Title: RECENT DEVELOPMENTS IN ELECTRICAL TRANSTHORACIC IMPEDANCE RESULTING IN REAL-TIME MONITORING OF CARDIAC OUTPUT.

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Introduction. The electrical bioimpedance used to quantify blood flow, originally described by Nyboer[1], and later by Kubicek[2] et al, has not gained widespread use for several reasons: a) good correlation with other techniques was demonstrated on healthy individuals only; b) calculated cardiac output on patients with a changed thoracic fluid content deviated by several binary orders of magnitude from actual values; c) there were unresolved questions about the accuracy of the measurements caused by changes in resistivity of blood (hematocrit); d) measurements of cardiac output had to be performed on patients in voluntary apnea, due to the strong changes in transthoracic electrical impedance caused by ventilation; e) band electrodes were unsuitable for long term monitoring; f) existing hardware was high cost/high complexity, requiring skilled operators. Recent mathematical improvements of the equation for stroke volume/cardiac output calculation, use of spot electrodes for long term monitoring, and design of a microprocessor assisted hardware, that alleviate all above mentioned drawbacks, will be discussed.

Methods and Materials. In order to understand the mathematical equation improvement, let's state the original Kubicek's equation for stroke volume:

$$SV = \frac{\rho \times L^2}{Z_o^2} \times T \times \left(\frac{dZ}{dt}\right)_{max}$$

Where: SV .. stroke volume (ml)
ρ .. specific resistivity of blood (Ωcm)
L .. distance between sensing electrodes (cm)
Z_o .. thoracic base impedance (Ω)
T .. ventricular ejection time (sec)
$\left(\frac{dZ}{dt}\right)_{max}$.. maximum rate of impedance change (Ω/sec)

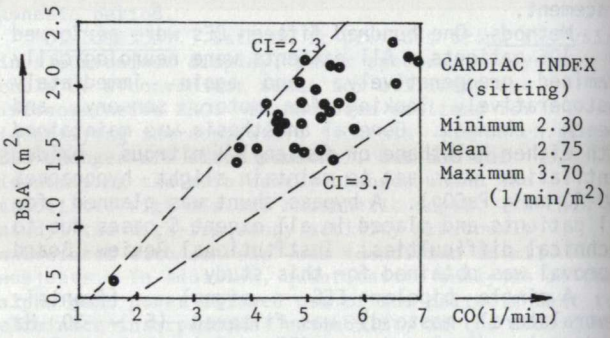
The analysis of the mathematical model and calculations, resulting in a modified equation, were discussed in separate papers[3,4]. The new stroke volume equation is:

$$SV = \frac{V_{ept}}{Z_o} \times T \times \left(\frac{dZ}{dt}\right)_{max}$$

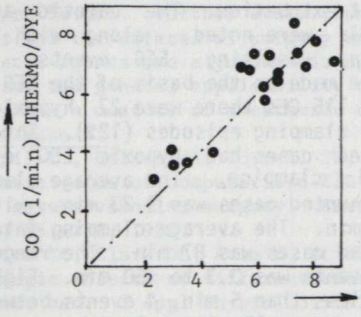
where the new component is
V_{ept}.. the physical volume of electrically participating thoracic tissue (ml)
(V_{ept} has been proven to be a function of L)

It is important to stress the effect of Z_o on the results of calculation of SV. The mean volume of Z_o of healthy individuals is 30 $\pm$ 8 Ω while the Z_o of patients with pulmonary edema or patients after thoracic surgery is as low as 6 Ω. Having Z_o in the first power and not using ρ in the new equation resolves complaints a,b and c noted in the introduction. Using an array of long-term monitoring spot ECG electrodes in place of Kubicek's bands[3,4] resolves the electrode problem. New microprocessor controlled, low cost hardware automatically suppresses the effects of ventilation. The speed of the Intel 8022 microprocessor allows continuous hands-free monitoring for every heart beat of: cardiac output (1/min), heart rate (Bpm), stroke volume (ml), maximum rate of electrical impedance change (Ω/sec) (to measure contractility), ventricular ejection time (sec), and base impedance (Ω) (to be used as a sensitive indicator of changes in thoracic fluid content).

Results. It was imperative to prove that the described methodology provides the user with absolute values of stroke volume/cardiac output over the whole patient population, obtained noninvasively in a beat-to-beat fashion: 1) A statistical method has been used on healthy individuals; cardiac output (CO)measured by the new method was plotted against the body surface area (BSA). All measurements were taken in a sitting position. The individual points had to fall between the minimum and maximum loci of cardiac indices. The following chart shows the results:



2) In order to prove the absolute measurement capability of the new method on patients, where previously the electrical impedance technology failed, cardiac output of coronary bypass patients was simultaneously measured by the new method and by thermo or dye dilution methods. The results are in the following correlation chart. (Z_o of all patients was between 8 and 11 Ω.)



References: (1) Nyboer,J.: Electrical Impedance Plethysmography. Charles C. Thomas, 1959. (2) Kubicek,W.G., Kottke,F.S., Ramos,M.V. et al: The Minnesota impedance cardiography-theory and applications. Biochem. Eng. 9: 410, 1974. (3) Sramek,B.B.: Noninvasive Technique for Measurement of Cardiac Output by Means of Electrical Impedance. Proc. 5th Int'l Conf. on Electrical Bioimpedance, 1981 Tokyo. (4) Sramek,B.B.: Cardiac Output by Electrical Impedance, Medical Electronics, April 1982.