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Transthoracic Impedance Study with Large Self-adhesive Electrodes

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***Abstract**: The external electrical therapy of the heart requires the application of high voltage electrical pulses via large external electrodes, placed on selected locations on the thorax surface. The position of the electrodes is one of the major determinants of the transthoracic impedance (TTI), which influences the intracardiac current flow during electric shock and therefore affects the defibrillation success. The indefinite nature of the factors affecting TTI raised our interest in clinical study of the TTI behavior during long-term applications of the defibrillation pads in different positions on the patient's chest. The study involved 86 randomly selected patients (39 male and 49 female, age (20-83) years, height (150-190) cm, weight (50-110) kg, chest size (86-130) cm, 67 patients with normal skin, 13 patients with dry skin and 6 patients with greasy skin, 70 patients without and 16 patients with chest pilosity). TTI was measured by passing of a low-amplitude high-frequency (23 kHz) current between the two PADs (active area about 92 cm^2). For each patient, the TTI was measured 10 s, 1 min and 5 min after sticking on the electrodes to the skin surface, separately for the two tested electrode positions - Position 1 (sub-clavicular/sub-axillar position) and Position 2 (antero-posterior position). TTI range is comparable for the two tested PAD positions - between 58 Ω and 152 Ω for Position1 and between 55 Ω and 149 Ω for Position 2. TTI mean±SD value in Position 1 (107,2±22,3) Ω is significantly higher than TTI in Position 2 (96,6±19,2) Ω. Both the pilosity and the skin type do not change significantly the TTI value, however the patients with chest pilosity presented slightly higher TTI than those without pilosity. The TTI was higher for normal skin, followed by dry and greasy skin. TTI presented weak correlation with both the patient chest size and weight (r<0,5, p<0,05). The mean value of the TTI decreases in time. In time-interval (10s to 1min) after sticking on the electrodes, TTI drops with about (3,8±4,03) Ω for Position 1 and (2,44±3,75) Ω for Position 2. The TTI drop (10s-5min) is (7,36±5,33) Ω for Position 1 and (5,06±7,08) Ω for Position 2.*

***Keywords:** Transthoracic electrical impedance, Defibrillation PAD electrodes, Low-amplitude high-frequency current, Pre-shock measurement.*

Introduction

The electrical therapy of the heart, including pacing and defibrillation is widespread and well-established procedure for resuscitation of cardiac arrest victims [8]. It can be achieved by either direct contact or indirectly through the thorax surface. The first method requires an invasive intervention aiming at implantation and permanent monitoring. The latter technique is also referred to as the external approach. Its noninvasive nature makes it easy accessible and suitable for emergency cases, such as the public access defibrillation. The external electrical therapy requires the application of high voltage electrical impulses via external electrodes, placed on selected locations on the surface of the thorax. The electrodes have large contact area (70 - 120 cm^2) [7] and provide high and supposedly uniform current density distribution in the heart, needed for excitation of most myocardial cells, thus forcing them to return to normal rhythm.

Obviously, higher energies are required to excite the heart when pulses are delivered from a more remote site. Higher energy also implies chest muscle contraction, pain and risk of thermal injuries in the vicinity of the electrodes. Therefore, the design of special paddles may be required in order to limit harmful side-effects from the nonuniform current density distribution, e.g. preference for circular edge electrodes rather than square ones, use of contact gel or an interface layer of intermediate resistivity, or addition of a high-resistivity perimeter ring [16].

The defibrillator load impedance, which includes the electrode-skin and the patient transthoracic impedance (TTI), determines the current amplitude, the delivered energy, and therefore the defibrillation success [3, 9, 14, 19]. Lower energy required for defibrillation was observed in patients with low TTI [11]. Different techniques for prediction of the TTI before or during defibrillation were used for design of current-based defibrillators [3, 14], ‘impedance-compensating' defibrillators with automatic control of the output energy [13], or defibrillators with adaptive modulation of the high-frequency chopping pulses [17]. Prediction equations were developed based on the statistical comparison of the pre-shock measured TTI with low-amplitude high-frequency (20-100 kHz) current and the apparent impedance measured during the shock by dividing the peak applied voltage to the peak current [6, 7, 15]. Although the results show high correlation, the individual differences up to 15-17% suggest that this approach should be considered with caution for approximate assessments and pre-settings of the adequate shock energy or current with the intention of increasing the possibility for positive results with the first shock and reduction of post-shock myocardial dysfunction.

The position of the electrodes is one of the major determinants of TTI, which influences the intracardiac current flow during electric shock and therefore affects the defibrillation success. The American Heart Association (AHA) Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care [1] recommends three conventional electrode positions for defibrillation: anterior-apex, apex-posterior and anterior-posterior. There are few data available comparing TTI of these positions [2, 5, 12], which indicate that these pad positions does not appear to have a significant impact upon TTI, although the reported differences among the mean values of each group. Moreover, the individual characteristics, like body weight or chest width could also be deterministic for the TTI [10]. The electrode application technique, as well as the eventual shunting effect through the skin or smearing gel between adjacent electrodes are also important since they may lead to different interelectrode impedances measured for the same electrode position in the same patient. There is not clear answer given about the extend of influence of the geometric size and location of the body organs, such are the heart, lungs, skeletal chest bones and muscles, the air gaps upon the TTI for the different electrode positions and among individuals.

The particular application of the large self-adhesive pads for cardiac pacing and defibrillation requires the use of the same electrodes for passive sense of the low-amplitude bioelectrical activity of the heart, e.g. the electrocardiogram (ECG), and active application of high-current density pulses for treatment. The contact between the metal-foil electrode surface and the skin is associated with charge distribution, which establishes both the electrode potential and the polarization impedance of the electrode-electrolyte interface [18]. Considering a particular electrode metal, these quantities are not constant and vary in time, altered by the passage of current (density and frequency), the temperature, the contact interface properties, the long-term foreign skin reaction, like diaphoresis, etc. According to the AHA guidelines [1], attention should be paid for male patients with hairy chest, who may have poor electrode-to-chest contact because of the air trapping between the electrode and skin caused by the hair. There are reports inspecting the pad mass reduction over time on exposure to air due to evaporation - an effect likely to lead to poorer conduction between skin and paddle, consistent with an increase in TTI [4].

The indefinite nature of the factors affecting the TTI raised our interest in clinical study of the TTI behavior during long-term applications of the defibrillation pads in different positions on the patient's chest. The study is aimed at investigation of both the skin type and the pilosity influence on the TTI, as well as the correlations between the transtoracic impedance and the individual patient characteristics (chest size, weight, height, age). Another purpose is to study the interelectrode impedance variance in time since the long-term application of the defibrillation self-adhesive electrodes in real cases is a widely established practice.

Method

The prospective study included 86 randomly selected patients (volunteers) of the "University Hospital St. Anna" - Sofia. The personal characteristics collected for each patient were: gender [M/F], age [years], height [cm], weight [kg], chest size [cm], skin type [normal/dry/greasy] and chest pilosity [yes/no]. Each patient was subjected to TTI measurements by sticking a pair of self-adhesive electrodes in two conventional chest configurations - Position 1 (sub-clavicular/sub-axillar position) and Position 2 (antero-posterior position), both shown in Fig.1.

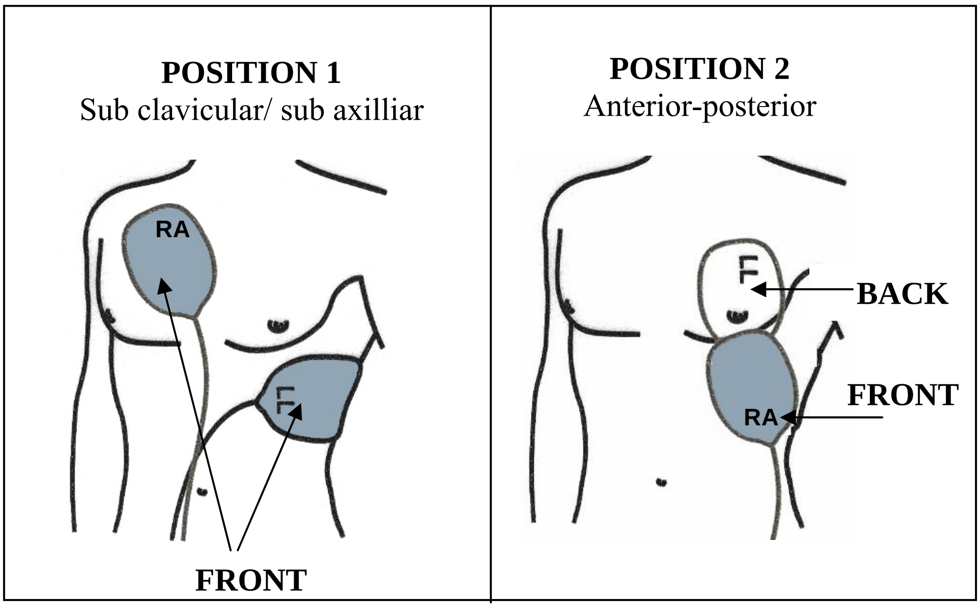


Fig. 1 Study of two positions for PAD electrodes placement

The study was performed with a type of self-adhesive PAD electrodes for defibrillation, pacing and monitoring, used by the Schiller AG Company devices (REF No R700OM-533854). The electrode active surface area was about 92 cm^2 (length of 11,5 cm, width of 8 cm). The TTI was measured according to the interelectrode voltage drop obtained by passing of a low-amplitude high-frequency (23 kHz) current between the two PADs. This is a validated test-impedance technique, which does not require defibrillation shock delivery. The TTI measurements were attendant by 'Impedance-Voltage' control calibration curve, estimated for a set of reference resistances in the total range of human TTIs (between 20 and 200 Ω). For each patient, the TTI was measured 10 s, 1 min and 5 min after sticking on the electrodes to the skin surface, separately for the two tested electrode positions.

Results

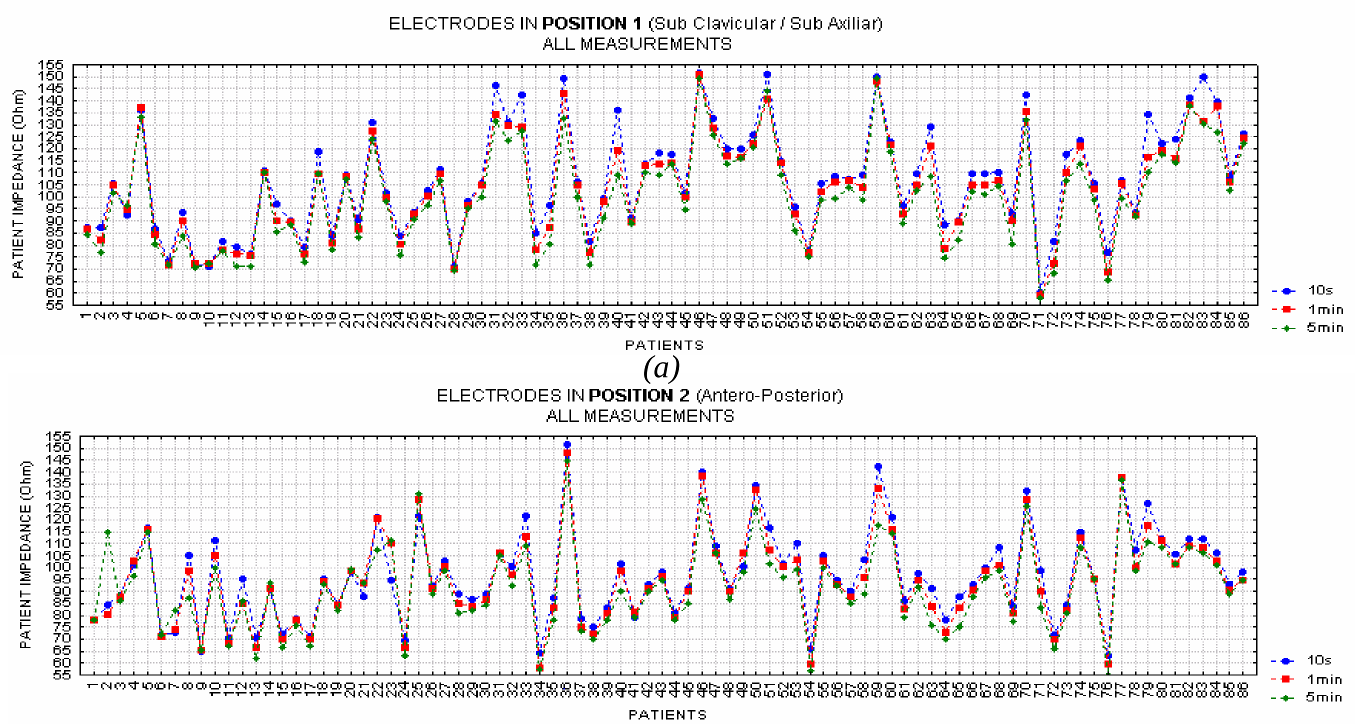
Patients

The population of patients included in the study had the following general characteristics:

- **Total number** of 86 patients - 39 **male** and 47 **female**;
- The **age** of the population was 57,3 ± 14,2 years, from 20 to 83 years;
- The **height** of the population was 167,1 ± 8,9 cm, from 150 to 190 cm;
- The **weight** of the population was 75,9 ± 15,1 kg, from 50 to 110 kg;
- The **chest size** of the population was 103,4 ± 10,7 cm from 86 to 130 cm;
- **Skin type**: 67 patients with **normal** skin type, 13 patients with **dry** skin and 6 patients with **greasy** skin;
- **Chest pilosity**: 70 patients **without** chest pilosity and 16 persons **with** chest pilosity.

TTI: Individual measurements for each patient

The impedance measurements were performed 10 s, 1 min and 5 min after sticking of the defibrillation electrodes in Position 1 or Position 2 over the patient's chest. For each patient, the measured impedance values are presented in Fig. 2.



(b)

Fig. 2 Graph of the TTI individual measurements for each patient, at 10 s (blue circle), 1 min (red square) and 5 min (green diamond) after sticking of the electrodes in Position 1 (a) and Position 2 (b).

TTI: Mean value, Standard deviation (SD), Min-Max ranges

Initially, the general assessment of the impedances for all patients (N = 86) was performed in 3 groups, depending on the passed time interval after sticking of the electrodes:
Group 1: **10s**; Group2: **1min**; Group3: **5min** (see Fig. 3 (a, b) – ALL CASES).
In order to assess the influence of the electrode-skin contact layer, we additionally categorize each of these groups in subgroups for **Pilosity** (categories: **No**, **Yes** – Fig. 3 (a, b) – Pilosity) and for **Skin type** (categories: **Normal**, **Dry**, **Greasy** – Fig. 3 (a, b) – SKIN TYPE).

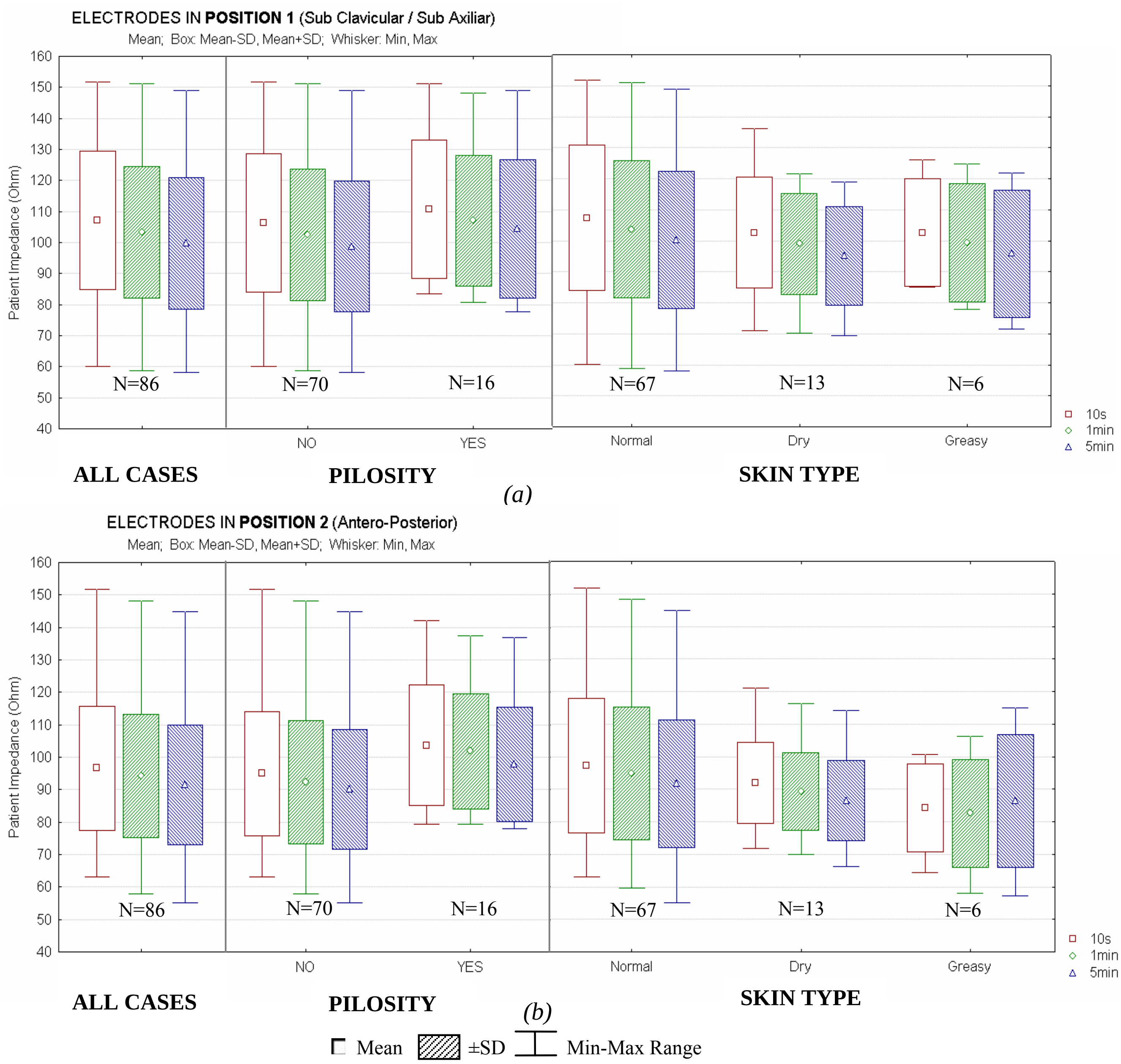


Fig. 3 TTI Study for all cases and for different categories, depending on the pilosity and the skin type. It presents box plot of the impedance Means, Standard deviations and Min-Max ranges for TTI measurements at 10s (red box), 1min (green box) and 5 min (blue box) after sticking of the electrodes in Position 1 (a) and Position 2 (b).

Table 1. Summary results for TTI measurements in electrodes Position 1

POSITION 1			10 s TTI [Ω]		1 min TTI [Ω]		5 min TTI [Ω]	
		N	Mean±Std	Min-Max	Mean±Std	Min-Max	Mean±Std	Min-Max
ALL CASES		86	107,2±22,3	60,2-151,8	103,4±21,1	58,8-151,1	99,8±21,2	58,1-149,0
PILOSITY	No	70	106,4±22,4	60,2-151,8	102,5±21,2	58,8-151,1	98,8±20,9	58,1-149,0
	Yes	16	110,8±22,4	83,5-151,8	107,1±21,0	80,7-148,3	104,5±22,3	77,8-149,0
SKIN TYPE	Normal	67	108,3±23,5	60,2-151,8	104,4±22,2	58,8-151,8	100,9±22,2	58,1-149,0
	Dry	13	103,7±18,1	70,9-136,1	100,1±16,5	70,2-121,7	96,2±16,1	69,5-118,9
	Greasy	6	102,7±17,5	85,1-126,1	99,3±19,0	78,0-124,8	95,8±20,5	71,6-122,0

Table 2. Summary results for TTI measurements in electrodes Position 2

Position 2			**10 s TTI [Ω]**		**1 min TTI [Ω]**		**5 min TTI [Ω]**	
		N	**Mean±Std**	**Min-Max**	**Mean±Std**	**Min-Max**	**Mean±Std**	**Min-Max**
All cases		86	96,6±19,2	63,1-151,8	94,2±19,0	58,0-148,3	91,5±18,5	55,2-144,9
Pilosity	No	70	94,97±19,0	63,1-151,8	92,4±18,9	58,0-148,3	90,1±18,5	55,2-144,9
	Yes	16	103,7±18,6	79,4-142,2	101,8±17,8	79,4-137,5	97,8±17,7	78,0-136,8
Skin Type	Normal	67	98,5±20,2	63,1-151,8	96,0±20,0	59,5-148,3	92,8±19,4	55,2-144,9
	Dry	13	92,6±12,7	71,8-121,0	90,0±12,2	69,9-116,2	87,6±12,1	66,3-144,2
	Greasy	6	84,3±13,4	64,5-100,7	82,6±16,5	58,0-106,2	86,3±20,4	57,3-115,0

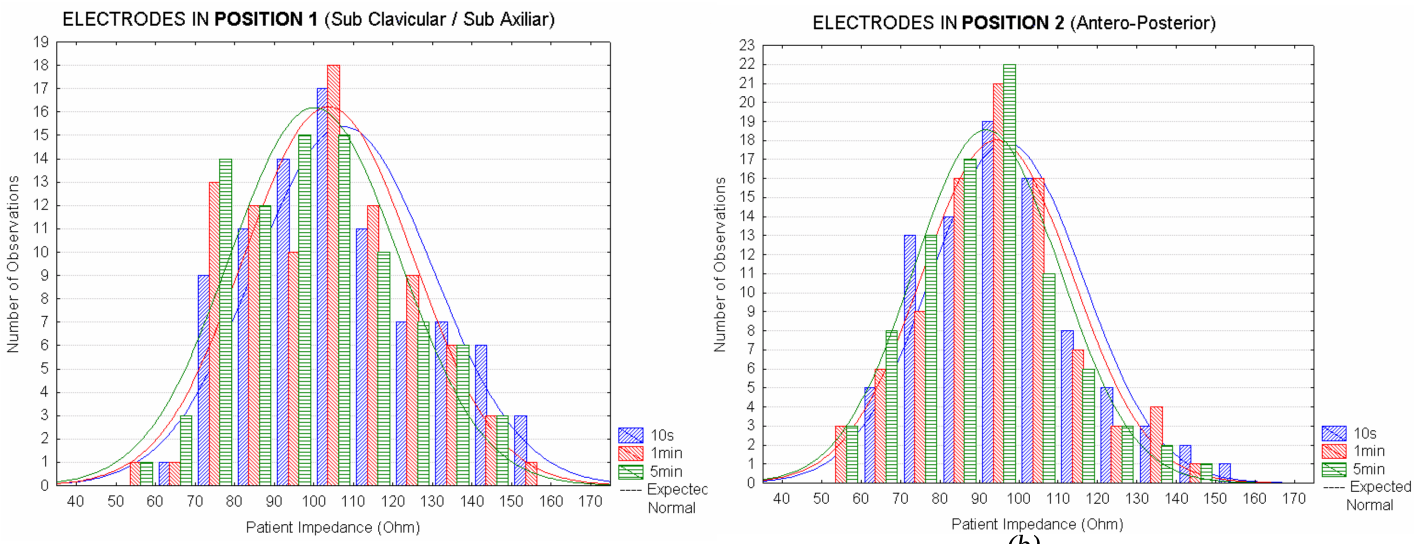
The Student t-test for independent samples, with 95% level of significance was applied for assessment of the differences between the means of the TTI groups in Table 1 and Table 2. We found significant difference ($p < 0,05$) only for the groups:

TTI Position 1:
- *All cases* (10 s) compared to *All cases* (5 min);
- *Pilosity 'No'* (10 s) and *Pilosity 'No'* (5 min).

TTI Position 2:
- *Pilosity 'Yes'* (10 s) and *Pilosity 'No'* (5 min);
- *Pilosity 'Yes'* (1 min) and *Pilosity 'No'* (5 min).

TTI Position 1 compared to TTI Position 2:
- *All cases*: (10 s), (1 min) and (5 min);
- *Pilosity 'No'*: (10 s), (1 min) and (5 min);
- *Skin Type 'Normal'*: (10 s), (1 min) and (5 min).

TTI: Histograms



(a) (b)

Fig. 4 Histograms and the expected normal distributions of TTIs, measured at 10s (blue bar), 1 min (red bar) and 5 min (green bar) in (a) – Position 1 and (b) – Position2

TTI: Correlation coefficients

The correlations between TTI and the individual patient characteristics (chest size, weight, height, age) were tested. The tests show a significant correlation ($p < 0,05$) only between TTI and 2 characteristics (chest size and weight), but all correlation coefficients (r) are bellow 0,5.

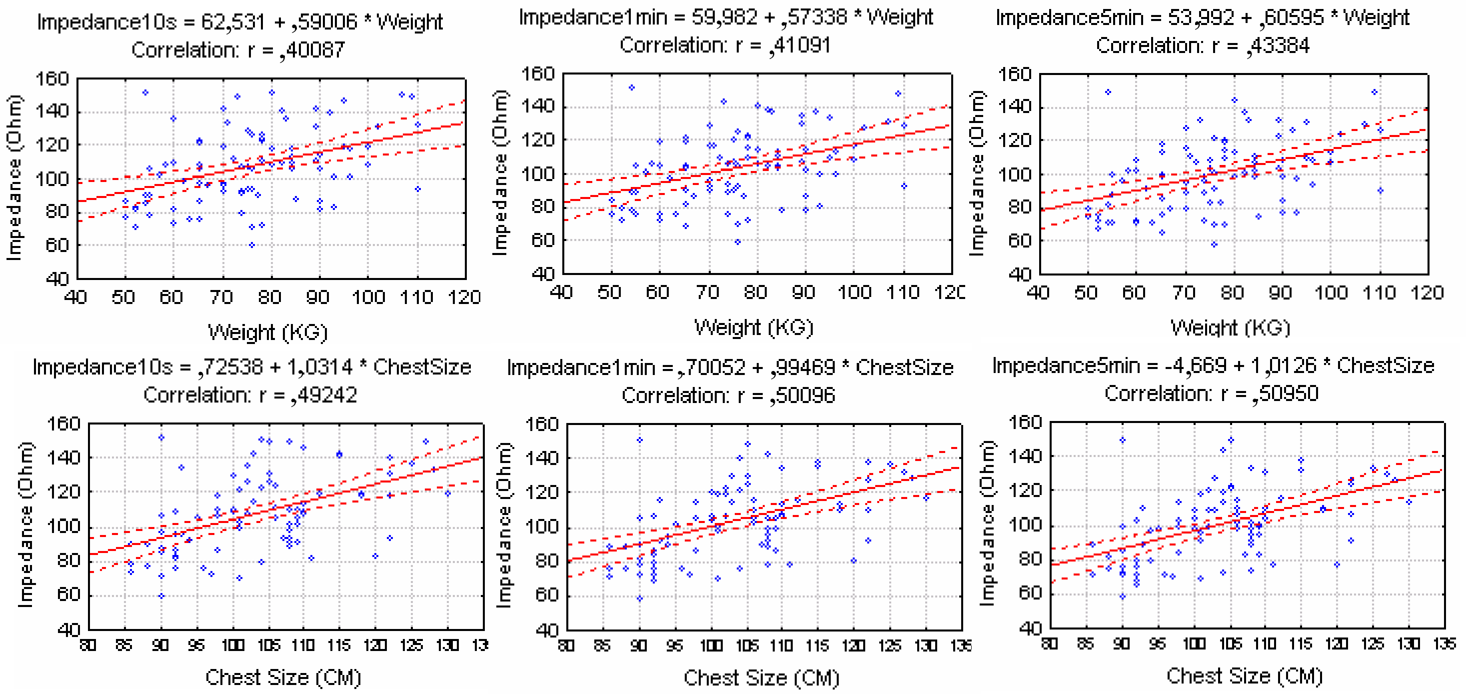


Fig. 5 Graph of TTI in Position 1 versus weight and chest size (observations for each patient). The red line represents the regression equation. The dot line is 95% confidence.

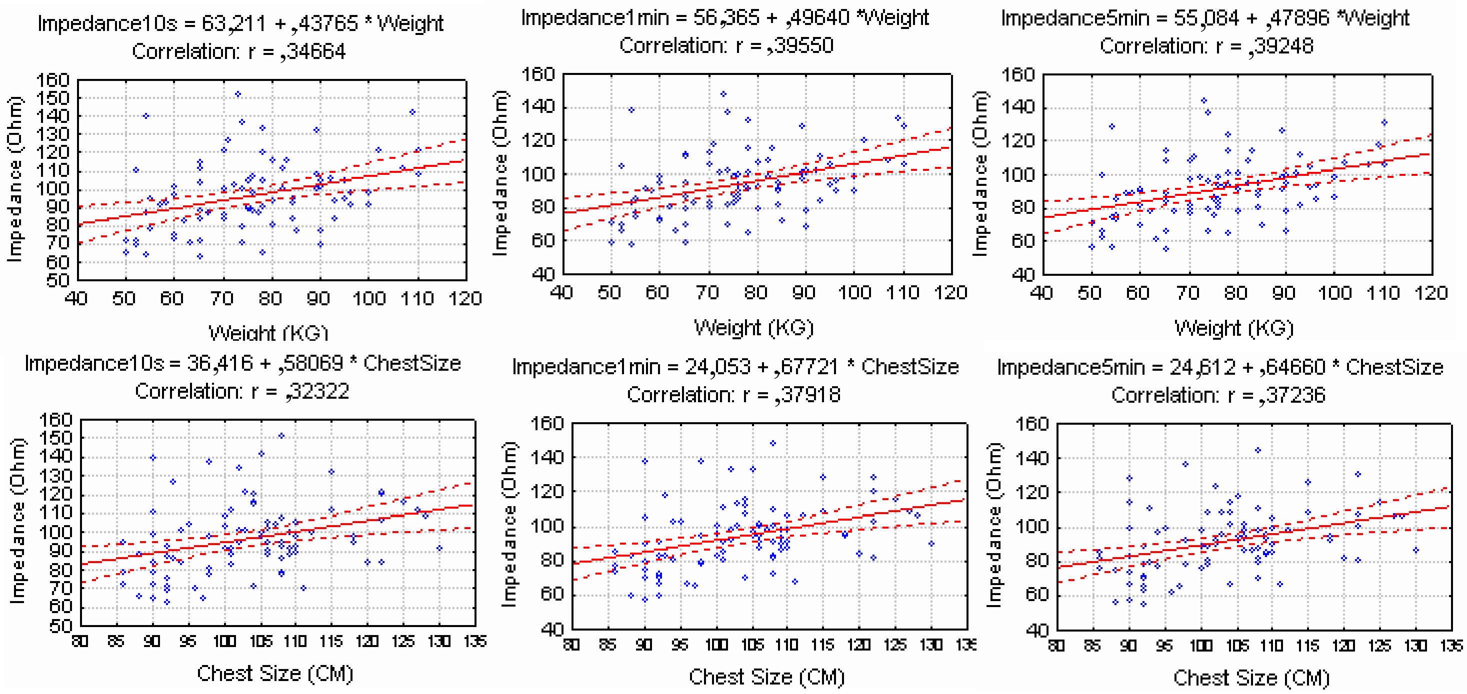


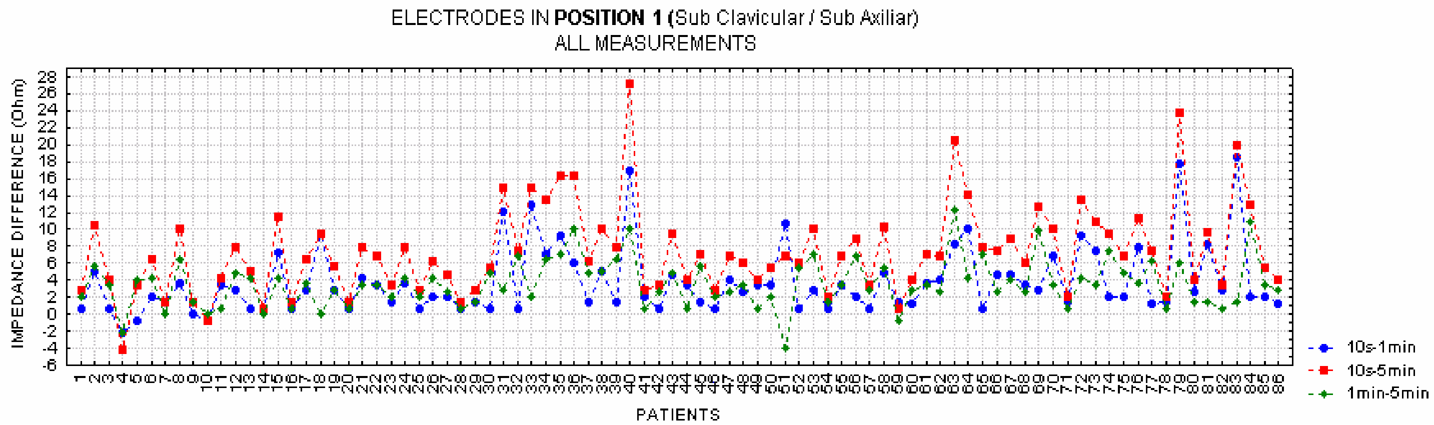
Fig. 6 Graph of TTI in Position 2 versus weight and chest size (observations for each patient). The red line represents the regression equation. The dot line is 95% confidence.

TTI Variance in time: Individual measurements for each patient

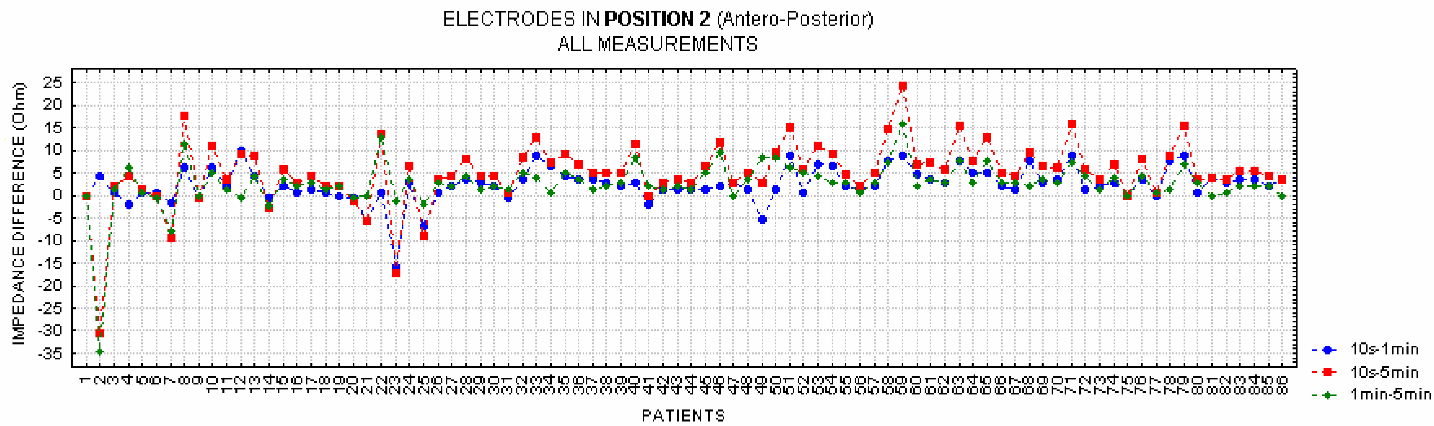
Since the long-term application of the defibrillation electrodes in real cases is a well established practice, we aimed at assessment of the interelectrode impedance variance in time by calculation of three differences:

- *ImpedanceDifference**1*** = *Impedance**10s*** - *Impdedance**1min***;
- *ImpedanceDifference**2*** = *Impedance**10s*** - *Impdedance**5min***;
- *ImpedanceDifference**3*** = *Impedance**1min*** - *Impdedance**5min***.

For each patient, the measured TTI differences are presented in Fig. 7a (Position 1) and in Fig. 7b (Position 2).



(a)



(b)

Fig. 7 Graph of TTI differences (specific for each patient) calculated for the above defined time intervals: '10s-1min' (blue circle); '10s-5min' (red square) and '1min-5min' (green diamond). The impedance measurements for the both electrodes positions – Position 1 (a) and Position 2 (b) were taken into account.

TTI Variance in time: Mean value ± SD, Min-Max ranges

Assessment of the TTI variance in time was presented by means, standard deviations and min-max ranges for the three groups defined below (see Fig. 8 (a, b) – ALL CASES):

Group1: *ImpedanceDifference**1*** = *Impedance**10s*** - *Impdedance**1min***;
Group2: *ImpedanceDifference**2*** = *Impedance**10s*** - *Impdedance**5min***;
Group3: *ImpedanceDifference**3*** = *Impedance**1min*** - *Impdedance**5min***.

In order to assess the influence of the electrode-skin contact layer, we additionally categorize each of these groups in subgroups for **Pilosity** (categories: **No**, **Yes** – Fig. 8 (a, b) – Pilosity) and for **Skin type** (categories: **Normal**, **Dry**, **Greasy** – Fig. 8 (a, b) – SKIN TYPE).

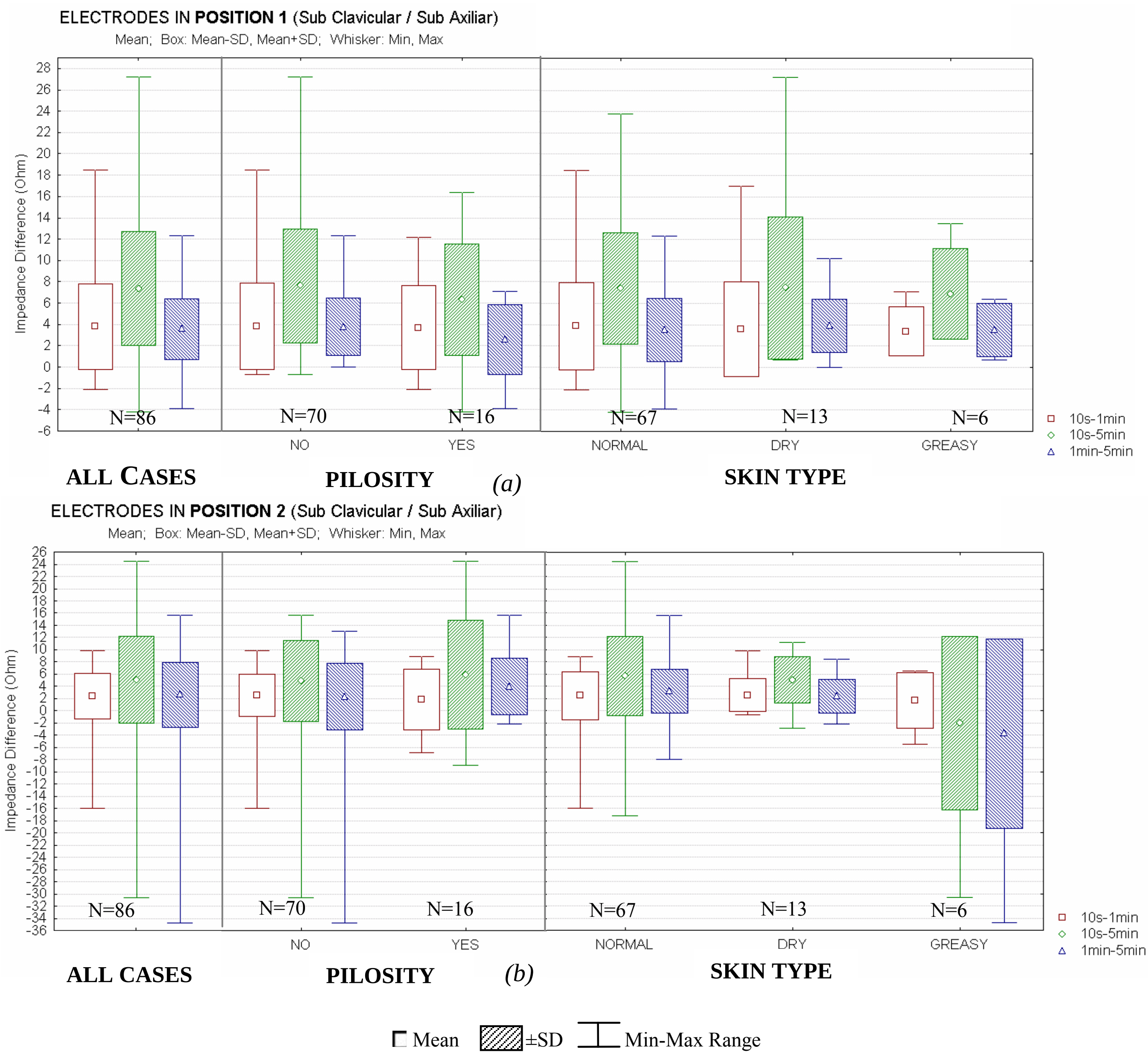


Fig. 8 Study of TTI variance in time for all cases and for different categories, depending on the pilosity and the skin type for electrodes Position 1 (a) and Position 2 (b). It presents box plot of the TTI variance: Means, ± SD and Min-Max ranges, calculated for the specified groups: '10s-1min' (red box); '10s-5min' (green box) and '1min-5min' (blue box)

Table 3. Summary results for TTI variance in time for electrodes Position 1

POSITION 1			**10 s - 1min Impedance Variation**		**10s - 5 min Impedance Variation**		**1min - 5 min Impedance Variation**	
		N	**Mean±Std**	**Min-Max**	**Mean±Std**	**Min-Max**	**Mean±Std**	**Min-Max**
ALL CASES		86	3,8±4,03	-2,1÷18,5	7,36±5,33	-4,2÷27,2	3,56±2,85	-3,9÷12,3
PILOSITY	No	70	3,83±4,08	-0,7÷18,5	7,61±5,36	-0,7÷27,2	3,78±2,72	0,0÷12,3
	Yes	16	3,71±3,91	-2,1÷12,2	6,29±5,22	-4,2÷16,4	2,58±3,28	-3,9÷7,1
SKIN TYPE	Normal	67	3,89±4,11	-2,1÷18,5	7,39±5,21	-4,2÷23,8	3,5±2,97	-3,9÷12,3
	Dry	13	3,57±4,44	0,7÷17,0	7,47±6,65	0,7÷27,2	3,9±2,49	0,0÷10,2
	Greasy	6	3,38±2,3	1,3÷7,1	6,88±4,25	2,8÷13,5	3,5±2,48	0,7÷6,4

Table 4. Summary results for TTI variance in time for electrodes Position 2

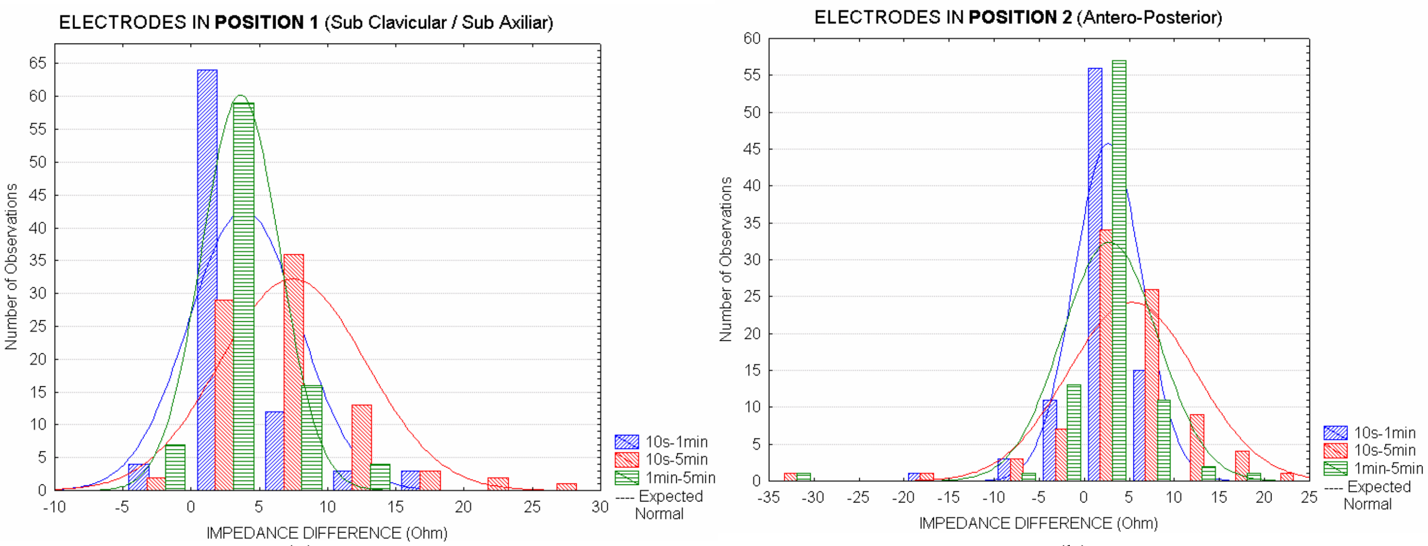
Position 2			10 s - 1min Impedance Variation		10s - 5 min Impedance Variation		1min - 5 min Impedance Variation	
		N	Mean±Std	Min-Max	Mean±Std	Min-Max	Mean±Std	Min-Max
All cases		86	2,44±3,75	-15,9÷9,9	5,06±7,08	-30,6÷24,5	2,62±5,29	-34,8÷15,7
Pilosity	No	70	2,56±3,44	-15,9÷9,9	4,88±6,64	-30,6÷15,7	2,31±5,41	-34,8÷13,0
	Yes	16	1,89±4,98	-6,8÷8,9	5,88±8,94	-8,9÷24,5	3,98±4,65	-2,1÷15,7
Skin Type	Normal	67	2,44±3,9	-15,9÷8,9	5,7±6,45	-17,2÷24,5	3,23±3,52	-7,9÷15,7
	Dry	13	2,6±2,63	-0,7÷9,9	5,05±3,8	-2,9÷11,3	2,45±2,77	-2,2÷8,5
	Greasy	6	1,7±4,53	-5,9÷6,5	-2,02±14,2	-30,6÷7,2	-3,72±15,51	-34,8÷8,3

The Student t-test for independent samples, with 95% level of significance was applied for assessment of the differences between the means of all TTI groups calculated in Table 3 or Table 4. When considering the total population (all cases), we found that there was no significant difference between the mean TTI variance for time intervals '10s-1min' and '1min-5min' ($p>0,05$). Significant difference existed ($p < 0,05$) only between:

- '10s-5min' and '10s-1min';
- '10s-5min' and '1min-5min'.

Moreover, we found that the TTI groups for the pilosity and skin type do not differ, because the t-test comparing these categories showed the p-level of significance above 0,05. The comparison between all similar TTI groups for the both electrode positions showed also no difference ($p > 0,05$).

TTI Variance in time: Histograms



(a) (b)

Fig. 9 Histograms and expected normal distributions of TTI variances in time, calculated for specified time intervals: '10s-1min' (blue bar); '10s-5min' (red bar) and '1min-5min' (green bar) for (a) – Position 1 and (b) – Position2.

Discussion and conclusion

We could formulate the following conclusions based on the performed TTI measurements with self-adhesive PAD electrodes (active area about 92 cm^2) on 86 patients:

- TTI range is comparable for the two tested PAD positions - between 58 Ω and 152 Ω for sub-clavicular/sub-axillar electrode position and between 55 Ω and 149 Ω for antero-posterior position.
- TTI mean/±SD value in sub-clavicular/sub-axillar position (107,2±22,3) Ω is significantly higher than TTI in antero-posterior position (96,6±19,2) Ω. The both TTI means are higher than reported results, e.g. Kerber et al. 1984 [12] found (75±21) Ω for apex-anterior or apex-posterior position; Garcia and Kerber 1998 [5] reported (82±24,7) Ω for anterior-apex, (71,2±23,5) Ω for apex-posterior, (77±24,7) Ω for anterior-posterior. However, TTIs in these studies were measured during shock [12] and test-pulse application [5] − a TTI measurement techniques, which are associated with electroporation leading to TTI reduction.
- Both the pilosity and the skin type do not change significantly the TTI value, however the patients with chest pilosity presented slightly higher TTI than those without pilosity. The TTI was higher for normal skin, followed by dry and greasy skin.
- TTI presented weak correlation with both the patient chest size and weight ($r < 0,5$, $p < 0,05$). Comparable results are reported for TTI correlation with body weight ($r = 0,45$) [10], chest width ($r = 0,8$) [10] and body surface area ($r = 0,6$) [5].
- The mean value of the TTI decreases in time for all defined groups, as well as for the two electrode positions. The impedance drop in the time interval (10s to 1min) after sticking on the electrodes is about (3,8±4,03) Ω for sub-clavicular/sub-axillar position and about (2,44±3,75) Ω for antero-posterior position. The impedance drop in the time interval (1min to 5min) after sticking on the electrodes is about (3,56±2,85) Ω for sub-clavicular/sub-axillar position and about (2,62±5,29) Ω for antero-posterior position. The total impedance drop for 5 min time interval of sticking on the electrodes is (7,36±5,33) Ω for sub-clavicular/sub-axillar position and about (5,06±7,08) Ω for antero-posterior position. For both electrode positions, the t-tests show no significant difference between the mean TTI variance for time intervals (10s-1min) and (1min-5min) ($p > 0,05$). However, both mean TTI variances (10s-1min) and (1min-5min) presents significant difference ($p < 0,05$) in comparison with the TTI drop estimated for the total period of observation (10s-5min).
- The electrode impedance drop in time is not influenced by the pilosity or skin type.

Acknowledgments

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