Linear Variation Analysis of Intracardiac Atrial Impedance During Internal Cardioversion using Rectilinear Waveforms and Energy Step Up Protocol

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Abstract

The major determinants of success during internal cardioversion of atrial fibrillation (AF) are voltage, duration and intracardiac impedance (ICI). However, there is a paucity of published data regarding evidence of ICI dynamics during internal cardioversion of AF using very-low-tilt rectilinear (VLTR) waveforms with stepped energy protocols. In this study, patients with persistent AF were internally cardioverted using both biphasic and monophasic very-low-tilt rectilinear (B-VLTR and M-VLTR) waveforms with a step up energy protocol (50V to 300V). The ICI of patients who had more than 4 shocks delivered were retrospectively analyzed from recorded voltage and current waveforms.

A significant reduction in ICI was noticed after each of the first shocks using B-VLTR. The linear change of ICI within a shock, as characterized by its slope (Zm), increased in algebraic value and presented polarity reversal between the positive and negative phase within a B-VLTR shock, particularly after the first shock, where both B-VLTR and M-VLTR presented positive 2nd derivatives.

The results obtained provide valuable evidence for understanding electrode-tissue interface factors depending on VLTR defibrillation waveform amplitude, duration and current reversal action.

1. Introduction

Atrial fibrillation (AF) is one of the most common cardiac arrhythmias encountered in medical practise. AF occurs in approximately 0.65% of the population between the ages of 45 and 64 years and has a prevalence of 9% among those over 80 years of age [1,2]. It is currently estimated to affect approximately 4.5 million people in Europe and over 2.2 million people in the USA.

Atrial fibrillation is one of the leading causes of stroke, with the associated after care costs identified as being almost entirely preventable. Consequently, the need for the continued investigations and improvements in AF associated therapies remains self evident [3,4].

For chronic AF sufferer's where pharmacological intervention is contraindicated or ineffective, internal synchronised electrical cardioversion using a step energy protocol is most often the only effective treatment available. However, optimisation of defibrillation shock waveform is still the subject of much debate. Historically, defibrillation shock waveforms have been generated using standard capacitive discharge circuits. However, it has been reported in the literature the successful use of a radio-frequency (RF) defibrillator for transcutaneous passive atrial defibrillation, which delivers a very low-tilt rectilinear (VLTR) power pulse waveform that has been found to be both safe and effective [5,6]; thereby enabling defibrillation thresholds as low as 1.27 joules in the acute AF case. Yet, strategies for the development of sub 1J defibrillation threshold protocols are required if patient sedation is to be avoided and the low-cost passive implantable atrial defibrillator is to become an attractive alternative [7].

The objective of this work was therefore to investigate the dynamic changes of intracardiac atrial impedance during internal cardioversion using a step up energy protocol with very-low-tilt monophasic and biphasic defibrillation waveforms; with a view to understanding the likely impact on AF electrical cardioversion protocol efficacy.

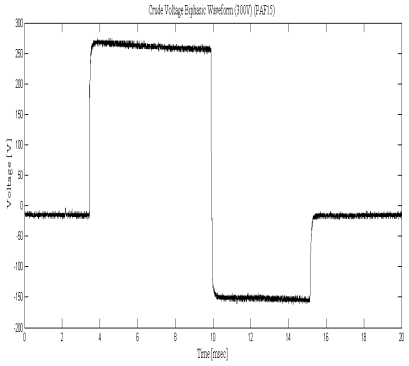
2. Methods

2.1. Study design and patients

Thirty patients with persistent AF, who would clinically benefit from electrical cardioversion and with previous history of failed transthoracic cardioversion were recruited for a comparative study of low tilt biphasic *and low tilt* monophasic waveform for internal cardioversion of atrial fibrillation. Each patient was fully anticoagulated for 4 weeks prior procedure. The patient was adequately sedated prior cardioversion. Internal

cardioversion was done using a step up protocol after adequate sedation. During internal cardioversion current and voltage was recorded using a digital oscilloscope (Tektronix TDS-3014B) and a current probe (Fluke 80i-110s). Dynamic intracardiac impedance (ICI) analysis of patients, who had more than 4 step up shocks were retrospectively analysed from the applied voltage and current shock waveforms recorded during cardioversion.

The Patients were randomised prior to internal cardioversion to 12-ms duration biphasic VLTR {B-VLTR, chronosymmetric (6ms/6ms), amplitude asymmetric (negative phase at 50% amplitude) waveform, (Fig. 1a)} and monophasic VLTR {M-VLTR waveform (Fig. 1b)} using random cards. Step up voltage protocol (50V to 300V) used during the study is as presented in Table 1.



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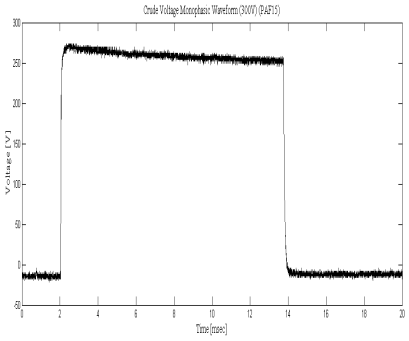

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Figure 1. RF defibrillator generated very-low tilt waveveforms: (a) biphasic (B-VLTR), 6/6ms, voltage waveform, (b) monophasic (M-VLTR), 12ms, waveform.

2.2. Electrodes location

Single use, commercially available defibrillation catheters (St. Jude 6 French Inquiry™ internal cardioversion catheter) was positioned in the right atrium and the distal coronary sinus, under fluoroscopic guidance (Fig. 2). The internal defibrillation catheter was connected to the custom built radiofrequency defibrillator using St Judes internal cardioversion junction box.

Table 1. Step up protocol with voltage and shock energy (referred to a 50Ω heart impedance).

	Study Arm 1 Biphasic, 6/6 (ms)		Study Arm 2 Monophasic, 12 (ms)	
Step	Ph1, Volts	Energy (J)	Voltage	Energy (J)
S1	50	0.38	50	0.6
S2	100	1.5	100	2.4
S3	150	3.38	150	5.4
S4	200	6.0	200	9.6
S5	240	8.62	240	13.8
S6	280	11.8	280	18.8
S7	300	18.5	300	21.6

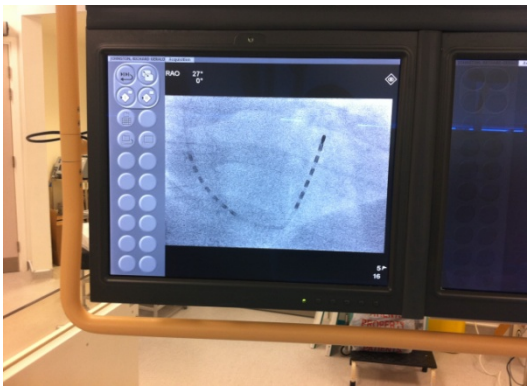


Figure 2. Position of defibrillation catheters in the right atrium (RA) and coronary sinus (CS) for internal cardioversion of AF (right anterior oblique view).

2.3. Signal and clinical data acquisition

Prior to the commencement of treatment, a low voltage test shock (50V) was delivered to a dummy load (47Ω) to verify system readiness and synchronisation with the patients ventricular activity (R wave). Defibrillation was then performed using either a monophasic or biphasic (randomised) VLTR electrical shock waveform as per the stepp up protocol (Table 1). The maximum voltage level is 300V. Success was defined as a return to normal rhythm for a period of 30 seconds or more. The voltage and current waveforms from each shock delivered were recorded using the digital oscilloscope (Tektronix TDS 3014B). The minimum sampling frequency used by the oscilloscope was 250kHz.

2.4. Dynamic impedance analysis

The internal cardiac impedance (ICI) across the RA and CS electrodes, was considered a dc impedance or resistive load, where voltage/current ratio provides a

reasonable estimate of the load into which the wave generator is working [8]. For the dc ICI analysis type, averaged voltage and current at each waveform phase were calculated to get an unique value for each pulse wave segment for B-VLTR (positive and negative phase segments) and M-VLTR waveforms, thus allowing to calculate the dc impedance value (V/I).

The second type of dynamic ICI analysis was done by computing the impedance slope, **Z(m)**, in units of Ω/s, in the early waveform segment part (1-5ms, positive phase in B-VLTR) and in the late segment part (7-11 ms, negative phase in B-VLTR). For this, the standard statistical linear regression slope component (m), was computed for the impedance sample points along each 4ms waveform segment (at least 1000 calculated impedance points). This robust approach was adopted in order to detect subtle ICI linear variations along the 4ms time period; without having to use a potentially controversial very-low frequency digital filtering based approach; due to associated RF defibrillator high frequency noise in the voltage and current waveforms.

2.5. Statistical analysis

Results are expressed as mean ± standard deviation in ohms for all ICI measurements, for both the B-VLTR (+ phase), B-VLTR (- phase) and M-VLTR. Student-t test was used to determine whether there was any significant difference between the groups. A paired, two-tail value of $p < 0.05$ was considered as statistically significant.

3. Results

Two types of dynamic ICI analysis were considered. First dc ICI values (average in a particular time-segment) were calculated from the recorded V and I waveforms (Table 2), then on the linear rate of ICI change (Z(m)), within the 12ms shock waveforms and along the step up of defibrillation shock voltages, particularly, progressive Z(m) changes in the first three shocks (Table 3).

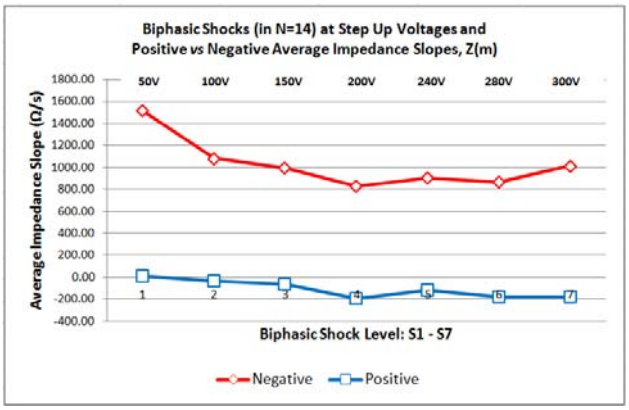
Table 2. Results of impedance (Z) change analysis with step up shocks and within a B-VLTR shock.

Shock Waveform Type/Part →	B-VLTR (N=14) Positive	B-VLTR (N=14) Negative	M-VLTR (N=12)
Mean Z @ S1 (Ω ± SD)	76.79 ±14.9	74.07 ±14.2	75.17 ±17.8
Mean Z @ S2 (Ω ± SD)	72.64 ±13.8	71.43 ±12.2	73.25 ±16.1
|ΔZ| after S1 (Ω) (p-value)	4.15 (p< 0.00053)	2.64 (p< 0.0581)	1.917 (p < 0.6284)
Mean Z @ S3 (Ω ± SD)	72.07 ±12.8	72.50 ±13.6	72.00 ±15.4
|ΔZ| after S2 (Ω) (p-value)	0.57 (p < 0.3276)	1.07 (p < 0.4242)	1.25 (p < 0.1192)
Mean Z: S4 → S7 (Ω ±SD)	68.93 ±11.9	70.48 ±12.5	71.00 ±14.6

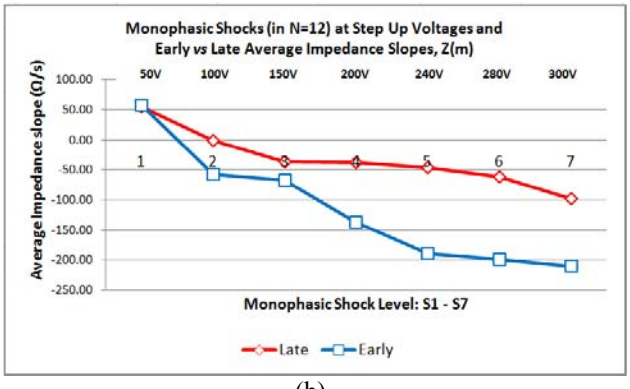
Table 3. Results of dynamic impedance slope Z(m) analysis within a shock, and with step up shocks.

Shock Waveform Type/Part →	B-VLTR (N=14) Positive	B-VLTR (N=14) Negative	M-VLTR (N=12) Early	M-VLTR (N=12) Late
Mean Z(m) @ S1 (Ω/s ±SD)	11.47 ±150.66	1518.4 ±640.02	57.93 ±154.97	55.37 ±153.75
Mean Z(m) @ S2 (Ω/s ±SD)	-37.00 ±124.5	1082.7 ±169.36	-56.81 ±147.12	-1.13 ±105.86
|ΔZ(m)| after S1 (Ω/s) (p-value)	48.47 (p< 0.487)	435.77 (p< 0.039)	114.74 (p< 0.120)	56.50 (p< 0.109)
Mean Z @ S3 (Ω/s ± SD)	-63.04 ±59.60	997.92 ±260.74	-66.90 ±73.91	-35.98 ±94.99
|ΔZ(m)| after S2 (Ω/s) (p-value)	26.04 (p< 0.40)	84.73 (p< 0.387)	10.09 (p< 0.986)	34.85 (p< 0.415)
Mean Z(m):S4→S7 (Ω/s ±SD)	-164.7 ±116.7	898.9 ±150.3	-180.5 ±89.8	-56.28 ±73.29

Dynamic ICI slope trends in particular segments of the B-VLTR (Positive *vs* Negative phase) and M-VLTR (Early *vs* Late) waveforms, along the seven increasing voltage steps, is graphically presented in Fig. 3. There, with B-VLTR waveforms, 14 patient cases were averaged at each shock step (S1-S7), and for M-VLTR waveforms, 12 patients were included and similarly averaged.



(a)



(b)

Figure 3. Average dynamic impedance slope (Z(m)) for (a) B-VLTR and (b) M-VLTR shock waveforms along the step up voltage protocol: S1 → S7.

4. Discussion

Significant reduction in dc ICI (ΔZ) was noticed after the first shock (S1) using B-VLTR waveform, and only in the positive phase (4.15Ω, p <0.00053). The difference between dc ICI in the positive and in the negative phase of B-VLTR was not significant within S1 (2.72Ω, p<0.057) and for subsequent shocks (0.71Ω, p<0.293). Impedance reduction was not significant with M-VLTR waveforms at any shock level at all, and in fact, for both waveform types, dc ICI reduction after S2 was minimal and practically negligible after S3, which was evidenced by smaller dc ICI standard deviations in the last 4 shocks (not presented in Table 2).

The estimated linear variation of ICI within early (positive) and late (negative) segments of a shock, characterized by its slope, Z(m), revealed a different and consistent behavioral pattern of ICI dynamics, as summarised by Table 3 and Fig. 3. From the ICI Z(m) analysis, it was noticed that Z(m) increased significantly in algebraic value and presented polarity reversal between the positive and negative phase within a B-VLTR shock, particularly after the first shock, where both B-VLTR and M-VLTR presented positive 2nd derivatives of Z(m). Results in Table 3 also indicate an overall insignificant variation of Z(m), that is |ΔZ(m)|, with step up shocks. Significant difference in values of |ΔZ(m)| are mainly observed between early and late segments (positive and negative phase in B-VLTR), within the 12ms of the shock waveform. This fact is more clearly evidenced in Fig. 3, as the red and blue curves in both Fig. 3(a) and Fig. 3(b), diverge from each other, without any crossover point after the first shock (S1).

Nevertheless, an interesting dynamic feature observed in Table 3, is that |ΔZ(m)| reached a significant difference after S1 for B-VLTR (Negative). An electrophysiological interpretation of this particular dynamic behaviour of Z(m), could be the possible condition for triggering complex dynamic voltage mediated channel ion currents; activated by the electric field reversal just at the first shock; however, this observation would lead us to ask why does this occur only for the first shock? This is something yet to be answered, but could be related to some findings that have reported for example that the first shock plays the most important role on AF ECG organization studies through Sample Entropy [9].

A contrasting difference between **intra-shock** dc ICI and Z(m) dynamic behaviour, is in their trends with step up voltage level, for both B-VLTR and M-VLTR waveforms. With dc ICI there is no clear tendency of change. Whereas with Z(m): Early *vs* Late segments, there is a significant incremental change (**ΔZm**) tendency with step up shock levels. This becomes consistently for both B-VLTR and M-VLTR after the S3 and up to the S7; (1068**Ω/s** ±81.1**SD**) and (123**Ω/s** ±20.3**SD**) respectively.

5. Conclusions

Significant dc ICI reduction was noted with B-VLTR waveforms after first shock at 50V level. ICI reduction with biphasic waveforms would correlate to higher cardioversion success rate when compared to monophasic waveforms. The non-significant effect on dc ICI by M-VLTR waveforms may suggest a significant dependence of ICI and the electrode-tissue interface upon providing a temporary current reversal within the shock duration.

The dynamic ICI slope (Z(m)) data obtained provides valuable evidence for understanding electrode-tissue interface factors depending on VLTR defibrillation waveform amplitude, duration and current reversal action. It also can reveal potential electrophysiological implications that could help to explain the evidenced superiority of B-VLTR over M-VLTR for AF cardioversion [6].

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