The Early History of Impedance Cardiography and Reflections on its Current State

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***Abstract* — My research and development of impedance cardiography started in 1963. The first success was the development of a band electrode arrangement that gave stable and repeatable data. After its early success, in 1966 NASA began to support a multiphasic research program and developed plans for its use in the upcoming moon space program. With NASA's support both animal and human studies took place. Clinical level hardware was designed and built for use by over 10 independent institutions. This intense work ended in 1970. During the early development phase the estimated source of the waveform changed many times. Current modeling and experimental work suggest vessels in the neck and upper thorax are the most likely source of the waveform.**

Keywords — impedance cardiography; impedance history; waveform origin.

I. INTRODUCTION

In July of 1962 I started his graduate program in electrical engineering at the University of Minnesota as a Research Fellow in the Department of Physical Medicine and Rehabilitation (PM&R) at the University of Minnesota. PM&R was developing a very intensive program in cardiac rehabilitation and was interested in creating non-invasive tools to assess cardiac function. At the time the standard of care after a myocardial infarction was six weeks of bed rest, but some researchers were testing only three weeks of bed rest.

In 1961, William Kubicek and Edwin Kinnen in PM&R obtained a two year US Air Force grant to measure cardiac stroke volume using impedance measurements on the chest. The US Air Force was developing high performance jets, which placed high g forces on the pilots, creating syncope. Spot electrodes were placed on various thoracic locations from which they obtain a pulsatile cardiac waveform similar to an arterial blood pressure waveform. Since the right and left ventricles have a typical total volume change of 160 ml with relatively low resistivity blood it seemed that stroke volume could be measured using the impedance waveform. Unfortunately, a consistent reliable waveform could not be obtained. The cardiac waveform changed far beyond what would be reasonably expected with changes in body position change and lung volume. Results were inconsistent between different individuals and even similar waveforms could not be obtained from day to day on the same individual. After 1.5 years of study the results did not look promising.

II. EARLY DELOPMENTS

In December 1962, William Kubicek, head of physiological research in PM&R, asked me to look at the project to see if I could come up with a better approach. Up to that time I was not involved with the project. The next week I learned that Kubicek was taking a medical leave to obtain shock treatments for severe depression. After about six weeks he did return although he had mental health issues for the remainder of his time at the University of Minnesota. He did not participate in any hands-on human or animal research after his return although he was listed first author on all grants, papers, and patents.

I immediately started to devote all my time to try to solve the problem. A new approach was needed that focused on obtaining a consistent, repeatable waveform that would not change in shape or amplitude beyond expected physiological changes with body position and lungs inflation. Since most heathy, resting adults have similar stroke volumes there should not be great amplitude and shape changes between different subjects. The first approach consisted of viewing the thorax as a cylinder in which during systole the left ventricle ejects about 80 ml of blood out of the thorax and the venous inflow would be relatively constant. Therefore, band electrodes were placed around the neck and lower thorax (Figure 1). Very consistent waveforms were obtain that did not change greatly with body position or lung air volume (Figure 2). But, one surprise occurred, during systole the impedance decreased instead of increasing as would be expected if it was it due to a bolus of blood leaving the thorax. Rethinking was needed. Since the lungs cover a large volume of the thorax and receive the output from the right ventricle, they were assumed to be the source of the signal. This hypothesis was the operating idea for the next few years.

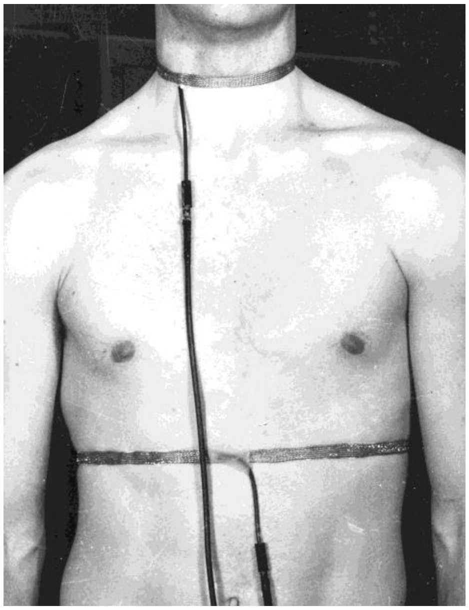


Figure 1. First two electrode band arrangement

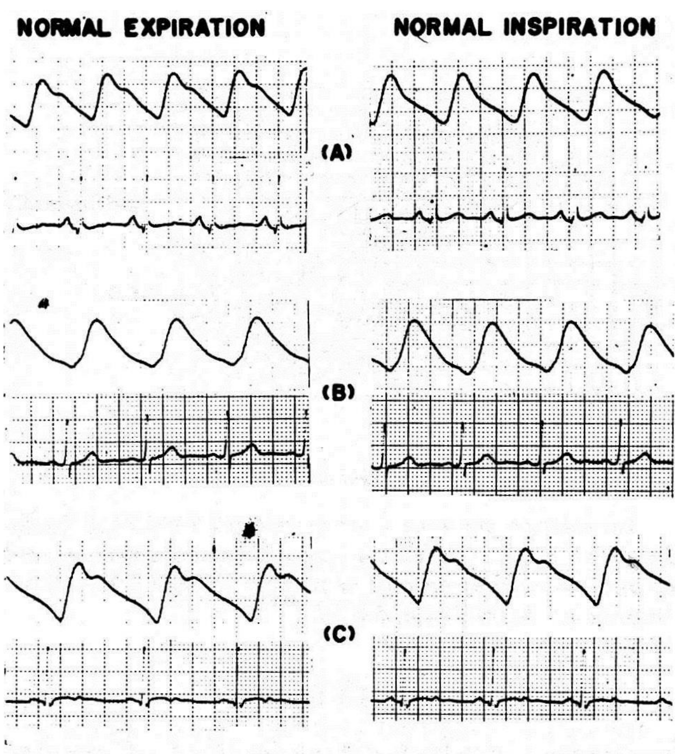
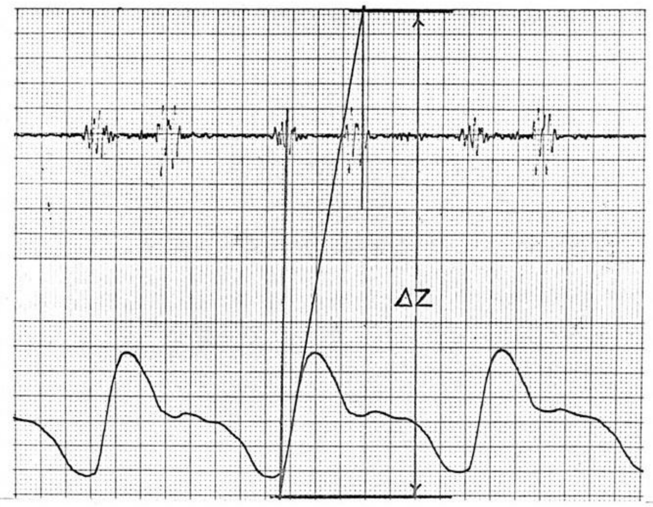


Figure 2

Impedance waveforms and ECG for subjects 1 (A), 4 (B), and 6 (C) Impedance decreases upward.

The parallel column model first proposed by Nybor was used to quantitate the volume change [1]. Just looking at the peak to peak amplitude of the impedance change resulted in a value far too small. It was assume this was caused by the venous blood leaving the lungs during systole. It was therefore assumed that we could use the initial rise in impedance as an indication of the right ventricle outflow rate and assume it continued for the entire duration of systole. This resulted in the slope procedure, which was replaced later by using the first derivative (Figure 3).



Typical impedance waveform along with heart sounds (upper tracing heart sounds, lower tracing impedance waveform, decreasing impedance upward)

Figure 3

The next major step was to compare the impedance method with an accepted standard for cardiac output. In the previous work with the US Air Force contract and the early studies, only two electrode impedance measurements were made. In order to carry out good quantitative studies a four electrode instrument was needed, but none was available. Therefore, I first designed and built a four electrode impedance instrument. Next a comparison study was started using 44 children aged 6 to 12 with ASD and VSD holes between their heart chambers. They were undergoing cardiac catheterization to evaluate their condition before surgical repair was performed. As part of the procedure their cardiac output was measured using the Fick method. The comparison with the Fick method in this group of children looked reasonably good. I presented the data at the First Annual Rocky Mountain Bioengineering Symposium in 1964 [2]. In the Proceeding of the meeting was a complete 15 page paper. The results were published in my Master Degree thesis in 1965 [3].

III. The NASA years

In 1965, NASA come to us to discuss the possibility of using the band electrode impedance technique to measure cardiac output for use in the Apollo moon mission. This resulted in a very intensive research and development program with many parts. The first effort was to work with a commercial manufacturer to produce space flight hardware and to provide continuous real time calculations using a computer. Second, to further verify the method by comparing it with the dye dilution cardiac output method on normal subjects under rest and exercise conditions. Third, to carry out animal studies to determine the source of the impedance waveform. This would be performed using electromagnetic flow meters on the pulmonary artery and aorta, with pressure measuring catheters in all the heart chambers and major vessels. Fourth, to design and manufacture a clinical impedance instrument for general cardiac function measurements, which could be used by other researchers to evaluate the method. This instrument was to be provided to over 10 other institutions for comparisons studies using either the Fick method or dye dilution to calculate cardiac output. After 2 years a meeting was to be setup to let all the researchers present their data.

Figure 2. The Minnesota Impedance cardiograph Model 304

The first paper from the NASA supported work was published in 1966 showing the comparison with the dye dilution in 10 normal subjects, supine, sitting and with bicycle exercise at two levels of 30 and 60 watts/per square meter of body surface. The results for relative changes in a given subject were reasonable with 85% of data within 20%, but the absolute numbers were significantly worse.

In the animal studies another surprise occurred. One dog developed left mechanical alternans, where the left heart only ejects blood on every other beat (Figure 4) with right heart ejecting on every beat.

When the left heart did not beat there was no impedance change. We learned how to create left mechanical alternans and could repeat the same observation, although in a few cases it was less clear. This again caused a change in our thinking on the possible source of the signal.

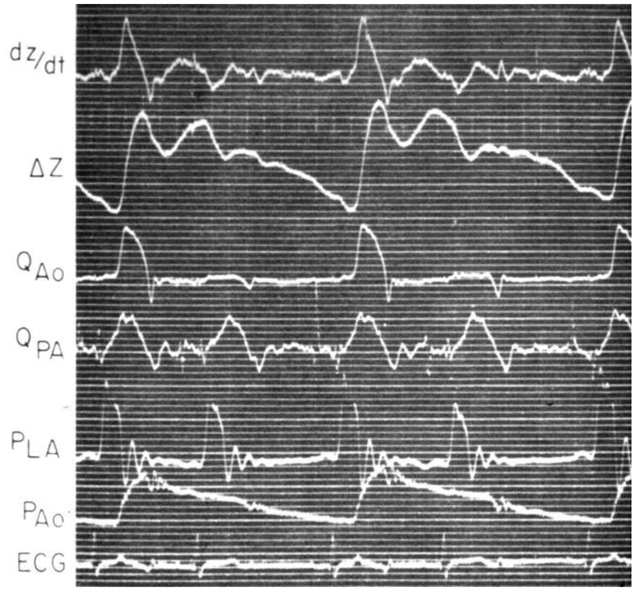


Figure 3 Example of left mechanical alternans

It had to be from the left heart pulse or arterial vessels. The first guess was the aorta, but later other vessels seamed a more likely source.

The final animal study was a three way comparison using dye dilution, an electromagnetic flowmeter (EMF), both accepted methods and impedance to try to determine the usefulness of the impedance method under possible clinical cardiac conditions. Since the accepted methods can have errors, if there are differences, it is not clear which is correct. The study used drugs that significantly increased and decreased cardiac output in 14 dogs. Grouping all the data for a total of 305 points showed correlation coefficients for EMF and dye, dye and impedance, and EMF and impedance of 0.89, 0.68, and 0.72 respectively. The results were disturbing as they showed that in about 25% of the dogs the agreement with either of the accepted methods were very poor and frequently showed changes in the opposite direction.

In 1970 the support from NASA ended. After 1970, the impedance research at Minnesota was focused on field mapping of external fields on the thoracic surface [6] and on building high resolution (3.8 million elements) computer based models using MRIs [7]. Figure 4, shows an analysis of the sensitivity of thorax to local resistivity changes using lead field theory. The results show high sensitivity in the upper thorax and neck for local changes in resistivity. These results along with surface field measurements suggest that the upper thorax and neck make a major contribution to the signal using the thoracic band electrodes.

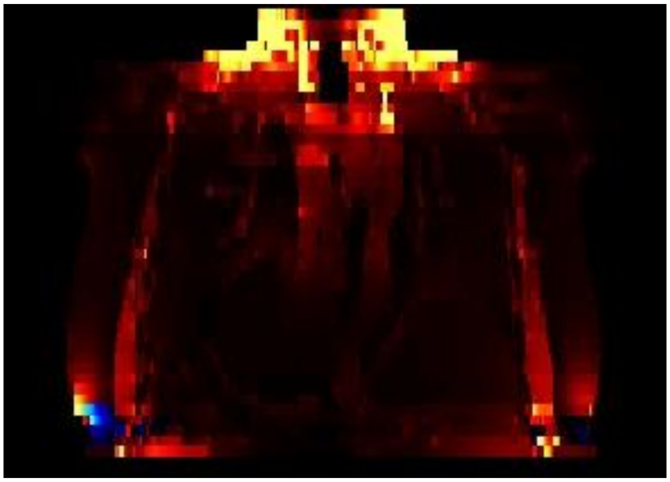


Figure 4. Sensitivity analysis showing cross section of thorax. Brighter colors reflection higher sensitivity to local resistivity change.

IV. Conclusion

The early development of a band electrode arrangement for stroke volume measurements started 1963 with an intensive program of research supported by NASA. The support by NASA contributed to wide spread interests in the method. Since that time, many studies have taken place by many difference groups. The author has focused on trying to determine the source of the impedance change waveform. Although it is still not absolutely clear, based on models and surface field maps, it appears that the best guess for the sources of the signal are volumes changes in arteries and veins in the upper thorax and neck. Although many studies report significant error in the measurement of stroke volume and cardiac output in clinical medicine, the waveform shape and amplitude may provide useful data showing the mechanical action of the heart.

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