ELECTRICAL IMPEDANCE METHODS FOR THE MEASUREMENT OF STROKE VOLUME IN MAN: STATE OF ART

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Abstract — Electrical impedance methods used in practice for stroke volume estimation, though having advantageous features, have their weaknesses, too. In the paper a survey of the methods is given with respect to improvement them using computer simulation and advanced signal processing. As well the Kubicek and Sramek methods as the Tischenko method are shown to be considerably empirical and unsuitable for such kind of modernisation. Improvement of electrical impedance methods for stroke volume estimation would be realised by using new technique - electrical impedance tomography.

Key words — impedance plethysmography, impedance cardiography, impedance tomography, bioimpedance, integral rheography, stroke volume, cardiac output, Kubicek method, Sramek method, Tischenko method

Introduction

Electrical impedance methods are based on measurement of the electrical impedance (i.e., the modulus of the full complex resistance) of the human body or its parts at sub-high frequency (20...200 kHz). It has been found that the impedance of body pulses in synchronism with the heart. This pulsation is the origin of impedance plethysmogram. Amplitude of the impedance plethysmogram comprises about 1/1000 ... 1/100 of the mean value of the observed impedance. Such a phenomenon is explained as a result of an impact of pulsation of blood content in tissues on the electrical resistivity of the tissues (Nyboer et al. 1950). Besides, considerable effect of changing the resistivity of blood itself with its linear velocity is detected (Moskalenko et al. 1959, Liebman et

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al. 1968, Dellimore et al. 1975), too. Several methods have been developed on the basis of described phenomenon for estimation of the volume flow of blood in different organs or parts of the body.

The beginning of use of the electrical impedance methods for the observation of physiological phenomena was in the second half of the 1930ies in Germany. Afterwards these ideas have spread to Austria, Russia, USA etc. The first actual model of genesis of the impedance plethysmogram was proposed by Jan Nyboer (Nyboer et al. 1950). He has derived a formula for calculation of the increment of blood volume $\Delta V$ from the corresponding decrement of electrical impedance $\Delta Z$ for the case of a cylindrical region of body (like arms or foots) that we can write as follows:

$$\Delta V = -\frac{\rho L^2}{Z^2} \Delta Z.$$  \hspace{1cm} (1)

Here $\rho$ is the resistivity (more exactly, the specific impedance) of blood, $L$ is the of the cylindrical section of body included into the measurement circuit (equated to the distance between the measurement electrodes). $Z$ is the mean value of the measured impedance.

(1) assumes the so-called parallel conductor model (Shimazu et al. 1982, Patterson 1989) of the impedance plethysmogram genesis: 1) the impedance change is assumed to be caused only by delivery of an additional amount of blood to the measurement region, 2) the additional blood volume in its turn is assumed to form a cylindrical region that electrically is connected in parallel with the main one.

As described above, $\Delta V$ and $\Delta Z$ vary with time quasi-periodically, $\Delta V = \Delta V(t)$, $\Delta Z = \Delta Z(t)$, having the frequency of the heart. $Z$ drifts slowly and, besides, changes typically in synchronism with breathing, $Z = Z(t)$. Thus Nyboer has introduced splitting the time course of the measured impedance into two additive components

$$Z(t) = Z(t) + \Delta Z(t) \hspace{1cm} (2)$$

having different magnitudes and different spectra.

Later W.G. Kubicek and co-authors used the basis founded by Nyboer to derive their method for estimation of the *stroke volume* (SV), i.e. volume of blood, put out by a ventricle of the heart during a contraction cycle. In the USSR M.I. Tischenko put forward his own method to do it, following the Russian tradition of impedance plethysmography (called *rheography*). Whilst having some non-principal modifications, these two methods remain as the main electrical impedance methods for estimation of stroke volume (and *cardiac output*, close connected with it) up to nowadays. In similar manner
Figure 1. Arrangement of electrodes at the recording of the electrical impedance for SV estimation: a - the Kubicek impedance cardiography, b - the Sramek bioimpedance method, c - the Tischenko integral rheography.

various methods for measurement of local (organ) blood flows were proposed.

The Kubicek method

This is an electrical impedance method for the estimation of the stroke volume. It was developed in the middle of 1960ies by a group, leader of which is considered to be William G. Kubicek, and was named impedance cardiography (Kubicek et al. 1966, 1970; see Patterson 1989). The Kubicek method constituted a new quality at its time of come out: a new technical solution and an advanced (relative to that time) signal processing algorithm were introduced.

Up to that time bridge circuits were used for impedance measurement in the impedance plethysmography. Kubicek’s co-author Robert Patterson developed the impedance cardiograph where four-electrode technique (Fig. 1.a) was used. This technique would enable to minimise the noise caused by variation of electrode-to-skin contact resistance due
to movements of patient. Special band electrodes put around the body were introduced. As the output impedance of the current source and the input impedance of the voltage amplifier can be very high, the changes of the contact resistance would affect not to the measurement current nor to the measured voltage.

The band electrodes later have came under criticism (Sramek 1986). Indeed, using of the band electrodes could replace the old mechanism of noise generation with another. Namely, in case of a non-uniform distribution of the contact resistance between the band and the body, the area of the best contact (the effective centre of location of the electrode) can drift on the surface of the body under the band. This will cause noise, because the effective location of the current leading electrodes or the position of the potential electrodes relative to the equipotentials will change. (This defect would be eliminated, if we divided the bands into several less electrodes and connected each of them with the lead cable by proper resistors.)

In case of perfect contact between the body and the band electrode, the band would enable to unify the distribution of potentials on the surface of body. Thus in this ideal case it makes for use the cylindrical conductor model of the body. But the calculation formula of the Kubicek method is just based on the cylindrical conductor model: the Nyboer's formula (1) has been boldly applied to such a complicated region as the thorax. This approach will be discussed further.

A typical Kubicek impedance cardiogram $\Delta Z=\Delta Z(t)$ of a normal healthy man is shown on Fig. 2, curve a. Here traditional inverse depiction is used where the direction of $Z$ increase is downward. Fig. 2, curve b represents its time derivative $dZ(t)/dt$, in inverse depiction too. Traditionally (Lababidi et al., 1970) its characteristic points are labelled as shown here.

![Figure 2. The Kubicek impedance cardiogram of a normal healthy man (curve a) and its time derivative (curve b). Curve c represents ECG R-wave timing pulses.](image-url)
The ideology of the Kubicek method includes the so-called Kubicek's (it ought to be called Patterson's) extrapolation. It tries to take account of outflow of blood from the measurement region (that takes place in the same time as the cardiac ejection occurs). The original justification of the Kubicek's extrapolation by its authors (Kubicek et al. 1966; Patterson 1989) was poor. The extrapolation consists an expedient to calculate, on the basis of the measured signal, the magnitude of the full impedance decrement $\Delta Z_{SV}$, that ought to correspond to the stroke volume:

$$\Delta Z_{SV} = \min_{t \in \text{Cycle}} \frac{dZ(t)}{dt} \cdot T_E .$$

Here $T_E$ is duration of heart ejection (that can be estimated using as well impedance as non-impedance methods, for instance phonocardiography), $dZ(t)/dt$ is time derivative of the registered impedance, formula (3) contains its minimum (peak) value for the heart cycle in operation. Putting into (1) the impedance decrement from (3) one gets the Kubicek formula for the calculation of stroke volume $\Delta V_{SV}$ (Kubicek et al. 1970):

$$\Delta V_{SV} = -\rho L^2 \frac{dZ(t)}{dt} \cdot T_E .$$

In practice impedance cardiograms often are registered at breathing, therefore breathing component is present in records then. Differentiation suppresses the lower frequencies of spectrum, thus the breathing component is significantly suppressed in $dZ(t)/dt$ signal. That is why in case of the Kubicek method breathing influence has much less effect than in any method that uses the amplitude of the impedance plethysmogram itself.

The Kubicek's extrapolation is one of the weakest elements of the ideology of the Kubicek method. The work by Rubal and co-authors (Rubal et al., 1980) suggests that as the second multiplier of the product on the right side of (3) is the duration of the heart ejection period, therefore the success of the Kubicek's extrapolation must be caused by existence of a correlation between the peak value of $dZ(t)/dt$ and the maximum flows in the aorta and, perhaps, in the pulmonary artery. Furthermore, it has been speculated (Sramek 1986, Ovsyshcher et al. 1993) that the wave form of the time derivative of the Kubicek impedance cardiogram is to certain degree similar to the flow wave forms in the named arterial vessels. The Kubicek's extrapolation seems to have its
success due to this fortunate, however irregular and uncomplete, similarity.

Absolute calibration of the Kubicek impedance cardiography is a widely discussed aspect of the method. In their first publications (Kubicek et al. 1966) the authors of the method suggested a constant empirical calibration coefficient of value 0.9 in the calculation formula. Further the location of the lower potential electrode was shifted 2 cm upward and was canonised at the level of xiphoid joint (Kubicek et al. 1970). Thus the calibration coefficient was omitted in the calculation formula. Boer and colleagues have shown (Boer et al. 1979) that the value of SV calculated according to Kubicek highly depends (for the lower electrode about +4.5% per cm) on the distance between the potential electrodes if they are shifted away from the canonical locations, even in case of the same patient at the same state. Thus we can conclude that the absolute calibration of the Kubicek method is empirical and the calculation formula does not evidently contain any calibration coefficient only due to suitable choice of the location of the lower potential electrode. Boer's result shows, besides, that one will easily get erroneous absolute values of SV if one does not accurately locate the potential electrodes. If the Kubicek formula (i.e., the cylindrical parallel conductor model) was more valid then such a dependence on the distance between the electrodes would not appear. It would be natural for the cylindrical conductor that the characteristics of the measured impedance and the distance between the electrodes changed in accordance with each other so that one could get the same SV estimat, independent of the deviations of the distance between the potential electrodes.

More than 20 years after designing the Kubicek impedance cardiography Robert Patterson published (Patterson 1989) his opinion formed about the method. Patterson presented data recorded in animal experiments. These data suggest that the Kubicek impedance cardiogram is determined as well by hemodynamic processes in systemic circulation as by processes in pulmonary circulation. (This fact has been clearly demonstrated yet before (Geddes et al. 1972).) Furthermore, the contributions of the both vary with individual anatomical and physiological characteristics. Naturally the heart has its contribution, too. Thus it can be concluded that the Kubicek impedance cardiogram constitutes only an integral view to a complex of complicated processes in a complicated spatial area, whereby a considerable number of characteristics or parameters describing the contributions of different processes are individually determined.

As the SV value is of great clinical importance and there is scarcely any other non-invasive method for its continuous measure-
ment, a great number of clinical evaluations of the Kubicek impedance cardiography have been carried out (see Ovsyshcher et al. 1993). Started by the authors of the Kubicek method, comparisons of the method with other (mostly invasive) methods were carried out and various contingents were studied.

A quite wide range of correlation coefficient $r$ values for the impedance cardiography and the comparative methods can be obtained in publications: $r = 0.4...0.99$. In typical evaluations $r$ was found to be $0.7...0.94$.

The evaluations suggest that the method is plausible in case of normal healthy adults. But there are shortcomings in critically ill ventilated patients, in pregnant, and difficulties or dissonances in children with intracardiac shunt, in adults with valvular regurgitation and low cardiac output. **Thus just the patients who most need careful watching for cardiac output cannot be reliably treated with the impedance cardiography method.** Comparing Fig. 3 to Fig. 2 one can see an example of differences between a patient's and a healthy man's impedance cardiograms that can cause difficulties.

Besides, one must notice that the evaluations have been carried out using correlation (i.e., statistical) methods. This fact reinforces opinion that **there is no individual measurement of the value of SV with the impedance cardiography method yet but only statistically fitted estimation.** It is generally considered that the existing impedance cardiography can rather serve for continuous watching the relative dynamism of SV than for sparse or single measurements of its absolute value.
To improve the diagnostics and watching for the cardiovascular patients who have their individual (unknown in advance) peculiarities, physicians would have something more reliable.

**Modifications of the Kubicek method**

**The Sramek method**

As the Kubicek method has certain shortcomings, several attempts to improve it were undertaken. Most of such modifications have little popularity. There are attempts to better account the individual dimensions of body (Storozhenko et al. 1983) caused by experience indicating such kind of lack in the Kubicek method. Location of the electrodes has undergone a non-principal modification (Pushkar' et al. 1977): the upper current electrode has been recommended to put around the head. As (4) includes blood resistivity $\rho$ as a scaling factor, methods are introduced to count its value from the individual blood test data (Mohapatra et al. 1977).

Since the Nyboer's formula (1) is significantly simpler if expressed not for the impedance $Z$ but for its reciprocal value $Y = 1/Z$ (named admittance), a modification named *admittance plethysmography* was introduced (Ito et al. 1976, Shimazu et al. 1982). If admittance is measured then the mean value of it will not be needed for SV calculation. But the equipment for this modification is technically more complicated.

There are several versions of the impedance derivative peak value measurement. The authors of the Kubicek method suggested to measure the C-wave (*Fig. 2*) amplitude from the zero line of the derivative. Lababidi and co-authors have recommended (Lababidi et al. 1970) to measure it from the B point level of impedance cardiogram. As this can be difficult because the B point is hardly detectable there is a version of measurement it from the X point level, with posterior appropriate calibration (Zhang et al. 1986).

**The Sramek method** constitutes an essential modification of the Kubicek method. It was proposed by B. Bo Sramek and co-authors in 1980ies (Sramek 1986) and it is called *bioimpedance technology* by them. There were reasons why this method has been proposed and has gained acceptance. The first reason is the described above lack of band electrodes which causes unexpected noise. To eliminate it, spot electrodes (like used for ECG) were introduced. They are put in 8 points on the lines where the band electrodes were laid, in convenient places on the both sides (*Fig. 1.b*).
The second reason of modification was difficulty with the resistivity (specific impedance) of blood. It is quite unhandy to measure the resistivity of patient’s blood (or haematocrit, for regressive calculation of resistivity). Sramek and co-authors have succeeded to avoid this need.

By splitting the square of basis impedance in (4) into product $Z^2 = Z \cdot \bar{Z} = \rho \cdot L/S \cdot \bar{Z}$, they got a volume-dimensional coefficient in the formula. It was declared to be an individual parameter (i.e., calibration coefficient) and was named **volume of electrical participating tissue** $V_{EPT}$. Using statistical and experimental data, a regression has been estimated:

$$V_{EPT} = \frac{P}{P_{IDL}(H)} \cdot \frac{(0.17H)^3}{4.2}$$

(5)

Here $P$ is the actual weight of the patient, $P_{IDL}(H)$ is its ideal value (“ideal weight”), that is a function of patient’s height $H$. Function $P_{IDL}(H)$ is different for men and women, it must be corrected on the constitutional type of the patient.

The formula for the calculation of stroke volume $\Delta V_{SV}$ in case of the Sramek method looks following:

$$\Delta V_{SV} = -\frac{V_{EPT}}{Z} \cdot \min_{\text{recCycle}} \frac{dZ(t)}{dt} \cdot T_E$$

(6)

Though the method has useful advantages (does not need determination of $\rho$, $L$), it seems to be a step towards the fully-regressive estimation of SV on the basis of only anthropometrical data. Thus we could get only mean statistical estimates but not individual measured values for the concrete person with his/her possible pathology.

As the formula (6) contains only the first power of $Z$, it may have dependence on the misplacement of electrodes that is different (and possibly more favourable) from the Kubicek’s one.

About the spot electrodes R. Patterson has noted (Patterson 1989): “Past work attempting to use spot electrodes on thorax to measure directly ventricular volume produced a much variable signal [than in case of the Kubicek method, I.V.] and, therefore, consistent quantitative results could not be obtained. Reproducibility continues to be one of the outstanding features of the band-electrode arrangement.”

Yet the modifications introduced by Sramek do not change the general character of impedance cardiography. **In this version the im-**
pedance cardiography even more constitutes a half-empirical method that enables only statistically calibrated SV estimation.

The Tischenko method

The method was developed by M.I. Tischenko in the beginning of 1970ies (Tischenko 1973, Tischenko et al. 1973). By the author it was named integral rheography. This designation refers to fact that this method comprises the whole human body as the object of measurement. A pair of connected together electrodes is put onto the limbs around the ankles and another similar pair is put onto the arms around the wrists (Fig. 1.c). The impedance between the wrists and the ankles is measured. The author of the method considered important some technical details that we now may conceive as non-principal. For instance, the original method prescribes using a bridge circuit, the measurement frequency has to be equal to 30 kHz.

The integral rheogram slightly differs from the Kubicek impedance cardiogram (compare Fig. 4 to Fig. 2). But the general forms of the both are quite similar. Therefore one can conclude that the main mechanism of genesis ought to be the same in the both cases. Tischenko himself considered his method to be an integral view of processes in the large blood vessels. We should agree with him.

![Figure 4. The Tischenko integral rheogram (curve a) of a normal healthy man (the same person as on Fig. 2) and its time derivative (curve b). Curve c represents ECG R-wave timing pulses.](image)

The Tischenko method offers formulae for calculation several physiological indices of man. For instance, the amount of extra-cellular liquid can be calculated. But the main aim of the method is to enable the SV estimation.
The SV calculation ideology is based on the Nyboer’s formula (1) again. This time it is applied to the longitudinal tubes in the human body: the large blood vessels - the aorta and arteries. In distinction to the Kubicek method, no sophisticated expedient to account the venous outflow is taken. The amplitude of the impedance pulse serves as the indicator of SV. It must only have an appropriate calibration. If the designations introduced above are used, the initial theoretical formula for SV calculation according to Tischenko will look as follows:

\[
\Delta V_{SV} = -\frac{T_C}{K T_D} \cdot \frac{\rho L^2}{Z} \Delta Z_{\text{MAX}}
\]

Here \(\Delta V_{SV}\) means the stroke volume, \(L\) is the distance between the foot and the arm electrodes measured along the main arteries, \(T_C\) is the duration of heart cycle, \(T_D\) is the duration of the catacrotic (“falling”, if the traditional inverse depiction is used) part of impedance curve, \(\Delta Z_{\text{MAX}}\) is the maximal impedance decrement, \(Z\) is the mean value of impedance, \(\rho = 150 \ \Omega \cdot \text{cm}\) is fixed value of blood resistivity, \(K\) is an empirical calibration coefficient.

The initial formula has been transmuted further. Though \(K\) varied in experiment in quite wide range (\(K = 0.27 \ldots 0.44\)), the author of the method has found a strong correlation (\(r = 0.985\)) between \(K\) and \(Z\), such that \(K \cdot Z = 100 \ \Omega\). So the power of \(Z\) has been reduced and a newly combined calibration coefficient has been introduced. Another transmutation has been done due to the length \(L\) of the longitudinal arterial tubes that had to be accounted. As this length correlated with the height \(H\) of person, corresponding regression has been built into the calculation formula. The regression obtained for men differed from the one got for women and therefore the resulting practical formula can be presented as follows:

\[
\Delta V_{SV} = k \cdot \frac{H^2}{Z} \frac{T_C}{T_D} \frac{\Delta \zeta_{\text{MAX}}}{d \zeta/dZ},
\]

where \(k = 2.75 \ \text{cm}\) for men and \(k = 2.47 \ \text{cm}\) for women. Following the original publication (Tischenko 1973), the formula (8) is given here in a form proper for manual handling of plotted records. Thus \(\Delta \zeta\) is deviation of the plot of impedance from its base line and \(\Delta \zeta_{\text{MAX}}\) is the amplitude of the rheogram (measured in cm, for instance), \(d \zeta/dZ\) is the sensitivity of recording system (correspondingly in cm/\(\Omega\)). By the
The sensitivity was prescribed to estimate for every measurement, turning on a special calibrating resistor.

The explicit use of calibration here seems to be caused by the bridge measurement technique. The apparatus may be unstable and bridge would change its sensitivity with changing the individual mean impedance of body. However, the method can be realised using the four-electrode technique as well.

One can notice a similarity between the formulae (6) and (8) in the next sense: 1) unlike the Kubicek formula (4), $Z$ is in the first power in the both, 2) the distance between the main electrodes is reduced (using statistical regression) to some usually measured anthropometrical data. The priority of this art evidently belongs to Tischenko.

All the foregoing demonstrates that the Tischenko method has qualitatively the same level of physical and physiological justification and is as well empirical and statistical as the Kubicek's and Sramek's ones.

As for comparative studies of the Tischenko method with other methods, there are quite few investigations. For instance, the author of the method has been compared it to the direct Fick method (resultant correlation coefficient was $r = 0.99$, $n = 28$ patients have been involved), to acetylene rebreathing method ($r = 0.84$, $n = 31$, healthy people) and to thermodilution method ($r = 0.95$, $n = 25$, patients) (Tischenko et al. 1973). The correlations look very good but there are too few investigations. While there are hundreds of investigations of the Kubicek method, the number of investigations of the Tischenko method seems to be several tens times less. Hence the weak points of the Tischenko method can be not found yet.
We saw above that the practical electrical impedance methods for SV measurement are still staying as half-empirical. The model of electrical conduction used is the Nyboer's parallel conductor model for a cylindrical region. Only rough depiction of haemodynamics is assumed. The modifications introduced have not changed this general character but only some details.

From the viewpoint of a biomedical engineer a following task could be set: to develop a model that with sufficient precision described the genesis of signal in case of any impedance plethysmographic method. This model must include co-operating model of haemodynamics and model of electrical conduction of the watched part of human body. If building of such a model for any existing method of SV estimation is impossible or too difficult, a new method of measurement must be developed. Then with the help of the model it would be possible to improve the methods for SV or blood flow estimation. A preliminary attempt of such approach exists already (Girling et al. 1979).

Simulation of the human circulation has intensively developed during last decades. Successful models of arterial haemodynamics have been built (Burattini et al. 1989, Campbell et al. 1990). There are hopeful attempts of simulation of overall circulatory dynamics in man, including arterial, cardiac and pulmonary dynamics of blood (Hardy et al. 1982, Vedru 1988). (However, venous haemodynamics has still remained a difficult to simulate subject because of its irregularity and individuality.)

Several attempts to develop conduction models for the impedance plethysmography have been done, mainly in connection with the Kubicek method. Simulation investigations of the distribution of electrical current in human thorax were carried out. Knowing the current distribution one can find contributions of different parts of the thorax and internal organs to the impedance plethysmogram.

Let us suppose the very complicated resistivity $\rho$ or conductivity $\sigma = 1/\rho$ distribution in the human body to be known. As the current density in a volume conductor is determined by the local value of the conductivity and the distribution of the electrical potential $\phi$, the problem above will be solved by finding the potential distribution. This problem, the direct problem of electrical impedance plethysmography, is well-known and has been solved by physicists in principle. The un-
known potential $\varphi$ must satisfy the following partial differential equation

$$\sigma \Delta \varphi + \nabla \sigma \cdot \nabla \varphi = 0$$

under the Neumann-type boundary condition

$$\sigma \frac{\partial \varphi}{\partial n} = j$$

on the surface of the body. Here $j$ is the density of external electric current that is led to the surface of the conductive region ($j \neq 0$ only under the electrodes). The conductive object (i.e., human body) constitutes a closed 3-dimensional region having complicated distribution of conductivity $\sigma$. Using finite elements or difference methods has enabled to solve numerically the direct problem for suitably simplified models (Patterson 1985, Kosicki et al. 1986, Kim et al. 1988).

Such investigations have shown that almost all the regions of the thorax do have considerable contribution to the Kubicek impedance cardiogram. Besides, the contribution of the blood movement to impedance cardiogram has been investigated by simulation. It occurred (Kosicki et al. 1986, Kim et al. 1988) to have about same magnitude as the contributions of dilatation of large blood vessels, lung and heart volume changes.

This result accords with the experimental findings referred above. On these grounds conclusion can be done that at least in case of the Kubicek (or Sramek) method for impedance measurement, attempt to build a more adequate electrical conduction model than the Nyboer's one has little chance of success. Such a model has to make allowances to too many individually varying (i.e., unknown) parameters that characterise the human thorax as a volume conductor and as a part of circulatory system as well. Therefore it could not help to improve the SV estimation.

It is possible that in case of the Tischenko method the electrical conduction model has better perspective to be built successfully. As this method treats of the whole body, it would be possible to neglect the thorax or to replace it with a simple model. But the haemodynamics still will cause difficulties: if one does not know the minimal value of the pulsing flow (as it occurs in case of any peripheral region), it will be impossible to estimate the mean value of the flow (but just the mean value quantifies the transport function of the flow) by its pulsation only.

In the recent years a new technique has been developed on the basis of impedance plethysmography. It is named electrical impedance tomography (EIT) (Price 1979, Murai et al. 1985, Brown et al. 1986, Newell et al. 1988). The EIT technique was initially proposed for getting
images of the interior of the human body. But in addition it makes possible to record time courses of local resistivities inside the body (Eyüboglu et al. 1989). The latter property of EIT would enable to overcome the described weakness of the impedance plethysmography.

EIT constitutes a sophisticated combination of multi-electrode (16 or 32 electrodes, for instance) impedance measurement and computation. There are several versions of the technique. One of the most successful versions (Eyüboglu et al. 1989) looks as follows.

The electrodes are placed around the body in a single plane onto its surface. A current source is connected between an adjacent pair of electrodes. Potentials of the other electrodes are measured then. After that the current source is connected to the next pair of electrodes and again similar measurements of potentials are done. Such shifting of current source with the consequent measurement of the potentials of all other electrodes is repeated until all the pairs of adjacent electrodes have passed through. This procedure is called a data cycle. Data sets recorded in several successive cycles are averaged to improve the signal-to-noise ratio. An averaged data set is called a frame and a single image can be built from these data. The equipment enables to record data for 24 images per second.

The recorded data are processed afterwards. The processing consists of estimation of heart cycles, elimination of breathing influence by averaging corresponding data over a certain amount (at least 100) heart cycles. Then a computational procedure called image reconstruction is carried out. This is a very complicated computation (see Yorkey et al. 1987) reasoning from the described above direct problem of electrical conduction in a complex region. But instead of the direct problem here an inverse problem (estimation of resistivity distribution from the potential distribution on the surface of region) is solved. The result is a time series of images showing time variation of conductivity distribution in the cross section of the body.

In the present stage of development EIT has spatial resolution not better than 10% of the diameter of the object. Though the resolution is low for the image processing, the result significantly improves localisation of measured impedance. Therefore EIT would enable to overcome excessive integrity of the impedance plethysmography.

Applying EIT to SV and blood flow measurement would enable better determination of the regions and organs which impedance is measured. This would clarify the situation described above in connection with the existing impedance-plethysmography-based methods and would enable to build workable conduction and haemodynamics models for the
measurement. Thus it would be possible to develop better methods for SV and blood flow estimation.

Conclusion

In biomedical measurement there still stays a gap: there is no reliable and convenient non-invasive method for stroke volume monitoring in clinic. Electrical impedance methods are able to fill this gap. A modern-day method for continuous non-invasive monitoring of the stroke volume would be built on the basis of the electrical impedance measurement. However, it is essential that automation or computer assistance of the existing methods (the Kubicek's, Sramek's and Tischenko's ones) is not enough to obtain a new quality in this field. As the measurement technique as well the signal processing and interpretation would be rearranged for this purpose.

The electrical impedance tomography technique has been developed from the impedance plethysmography technique during last decade of years. This technique would be a component of the basis for new methods of stroke volume estimation. Computer simulation of cardiovascular system would be the second component of this basis and advanced signal processing would be the third.

References


14. Kubicek WG, Patterson RP, Witsoe DA (1970) Impedance cardiography as a noninvasive method of monitoring cardiac function and


