having an input impedance of 2×20 MOhm. The experiment has been carried out only when the polarization potential of the cell did not exceed 10 μV. Immediately before the start of registration, a low-noise resistor of 20 MOhm was connected to the measuring (recording) electrodes. It shunted the electrodes at frequencies close to zero and matched the cell with the line at frequencies close to 30 Hz. In order to eliminate the Earth's magnetic field influence, the signal has been recorded twice in north-south and west-east orientation of the installation.

After stabilizing the installation and achieving a stable zero line position on the oscilloscope screen, the solution was pumped in one of the directions. Hence, a short-term (0.1 s) flow in the resting bulk solution has appeared while the solution level in the cell remained permanent due to the reverse movement of the second piston. The jet diameter at the exit point was 2 mm. The maximum response of the recording device at the time the jet appeared in the resting bulk electrolyte solution was approximately 180 μV, the signal recorded appearance is shown in figure 3.

3. A simple theoretical model

The considered sodium chloride is a strong electrolyte, a characteristic feature of which is the complete electrolytic dissociation of a substance dissolved in water. When an external electric field is applied to the solution of electrolyte, the ordered movement of hydrated ions arises. Ion velocities in a viscous medium are different due to the unequal size of the hydrated ion shells. A similar difference in ion velocities is also observed in the case of uniformly accelerated (or decelerated) motion of them because of external mechanical forces.

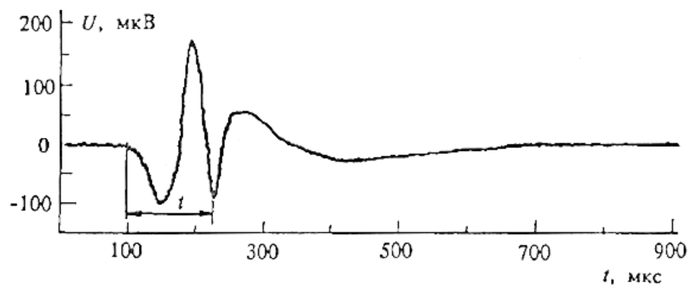

Figure 3: The appearance of the output signal. 2 ml of liquid electrolyte solution having density of ∼1 g/ml has been pushed out by the movement of the piston. This volume of solution passed through 2 mm diameter pump output hole for a time t = 0.1 s with a linear velocity of ~64 cm/s. It lead to potential difference of 180 μV between the measuring electrodes

Let us consider the rectilinear motion of an ion having a mass m with velocity v in a liquid medium. Motion going on due to the force F directed along the vector of motion. The friction force (due to viscosity) and the drag force (which acts on the ion “front surface”) both counteracts ion motion. We can express both of these forces like some velocity function $\phi(v)$. Thus, the ion moves in liquid due to the force F with acceleration determined from the equation:

$$m\frac{dv}{dt} = F - \phi(v). \tag{1}$$

At the initial moment of time, $v = 0$ and $\phi(v) = 0$. Therefore, the ion begins to move with acceleration equal to

$$\frac{dv}{dt} = \frac{F}{m}. \tag{2}$$

Over time, the acceleration will decrease to

$$\frac{dv}{dt} = \frac{F - \phi(v)}{m} \tag{3}$$

and finally, at velocity equal to v_0, the forces will be equal:

$$F = \phi(v_0),$$

acceleration will turn to 0 and the ion will move at a certain constant velocity. However, in the time interval when the ions move uniformly accelerated (due an external force), the more mobile ions will be displaced relatively to less mobile ones by a some length equal to ξ in the direction of the force F. At this point, there will be an electrostatic interaction of negative and positive charges within the Debye radius [3]. In accordance with the d’Alembert equation, the second derivative of the electrostatic field potential of these charges will be equal to [4]:

$$\frac{\partial^2\phi}{\partial x^2} = -\frac{\rho}{\varepsilon_0}, \tag{4}$$

where ρ is the volume charge density; ε_0 is the dielectric constant of the medium. Expressing the volume charge density in a liquid electrolyte as

$$\rho = -q_0 n\frac{\partial\xi}{\partial x}, \tag{5}$$

where q_0 is the ion charge; n is the concentration of ions in solution; dx is the layer thickness, finally we have:

$$\frac{\partial^2\phi}{\partial x^2} = -\frac{q_0 n}{\varepsilon_0}\frac{\partial\xi}{\partial x}. \tag{6}$$

After integration we get:

$$\frac{\partial\phi}{\partial x} = -\frac{q_0 n}{\varepsilon_0}\xi + C, \tag{7}$$

where C is determined from the condition that for $\xi = 0$ the potential gradient is 0, i.e. $C = 0$. Hence the field strength

$$E_x = -\frac{\partial\phi}{\partial x} = -\frac{q_0 n}{\varepsilon_0}\xi, \tag{8}$$

and, correspondingly, the ion force is:

$$F_x = -q_0 E_x = -\frac{q_0^2 n}{\varepsilon_0}\xi. \tag{9}$$

Neglecting the viscosity forces, one can write the equation of ion motion like:

$$m\frac{\partial^2\xi}{\partial t^2} + \frac{q_0 n}{\varepsilon_0}\xi = 0. \tag{10}$$

The solution to this equation has the form [5]:

$$\xi = \xi_0 e^{-j\omega_0 t}, \tag{11}$$

where:

$$\omega_0 = q_0\sqrt{\frac{n}{\varepsilon_0 m}} \tag{12}$$

In other words, because of an external force F directed towards the movement of ions, longitudinal electrostatic waves arise due to ion vibrations in a liquid electrolyte solution. These waves are inherently similar to Langmuir waves arising in a plasma [4]. In this case, the potential change rate in a liquid electrolyte is equal to:

$$\frac{\partial\phi}{\partial x} = \frac{q_0 n}{\varepsilon_0}\xi = \frac{q_0 n}{\varepsilon_0}\xi_0 e^{-j\omega_0 t}. \tag{13}$$

Taking into account the thermal motion of ions, a change in the volume charge density has the form:

$$\frac{\partial\rho}{\partial x} = q_0 n\frac{\partial^2\xi}{\partial x^2}, \tag{14}$$

and interaction force is equal to:

$$f'_x = 3kT\frac{\partial^2\xi}{\partial x^2}, \tag{15}$$

where k is the Boltzmann constant, T is the temperature, K.

Then ion motion equation can be rewritten as follows:

$$m\frac{\partial^2\xi}{\partial t^2} + \frac{q_0 n}{\varepsilon_0}\xi - 3kT\frac{\partial^2\xi}{\partial x^2} = 0. \tag{16}$$

If denote

$$\alpha = \frac{3kT}{m} \tag{17}$$

and

$$\omega_0^2 = \frac{q_0 n}{\varepsilon_0} m, \tag{18}$$

then equation (23) can be represented as:

$$\frac{\partial^2 \xi}{\partial t^2} - \alpha \frac{\partial^2 \xi}{\partial x^2} + \omega_0^2 \xi = 0. \tag{19}$$

Its solution has the form [5]:

$$\xi = C e^{j(kx - \omega t)} \tag{20}$$

where

$$k = \sqrt{\frac{\omega^2 - \omega_0^2}{\alpha}}. \tag{21}$$

The phase velocity of the wave is:

$$v_0 = \left[\frac{\alpha}{1 - \left(\frac{\omega_0}{\omega}\right)^2} \right]^{1/2}. \tag{22}$$

From (22) it is seen that the phase velocity depends on the frequency ω, i.e. in this case, conditions arise in the medium that lead to the appearance of frequency modulation of the field potential. Finally, taking into account the influence of viscous forces, the equation of motion of the ion will have the form:

$$m \frac{\partial^2 \xi}{\partial t^2} - \beta \frac{\partial \xi}{\partial t} + \frac{q_0 n}{\varepsilon_0} \xi - 3kT \frac{\partial^2 \xi}{\partial x^2} = 0. \tag{23}$$

Its solution is as follows [5]:

$$\xi = C e^{-kt} e^{j(kx - \omega t)} \tag{24}$$

Thus, the displacement of charges because of external mechanical force is a damped oscillatory process.

4. Discussion

For the case under consideration, the flow rate of liquid electrolyte solution in the pump output hole can be found as:

$$v_0 = \frac{\partial m / \partial t}{d \frac{\pi D^2}{4}} \tag{25}$$

where $\partial m / \partial t$ is the rate of decrease in mass; d is the density of the solution; D is the diameter of the jet at the exit. For a model experiment we have:

$$v_0 = \frac{2.0/0.1}{1 \frac{\pi (0.2)^2}{4}} \approx 64 \text{ cm} \cdot \text{s}^{-1}.$$

In the present experiment, the accurate measurement of potentials observed was not aimed, since the elements of the experimental setup do not simulate the cardiovascular system. But the order of magnitudes can be approximated for a more realistic model. Having taken the stroke volume of the expelled blood equal to 100 ml, the aortic diameter equal to 3 cm and considering the blood density approximately equal to 1 g/ml, we are able to calculate the jet velocity at the time of expulsion from the left ventricle. According to (25):

$$v_0 = \frac{100/0.3}{1 \frac{\pi (0.3)^2}{4}} \approx 47 \text{ cm} \cdot \text{s}^{-1}.$$

Moreover, in humans, the acceleration of blood at the beginning of the stage 4 (ejection) reaches 1900 cm $\cdot$ s^{-2} [6]. In a healthy awake dog, the peak value of velocity can reach 1000 cm $\cdot$ s^{-1}, and the peak value of acceleration is 5-10 g [6]. Thus, with real heart contraction, conditions are created that lead to the spatial redistribution of ions having different mobility in the blood ejected. The occurrence of such a redistribution of electric charges leads to the appearance of signals on the surface of the body. They usually are recorded and recognized as electrocardiographic ones, being superimposed on cardiomyocytes excitation signals. In other words, the surface ECG has a hemodynamic contribution that can be extracted from the original summary cardiac signal (SCS) to reflect the peculiarities of intracardiac hemodynamics.

The hemodynamic aspect of surface ECG waves formation problem has not been considered in the past. Moreover, the separation of the hemodynamic contribution to the SCS cannot be performed due to overlapping spectra of the myocardial and hemodynamic contributions to the signal and their coincidence in time (in accordance with the main provisions signal separation theory). The latter is true if a hemodynamic-related signal occured within a time interval corresponding, according to modern concepts, to excitation of the heart.

In the present work, separation of low-amplitude negative potentials during the stage 2b (inflow, slow filling of the ventricles) was possible, since both contributions to the SCS are separated in time. An *in vitro* experiment confirmed the existence of electrogenic properties in a blood moving with changing acceleration and allowed us to associate the observed phenomenon with this effect.

The complex zonal structure of the regions of negative potential recorded and the features of its evolution are apparently associated with the peculiarities of intracavitary movements of blood masses during aortic insufficiency. This structure characterizes the properties of retrograde blood flow.

Without touching the biochemical side of the issue, we would note that in diastole, together with a mechanical movement of the whole heart, the displacements of conductive fluid occur. They are characterized by significant linear velocities and variable accelerations, in view of the complex spatial organization of the cavities. It is unlikely that such processes would not be reflected on a surface ECG. The identification of the described phenomenon confirms the foregoing and allows us to state that a significant contribution to the origin of surface potentials is made by intracavitary blood. Such blood pumped over during the different phases of the cardiac cycle acts not only as a transmission factor but as a generating one. In other words, the transferred intracavitary blood has electrogenic properties, the contribution of which must be taken into account when considering the formation of a surface ECG.

5. Conclusions

1. Low-amplitude slowly varying negative potentials (relative to the central Wilson terminal) recorded during the stage 2b (inflow, slow filling of the ventricles) on the torso surface in patients with aortic insufficiency, reflect the electrogenic properties of blood moving with variable acceleration.
2. Distributions of potentials on the surface of the torso during the stage 2b and their evolution over time in patients with aortic insufficiency reflect the features of intracavitary movements of blood masses.
3. The origin of the atrial and ventricular complexes of the surface ECG is due to both myocardial contribution and electrogenic effect of the moving intracavitary blood because of its changing acceleration.
4. The investigation of the electrical aspects of cardiac hemodynamics will provide information on intracardiac blood flow based on the analysis of surface electrocardiograms.

References

[1] E. Lepeshkin, Vlijanie fiziologicheskih uslovij na faktory peredachi, svjazyvajushhie toki serdca i potencialy na poverhnosti tela, in: M. Gezelovic, K. V. Nelson (Eds.), Teoreticheskie osnovy jelektrokardiologii, Medicina, 1979, pp. 168–196.

[2] R. K. Barr, Fiziologija i patofiziologija serdca, volume 1, Medicina, 1990, p. 214.

[3] L. D. Landau, V. M. Livshic, Statisticheskaja fizika, Gostehizdat, 1951.

[4] S. V. Belljustin, Klassicheskaja jelektronnaja teorija, Vysshaja shkola, 1971.

[5] J. Kemke, Spravochnik po obyknovennym differencial'nym uravnenijam, Fizmatgiz, 1961.

[6] C. G. Caro, T. J. Pedley, R. C. Schroter, W. A. Seed, The Mechanics of the Circulation, Oxford University Press, 1978.