Heart failure monitoring with implantable defibrillators

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Abstract

Heart failure is one of the most frequent diseases and a leading cause for hospital admission and death in Germany and other industrialized countries. Two types of impedance sensors are presented that promise to allow improved disease monitoring and hence better therapy adaptation in heart failure patients with an implanted defibrillator: thoracic impedance to estimate the lung fluid status of the patient, and intracardiac impedance for assessment of cardiac hemodynamics.

1 Introduction: Heart failure

Congestive heart failure (CHF) is a symptomatic cardiac disease and denotes the inability of the heart to provide sufficient pump action to meet the metabolic requirements of the body. Causes are manifold, the most frequent one being coronary artery disease. [1]

In combination with a pharmacological treatment, patients are typically provided with a biventricular implantable cardioverter-defibrillator (ICD), which is able to treat asynchronous contraction of the heart chambers as well as arrhythmias by delivering electrical stimuli to the myocardium via implanted electrodes.

With an incidence of 0.33%, a prevalence of 4.2% in the entire population and 48,000 cases of death per year in Germany, heart failure is one of the most frequent diseases and a leading cause for hospital admission and death in Germany as well as other industrialized countries [2, 3]. Its treatment causes a financial burden of 3.2 bn. € per year for the German health care system [2]. As the prevalence of CHF shows a nearly exponential increase with age, rising up to 13.8% in the over 65 years old [2], the aging of the population will even aggravate the problem in the upcoming decades.

As about two thirds of the costs are due to hospitalizations [4], steps are to be taken to reduce the rate of hospitalizations. For this purpose, early detection of disease deterioration is necessary to afford timely medical treatment. Automatic assessment of cardiac status by use of sensor data from implantable defibrillators provides means to reach this target.

Impedance measurements are particularly useful for this purpose. Here, the electrodes – actually implanted to deliver electrical stimuli and shocks for therapeutic use – are used for diagnostic purposes. Depending on the configuration used, impedance provides information about lung congestion and edema, a typical syndrome of worsening heart failure, as well as about cardiac hemodynamics themselves.

With Biotronik Home Monitoring®, these data are transmitted from the implant to a service center and displayed to the physician on a daily basis. This way worsening of heart failure can be detected and treated much earlier than up to now.

2 Thoracic impedance

2.1 Measurement principle

Thoracic impedance (TI) measures the electrical resistance between the housing and the shock electrode of the defibrillator (see figure 1). As most of the current is conducted by the lung tissue, a change in conductivity of the lung, particularly by the aggregation of fluid, will affect the TI. This property is useful for diagnostic purposes, as case reports clearly show that the development of lung edema leads to a decrease of the TI [5]. Lung edema in turn is a typical symptom of worsening of heart failure: It results from blood congestion in the pulmonary system due to a deteriorated pumping function of the left ventricle. It is therefore expected that worsening of (particularly left) heart failure can be detected by appropriate algorithms from a downward trend of TI.

Figure 1: Measurement principle of thoracic impedance (TI). i – injected sub-threshold current, v – resulting voltage.
Besides lung fluid status, however, other influencing factors have an impact on the TI signal as well. One of them is body position, which can be studied by the change between upright and supine posture of the day–night rhythm.

### 2.2 Clinical data

Currently the TI is investigated in the framework of a patient registry conducted at the University hospital Erlangen. 66 patients suffering from congestive heart failure and with an implanted ICD (Lumax 540, Biotronik, Germany), which is capable of TI measurement, were enrolled. The age of the subjects ranged from 45 to 85 years (67±11 yrs. in average), NYHA class from 1 to 4 with an average of 2.0±0.8. From all patients daily Home Monitoring data was available including 24 hourly average TI values. The patients were advised to determine their blood pressure and body weight three times a week and document the values in a patient diary.

#### 2.2.1 Worsening of heart failure

Figure 2 shows an example of acute worsening of heart failure in one patient. TI was measured by the implant; both average TI per day (black) and per hour (blue) are given in the topmost panel. Blood pressure (middle panel) and patient weight (lower panel) were taken from the patient diary. During the deterioration of the patient’s state of health, systolic blood pressure rises by approx. 30 mmHg and weight by about 3kg. At September 11, during a telephone call by the study nurse, the patient complains about malaise. Within one week after the call, the patient recovers, possibly by more regular medicament intake; TI and patient weight regain their previous levels. At September 24 the patient reports normal well-being.

![Figure 2: Example of acute worsening of heart failure](image)

The example shows that a drop in TI by several Ohms over approximately 1–2 weeks indicates the accumulation of lung fluid and hence the worsening of cardiac status. Other studies with a larger patient population, e.g., the Home-CARE II study [6], will answer the question whether these observations can be generalized to the entire heart failure patient population.

#### 2.2.2 Circadian rhythm of TI

Figure 3 shows a typical TI course over 24 hours. Different days of the week are plotted separately with working days in blue and weekend days in red, respectively. Each curve was obtained by averaging over eight corresponding 24h measurements. The sleeping phase was inquired from the patient and is indicated as light blue area.

![Figure 3: Example of circadian variance of TI from a working patient](image)

The TI sharply rises after the patient got up in the morning and reaches its maximum after approx. 6h around noon. During the afternoon impedance slightly decreases, followed by a sharp drop as soon as the patient goes to bed and takes a fully supine body position. The major contribution of this circadian variation of TI can be attributed to posture effects. On the one hand, the changes in TI are caused by a short-term redistribution of blood volume within the vascular bed: Upon rising blood is shifted from the trunk into the lower limbs and vice versa upon reclining. On the other hand, a long-range process takes place, which is effective over several hours: If the patient is upright, fluid from the vascular bed is absorbed into the extravascular space due to the high local...
blood pressure, which concentrates even more fluid in the legs [7].

Additional determinants of TI are presumably hormones that regulate urinary excretion such as antidiuretic hormone, cortisole and aldosterone. These are known to exhibit a circadian rhythm too [8, 9].

The hypothesis that TI circadian variation is mostly caused by postural changes is supported by the sharp rise in the morning hours.

Furthermore, the amplitude of TI is observed to be significantly diminished during the two weekend days, where the patient may spend less time actively and has more recreational pauses.

In order to quantify the observations above, the effect of getting up in the morning on TI was computed for all subjects of the registry. Information about the time of rising was inquired from the patients. Thoracic impedance $Z$ was measured hourly by the implant within an observation window of 14 days before to 14 days after the inquiry. The signal was smoothed with a 3-point moving window. The hourly measurements were averaged over all days, in order to obtain a representative TI curve. The last four measurements before rising were averaged as well as the four measurements between 4 and 8 hours after rising. The difference between the two mean values gives

$$\Delta Z = \left\langle Z(t_{\text{rising}} + 4h < t < t_{\text{rising}} + 8h) \right\rangle - \left\langle Z(t_{\text{rising}} - 4h < t < t_{\text{rising}}) \right\rangle$$

as a measure for the change of impedance in the hours after rising.

Full data was provided by 45 patients. The median of $\Delta Z$ was 2.6 $\Omega$ (mean 2.7 $\Omega$), the standard deviation 2.2 $\Omega$. Further statistical properties of the data set are given in the boxplot in figure 4.

It becomes obvious from the figure that except for a few outliers $\Delta Z$ is greater than zero. A two-sided Wilcoxon rank test confirms that $\Delta Z$ is distributed with median different from zero on an error level of $p = 10^{-7}$. TI hence shows a significant increase after rising in the morning and confirms the hypotheses that postural changes have an impact on TI.

### 2.2.3 Conclusion

Above, two situations were described where a significant change in TI is expected: fluid aggregation in the lung due to a worsening of heart failure, and changes in body position. In both cases, the expected change was observed, which supports the hypothesis that TI monitors fluid volume in the trunk and the redistribution of body fluid, respectively.

### 3 Intracardiac impedance

#### 3.1 Measurement principle

As shown above, HF monitoring with TI focuses on early detection of lung edema as a typical result of deteriorated cardiac function. Hence, TI may serve as an indirect marker of the worsening of the disease. Intracardiac impedance (ICI) in contrary is intended to directly assess the hemodynamics of the heart.

It is derived from a quadrupolar impedance measurement with a current induced between the two right-ventricular electrodes and the voltage measured between the left-ventricular electrodes (see figure 5). As it is a measure of the electric resistance between left and right ventricle, it is expected to provide a direct measure of left ventricular filling and stroke volume.

![Figure 5: Measurement principle of intracardiac impedance. $i$ – injected sub-threshold current, $v$ – resulting voltage](image-url)
3.2 Outlook: Upcoming clinical investigation of ICI

Intracardiac impedance will be studied in an upcoming clinical study, which is part of the same project as the previously described registry. Approximately 40 patients will be enrolled, half of them undergoing acute ICI measurements additional to chronic surveillance. The study is intended to assess the influences of pacing parameters, body position and physical load on the ICI. Furthermore, the chronic observation will give insight into the factors of daily life that cause variations of the ICI.

4 Conclusion

Parameters derived from thoracic and intracardiac impedance promise to be indicators of cardiac status in patients suffering from congestive heart failure. Both sensors add different information for heart failure monitoring and thus complement each other. TI provides information about acute deterioration of the disease accompanied by lung congestion and may serve for early detection of critical states. On the other hand ICI enables the physician to continuously monitor the hemodynamics of the heart, and possibly contributes to early prevention of acute destabilization [11].

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References