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An Optimal Spot-electrodes Array for Electrical Impedance Cardiography Through Determination of Impedance Mapping of a Regional Area along the Medial Line on the Thorax

Akira Ikarashi, Masamichi Nogawa, Takehiro Yamakoshi, Shinobu Tanaka and Ken-ichi Yamakoshi, *Member, IEEE*

Abstract—**Electrical impedance or admittance cardiography is a simple method for non-invasive, continuous measurement the stroke volume and cardiac output. For the Electrical impedance cardiography, the band-electrodes array proposed by Kubicek et al has been widely used, and various spot-electrodes array have been experimented in search of a less uncomfortable and equally reliable electrodes array that is easier to attach. From the uniformity of current distribution on the thorax, we have reinvestigated focusing on the measurement of contour maps of static and pulsatile components of a regional area along the medial line on the frontal part of the thorax. Consequently, the appropriate electrodes locations for current injection were determined as the back of an ear and on the lower abdomen, while those for voltage pick-up was on the medial portion at the level of clavicle and on the portion above the xiphisternum. Preliminary comparison experiments between the cardiac output values obtained by the electrical impedance cardiography and by a pulse dye-densitometry showed a fairy good agreement.**

I. Introduction

Electrical impedance cardiography (ICG) [1], [2] or admittance cardiography (ACG) [3] has still been one of the most convenient and useful methods for non-invasive and continuous measurement of stroke volume (SV) or cardiac output (CO). The tetra-polar band-electrodes method proposed by Kubicek et al. [2] has been one of the most commonly used electrodes array. The Kubicek's method is based on the two-compartment coaxial cylinder model of the thorax. This thorax model was originally proposed by Nyboer [1]. For the band-electrode system, two pairs of electrodes are placed around the subject's neck and abdomen for current injection and voltage measurement. Attaching the band electrodes to a patient lying on a bed is inconvenient, and long-term use as well as ambulatory use of the band-electrodes is often uncomfortable and causes inflammation in the skin. An improved arrangement of electrodes is desired for clinical practice.

Akira Ikarashi is with Ishikawa Sunrise Industries Creation Organization, Kanazawa, Japan, on loan to the Division of Innovative Technology and science, Graduate School of Natural Science and Technology, Kanazawa University, Kanazawa, 920-1192, Japan (e-mail: aikrs@ kenroku.kanazawa-u.ac.jp).

Masamichi Nogawa, Takehiro Yamakoshi, Shinobu Tanaka and Ken-ichi Yamakoshi are with the Division of Innovative Technology and science, Graduate School of Natural Science and Technology, Kanazawa University, Kanazawa, 920-1192, Japan.

Replacement of band-electrodes with spot-electrodes has been investigated [4]-[9]. Several arrangements of spot-electrodes have been proposed, and the SV and CO measurements based on these spot-electrodes have been compared to the measurements based on the band-electrodes arrays or other CO measurement methods. The current distribution on the thorax is an important factor that determines the utility of the spot-electrodes array. However, the current distribution on the thorax has been scarcely measured for the proposed spot-electrodes arrays. We have previously proposed an optimal spot-electrodes array based on the measurement of contour maps of static (Z_0-maps) and pulsatile components (ΔZ-maps) of the thoracic impedance, so as to nearly satisfy an electrical conductance model composed of two-compartment coaxial cylinder of the thorax, i.e., uniformity of Z_0-maps and ΔZ-maps during cardiac blood ejection period: A pair of spot-electrodes for current injection was on the forehead and on the left medial knee, whiles those for voltage pick-up was on the medial portion at the level of clavicle and on the portion above the xiphisternum [10]. In order to improve the placement of current spot-electrodes in view of a spiffy-looking and easier locations as well as less motion artifacts for practical monitoring, we have further reinvestigated focusing on detailed measurements of the Z_0-maps of a regional area along the medial line on the frontal part of the thorax by changing various placements of a pair of spot-electrodes. Preliminary comparison experiments between the CO values obtained by the ICG and by a pulse dye-densitometry (PD) were also made in healthy volunteers.

II. Material and Method

A. Outline of the System

Fig. 1 shows a block diagram of the impedance mapping system newly designed for measuring the current distribution of a regional area along the medial line of the thorax. This system mainly consists of a current source (50 kHz sinusoidal signal of $2mA_{rms}$), voltage sensing units, an A/D converter unit (14-bit, 1ms of sampling interval per channel; NR-500, Keyence Co., Japan) and a personal computer. The current flows through a subject's thorax by a pair of spot-electrodes (disposable ECG electrode, 35mm wide and 45 mm long; BIOTRACE-HR 1212, MSB Ltd., UK). The resultant voltage drop between a reference spot-electrode and each of 18 selected measurement points was measured with the voltage sensing units. A voltage sensing unit consists of a pre-amplifier, a rectifier and an AC amplifier (with a 1.6 second time constant). The rectifier output is proportional to the instantaneous value of the impedance and free of the 50 kHz component. The rectifier output is the voltage signal for impedance measurement (Z_0 signal), and the output of the AC amplifier is the voltage signal for the pulsatile component of the impedance (ΔZ signal). Each voltage sensing units has a measurement range of 0~68 Ω for the Z_0 value and ±0.34 Ω for the ΔZ value, both within ±1.2% of error. One of the voltage sensing units is used to measure an ECG signal, in order to observe a synchronization of cardiac cycle time. The Z_0-maps were obtained for different positions of spot-electrodes for current injection from the 18 Z_0 signals. The contours were determined through a cubic spline data interpolation method using the MATLAB software (The MathWorks, Inc., USA). Each of these Z_0-maps was compared to an ideal Z_0-maps calculated as the cylinder model having uniform current distribution.

On the other hand, an appropriate spot-electrode array for voltage pick-up was investigated through the measurement of ΔZ-maps, which were also obtained from the 18 ΔZ signals. To construct the ΔZ-maps, the ΔZ value at the time of the ECG-P wave was selected as the reference value for each measurement point, and the increments from the reference value were used to draw the ΔZ-maps at various time points.

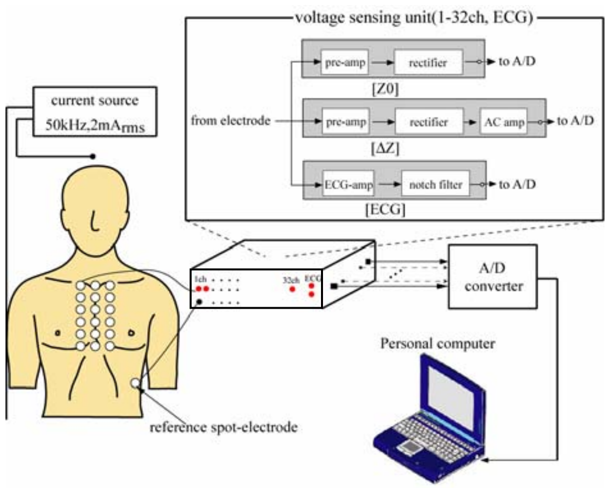

Fig. 1. Schematic block diagram of the impedance mapping system newly designed for measuring the current distribution of a regional area along the medial line of the thorax.

B. *Subjects and method*

The new, optimal spot-electrodes array was determined as an approximation of the cylinder model. These measurements were done using 11 normal male volunteers (21-32 years old, 53-85 kgf of body weight) under supine, sitting and standing positions. The data were acquired during breath holding at the resting expiratory level. Informed consent was obtained in each subject before the studies were carried out.

On the other hand, preliminary comparison experiments between the impedance method with the new spot-electrode array thus determined and the PD (DDG Analyzer; DDG-2001, Nihon Kohden Co., Japan) were made in 6 healthy male volunteers (22-43 years old, 53-85 kgf of body weight). The subjects were asked to ride a bicycle ergometer under supine position on a bed, in order to change the CO values. The data were acquired immediately after the ergometer exercise. Informed consent was obtained in each subject before the studies were carried out. As for the calculation of the SV value, the SV value was calculated according to the Kubicek's equation [2]. The blood resistivity value of 150 Ωcm given in [2] was assumed for this study, and the ventricular ejection time was determined according to the method given by Lababidi et al [11]. Finally, the CO value was calculated by using the SV value and the instantaneous heart rate from ECG signal.

III. Results and Discussion

Fig. 2 shows several examples of the Z_0-maps obtained with the previously proposed spot-electrodes array (a) and the newly proposed spot-electrodes arrays for current injection ((b)-(e)). While observing the Z_0-maps, a pair of spot-electrodes for current injection was relocated to various points on a subject's body, and optimum locations were searched through trial and error. As a result, the appropriate electrode locations for current injection were determined as the back of an ear and on the lower abdomen. The Z_0-map obtained with this arrangement (Fig. 2b) is similar to that

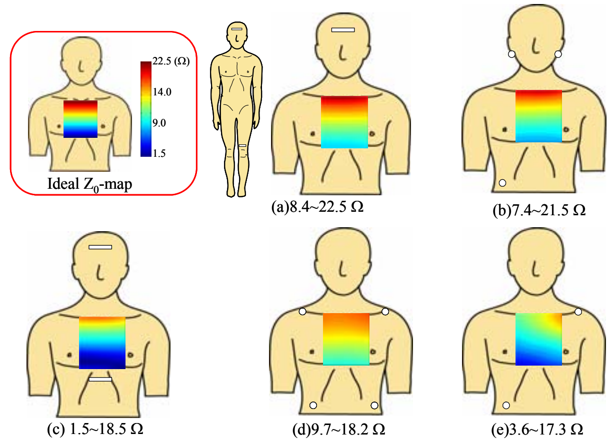

Fig. 2. Examples of Z_0-maps obtained with the previously proposed spot-electrodes array and the newly proposed spot-electrodes arrays for current passing.

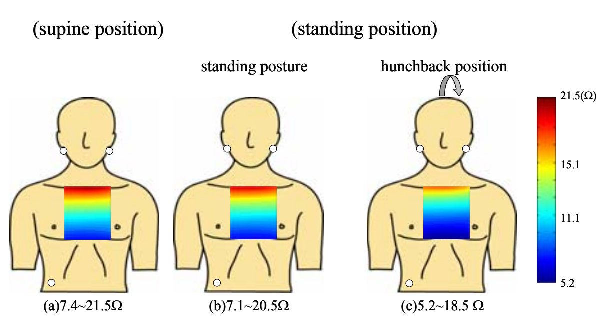

Fig. 3. Examples of Z_0-maps obtained with various postures.

obtained with the previously proposed spot-electrodes array (Fig. 2a). The Z_0-maps obtained with the two electrodes array correlate well with Z_0-map calculated for the cylinder model of thorax assuming the uniform current distribution. The Z_0-map obtain with this arrangement (Fig. 2b) is relatively similar to that obtained with the Kubicek's band-electrodes array [10]. It implies that the cylinder model of the thorax is as valid with the new spot-electrodes array for current injection as with the band-electrodes array. On the other hand, the three sets of Z_0-maps shown in Fig 2(c)-(e) clearly show little uniformity of current distribution in the thorax and undesirable concentrations near the current injection electrodes. It implies that cylinder model of thorax with the assumption of uniform current distribution is not a good model for these electrodes arrays.

Furthermore, Fig. 3 shows the example of Z_0-maps obtained with various postures. The uniform current distribution on the thorax is comparatively obtained even

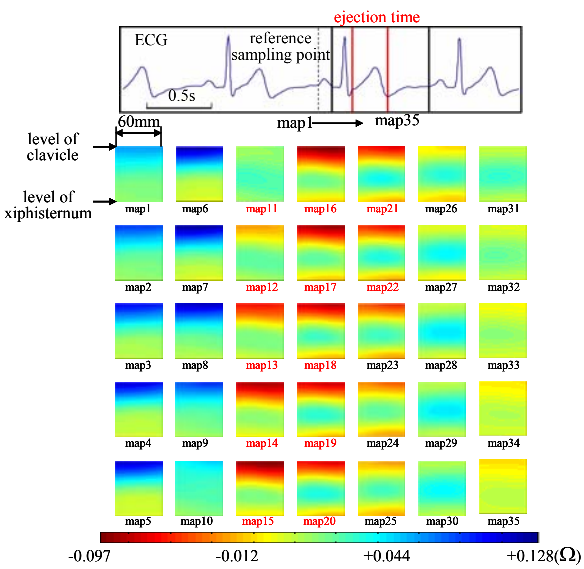

Fig. 4. Examples of the time-series data of ΔZ-maps obtained by the new spot-electrodes array for current passing. The time-course of the ΔZ-maps is displayed from the upper left (map1) to the lowest panel (map35) at 20 ms intervals (Δt=20ms).

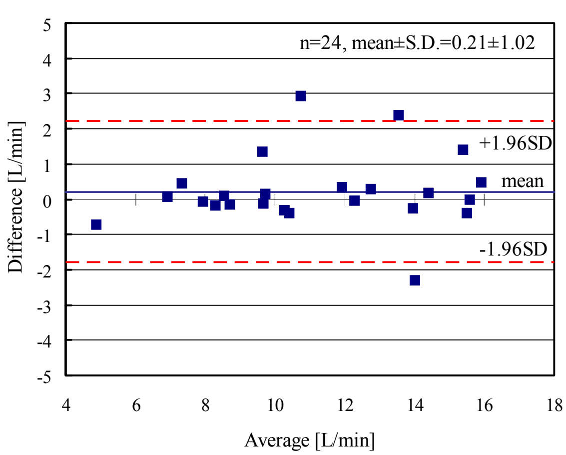

Fig. 5. Bland-Altman Plots of CO measured by the ICG and the PD

with hunchback position (Fig. 3c). It seems to be small that the new spot- electrodes array is influenced by the posture change. Therefore, it appears more useful for long-term monitoring in ambulatory use.

Similarly, an optimal location of the spot-electrodes for voltage pick-up was investigated by the ΔZ-maps. Fig. 4 shows the time sequence of ΔZ-maps together with the ECG signal obtained for the same subject as Fig. 2 was obtained for. The new spot-electrodes array was used for current injection. The time increment is 20 ms (Δt=20 ms). The figure clearly shows that the ΔZ-maps change in accordance with cardiac blood ejection cycle. The ΔZ-map was nearly uniform during the increase in blood volume into the aorta, and clear changes of the ΔZ values are observed along the medial line on the frontal part of the thorax in Fig. 4. From these reasons and an anatomical viewpoint, the appropriate locations for voltage pick-up are the medial portion at the level of clavicle and the portion above the xiphisternum.

Fig. 5 shows the Bland-Altman plots of CO measured by the new spot-electrodes array and the PD. No significant bias was seen (mean ± S.D. = 0.21 ± 1.02 L/min.), and almost all plots were within ±1.96 S.D., indicating reasonable accuracy of the new spot-electrodes array. However, the difference between these two methods was occasionally seen in some subject. This issue seems to relate by a little changes of the ΔZ value near the xiphisternum during the cardiac blood ejection period. Further comparison experiments using many subjects would be required to solve this issue. In addition, it would be necessary to analyze a three-dimensional finite element model of the upper body [12].

IV. Conclusion

The new spot-electrodes array proposed here is an available replacement of the conventional band-electrodes array, and appears more useful for long-term monitoring of continuous SV or CO in clinical as well as in ambulatory use.

Acknowledgment

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