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Waveform analysis of biphasic external defibrillators

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Abstract

Background and Objective: All internal defibrillators and some external defibrillators use biphasic waveforms. The study analysed the discharged waveform pulses of two manual and two semi-automated biphasic external defibrillators. *Methods and Results:* The defibrillators were discharged into resistive loads of 25, 50 and 100 Ω simulating the patient's transthoracic impedance. The tested biphasic defibrillators differed in initial current as well as initial voltage, varying from 10.9 to 73.3 A and from 482.8 to 2140.0 V, respectively. The energies of the manual defibrillators set at 100, 150 and 200 J deviated by up to + 19.1 or − 28.9% from the selected energy. Impedance-normalised delivered energy varied from 1.0 to 12.5 J/Ω. Delivered energy, shock duration and charge flow were examined with respect to the total pulse, its splitting into positive and negative phases and their impedance dependence. For three defibrillators pulse duration increased with the resistive load, whereas one defibrillator always required 9.9 ms. All tested defibrillators showed a higher charge flow in the positive phase. Defibrillator capacitance varied between approximately 200 and 100 μF and internal resistance varied from 2.0 to 7.6 Ω. Defibrillator waveform tilt ranged from − 13.1 to 61.4%. *Conclusions:* The tested defibrillators showed remarkable differences in their waveform design and their varying dependence on transthoracic impedance. © 2001 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: Automated external defibrillator (AED); Cardiac arrest; Defibrillation; Emergency medical services; Manual defibrillator; Transthoracic impedance

Resumo

Contexto e Objectivo: Os desfibrilhadores internos e alguns desfibrilhadores externos utilizam ondas bifásicas. O estudo analisou as ondas geradas por dois desfibrilhadores externos manuais e dois semi-automáticos bifásicos. *Métodos e Resultados:* Os desfibrilhadores foram descarregados contra cargas de resistência de 25, 50 e 100 Ω, simulando a impedância transtorácica dos doentes. Os desfibrilhadores bifásicos testados diferiram na corrente, que variou de 10.9 a 73.3 A e na voltagem iniciais de 482.8 a 2140.0 V, respectivamente. As energias dos desfibrilhadores manuais, definidas a 100, 150 e 200 J desviaram-se até + 19.1 ou –28.9% da energia seleccionada. A energia administrada, com impedância normalizada, variou de 1.0 a 12.5 J/Ω. Para cada descarga foram analisadas a energia administrada, a duração do pulso e a direcção da carga em relação à onda total, subdividindo-se em fases positivas e negativas e quanto à dependência da impedância. Para três desfibrilhadores a duração do choque aumentou com a carga de resistência, enquanto um desfibrilhador requereu sempre 9.9 ms. Todos os desfibrilhadores testados mostraram uma corrente de carga maior na fase positiva. A capacitância dos desfibrilhadores e a resistência interna variaram, entre aproximadamente 200 e 100 μF e entre 2.0 a 7.6 Ω respectivamente. O 'tilt' da onda dos desfibrilhadores variou de –13.1 a 61.4%. *Conclusões:* Os desfibrilhadores testados mostraram diferenças importantes no desenho das suas ondas e evidenciaram dependência variável da impedância transtorácica. © 2001 Elsevier Science Ireland Ltd. All rights reserved.

Palavras chave: Desfibrilhador automático Externo (DAE); Paragem cardíaca; Desfibrilhação; Serviços de Emergência Médica; Desfibrilhador manual; Impedância transtorácica

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1. Introduction

Ventricular fibrillation is the principal cause of sudden cardiac arrest. The most effective treatment for ventricular fibrillation is electrical defibrillation [1]. Besides performing defibrillation at the earliest possible time, the waveform may also be crucial for success. Presently the majority of external defibrillators use monophasic waveforms. In contrast to external defibrillators, state-of-the-art internal defibrillators use biphasic truncated exponential waveforms [2] which have proved superior to monophasic waveforms [3,4]. Positive evidence for safety and clinical effectiveness of biphasic truncated exponential waveforms for internal and external use was ascertained by the AHA ECC committee [1,4].

Clinical studies [5–12], reports [13] and animal experiments [14–18] have shown at least equality between biphasic and monophasic waveforms for transthoracic defibrillation and transthoracic cardioversion. Biphasic waveforms offer the benefit of a lower defibrillation threshold; the risk of heart damage from excessive pulse energy is thus lowered and the chance for successful defibrillation increases.

Using different waveforms and variable energy levels defibrillator manufacturers offer various types of external defibrillators. This holds both for monophasic [19] and biphasic waveforms. The aim of the present laboratory study was to determine the energy content of the discharge in comparison to the selected energy and to ascertain the actual discharge waveform described by different characteristic parameters.

The discharged pulse energy and waveform of two manually biphasic external defibrillators (MCED) and two semi-automated biphasic external defibrillators (SAED) was analysed.

2. Materials and methods

Two MCED, the Medtronic Physio-Control LIFEPAK 12 (LIFEPAK 12) and the Zoll M-Series Biphasic (M-Series), and two SAED, the Laerdal Heartstart ForeRunner (ForeRunner) and the Survivalink FirstSave STAR (FirstSave), were tested. The MRL defibrillator was not available to the authors.

The MCED provide a variety of shock energies from 2 to 360 J. The appropriate energy is selected before defibrillation. The SAED, as first-responder devices, do not allow manual selection of energy.

2.1. Pulse generation

According to the manufacturer's manuals, three of the four tested defibrillators, LIFEPAK 12, ForeRunner and FirstSave, use a truncated exponentially decaying waveform (Fig. 1), both for the positive and negative part of the biphasic waveform. These defibrillators store their electrical energy in a capacitor which is charged to a certain voltage level according to the required energy. Discharging a charged capacitor into a resistor results in an exponential decay of the shock waveform. To achieve a biphasic truncated exponentially decaying waveform, the current of the capacitor discharge is switched off automatically after a certain time (time of phase reversal). Then the current is reversed in polarity and switched on again for a certain negative shock period.

In contrast, the M-Series defibrillator employs a serrated positive waveform phase and an exponentially decaying negative waveform phase (Fig. 1). The serrated positive component is brought about by adjusting the defibrillator's internal resistance during the first waveform phase.

The capacitor, the internal resistance, the waveform-truncating and phase-reversing timing circuit and the patient's transthoracic impedance constitute the discharge circuit of the four tested defibrillators. By changing the patient's transthoracic impedance the characteristics of the discharge circuit can be altered. Consequently, the patient's transthoracic impedance determines the waveform of the shock and thus its energy, initial voltage, pulse duration and time of phase reversal.

In order to detect the patient's transthoracic impedance the defibrillators may use manufacturer-dependent integrated measuring devices (patents: US 5645571, US 6047212, US 5230336, US 5431687, US 5800462, US 5904706, US 5111813, EP 315368, EP 457604; [20]).

2.2. Waveform measurement

The defibrillators were discharged into resistive loads of 25, 50 and 100 Ω simulating the patient's individual transthoracic impedance, as described recently for monophasic defibrillators [19]. The various loads were achieved by combining two resistors, a 1 Ω resistor and an adjustable 1–100 Ω resistor, in a series configuration providing voltage proportioning. The voltage across the 1 Ω resistor was connected to a PC-based measurement system (Dewetron, Graz, Austria). The waveform was digitised and stored at a sampling rate of 20 kHz and 16 bit amplitude resolution. Pulse amplitude resolution was better than 0.6 V or 6 mA for 100 Ω (12 mA for 50 Ω and 24 mA for 25 Ω).

The two MCED LIFEPAK 12 and M-Series were charged to selected energies of 100, 150 and 200 J and discharged into the different resistive loads. The two first responder devices ForeRunner and FirstSave did not allow manual selection of energy.

Regular calibration guaranteed reliability and accuracy of the test resistors. Each test was performed at least three times.

2.3. Data analysis

The recorded waveforms were analysed using mathematical software (MatLab 5.3, The Mathworks Inc, Natick, MA).

The waveform energy content, impedance-normalised delivered energy, initial voltage and initial current, waveform duration, charge flow as well as the tilt were calculated. The impedance-normalised delivered energy is defined as the waveform energy content, i.e. the total delivered energy, divided by the test resistance. The charge flow Q of a current pulse $I(t)$ is the integral

$$Q = \int I(t)\mathrm{d}t$$

over the time of the shock. The tilt of a defibrillator's pulse is defined as

$$(A - D)/A,$$

where A is the initial voltage (of the positive shock) and D is the absolute value of the initial voltage of the negative shock. The initial voltage of the positive and negative pulse is defined as the maximum voltage within the first millisecond of the positive and negative pulse, respectively. The initial current was computed by dividing the initial voltage by the test resistance, i.e. by applying Ohm's law.

The energy discharged during the positive and the negative phase and their ratio to the total discharged energy, the duration of the positive and the negative phase and their ratio to the total duration, and the charge flow of the positive and the negative phase and their ratio to the sum of both absolute values were computed. The absolute values are given as mean ± S.D.

Finally, the capacitor capacitance of three defibrillators was computed by fitting the exponential decay of the negative pulse for different resistive loads. A charged capacitor discharges into a series configuration of an internal resistor and a test resistor according to

$$U(t) = U(0)\exp(-t/\tau),$$

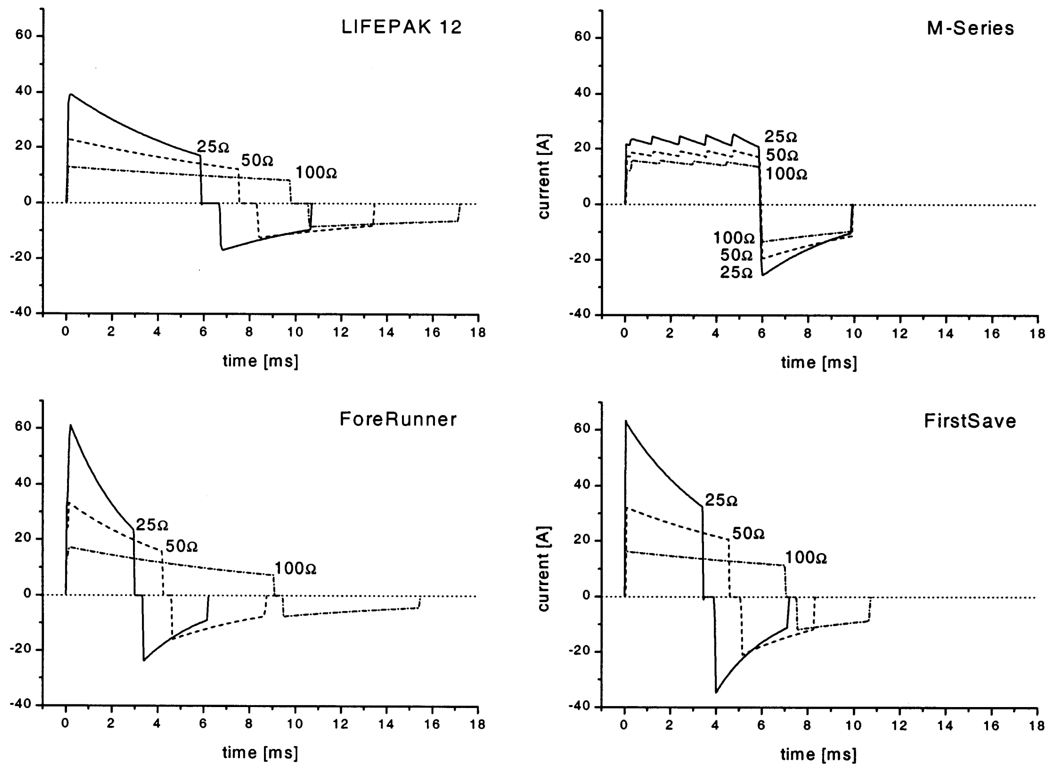

Fig. 1. Different biphasic defibrillation waveforms for resistive loads of 25, 50 and 100 Ω. An energy of 150 J was selected for the Medtronic Physio-Control LIFEPAK 12 and the Zoll M-Series Biphasic. The Laerdal Heartstart ForeRunner automatically delivers an energy of approximately 150 J for any test resistor. For the Survivalink FirstSave STAR the second shock after turning on the defibrillator was chosen, delivering mean energies of 219.3 J (25 Ω), 194.2 J (50 Ω) and 165.0 J (100 Ω). The Medtronic Physio-Control LIFEPAK 12, the Laerdal Heartstart ForeRunner and the Survivalink FirstSave STAR show a biphasic truncated exponential waveform. The Zoll M-Series Biphasic shows a biphasic truncated exponential waveform with serrated positive waveform phase.

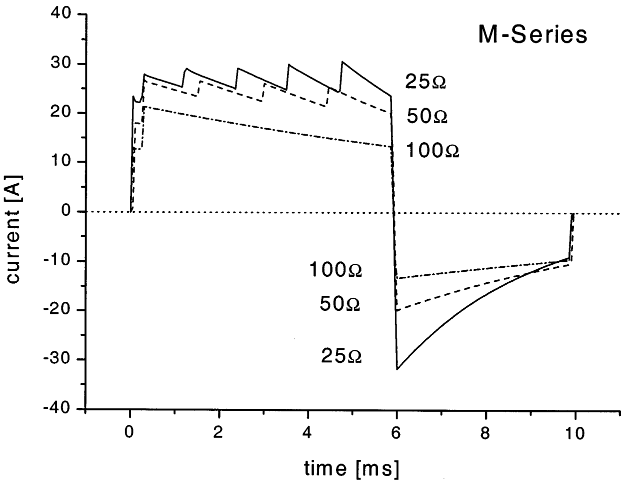

Fig. 2. Defibrillation waveforms for the Zoll M-Series Biphasic defibrillator for test resistive loads of 25, 50 and 100 Ω and a selected energy of 200 J. In contrast to all other configurations, the M-Series does not show the typical serrated positive waveform at an energy-impedance configuration of 200 J and 100 Ω, using a truncated exponential waveform instead.

where $U(t)$ is the voltage across the test resistor t seconds after the beginning of the discharge process. The time constant τ depends on the capacitor capacitance C, the internal resistance R_i and the test resistance R via

$$\tau = C(R_i + R).$$

Fitting the exponential decay of the negative pulse yields the time constant τ. Assuming the internal resistance R_i (and the capacitance C) to be constant for two different test resistances R_1 and R_2, one can extract the capacitance C and the internal resistance R_i from the two time constants τ_1 and τ_2, corresponding to R_1 and R_2, respectively:

$$C = (\tau_2 - \tau_1)/(R_2 - R_1) \quad (1)$$

and

$$R_i = \tau_1/C - R_1 = \tau_2/C - R_2. \quad (2)$$

For the LIFEPAK 12, the ForeRunner and the FirstSave calculations (1) and (2) were made for all

Table 1
Mean ratio of the energies of the positive and negative waveform phase together with the absolute values, the total delivered energy (TDE) and the impedance-normalized delivered energy (INDE)[a]

Selected energy (J)[b]	Test resistive load: 25 Ω Positive	25 Ω Negative	50 Ω Positive	50 Ω Negative	100 Ω Positive	100 Ω Negative
Medtronic Physio-Control LIFEPAK 12						
100	88 (83.9 ± 0.0)	12 (11.8 ± 0.0)	82 (80.2 ± 0.2)	18 (17.5 ± 0.0)	76 (75.2 ± 0.0)	24 (23.4 ± 0.0)
	TDE: 95.8 ± 0.0	INDE: 3.8 ± 0.0	TDE: 97.8 ± 0.2	INDE: 2.0 ± 0.0	TDE: 98.7 ± 0.0	INDE: 1.0 ± 0.0
150	87 (109.9 ± 0.8)	13 (16.6 ± 0.2)	82 (112.0 ± 0.5)	18 (25.3 ± 0.2)	76 (107.5 ± 0.3)	24 (34.6 ± 0.3)
	TDE: 126.6 ± 0.8	INDE: 5.1 ± 0.0	TDE: 137.5 ± 0.6	INDE: 2.7 ± 0.0	TDE: 142.2 ± 0.6	INDE: 1.4 ± 0.0
200	88 (169.7 ± 1.0)	12 (24.1 ± 0.2)	82 (161.5 ± 0.3)	18 (35.3 ± 0.1)	76 (149.9 ± 0.1)	24 (47.2 ± 0.0)
	TDE: 194 ± 1.2	INDE: 7.8 ± 0.0	TDE: 197.1 ± 0.1	INDE: 3.9 ± 0.0	TDE: 197.7 ± 0.1	INDE: 2.0 ± 0.0
Zoll M-Series Biphasic						
100	72 (50.7 ± 0.1)	28 (20.1 ± 0.1)	68 (63.4 ± 0.2)	32 (30.4 ± 0.1)	71 (84.1 ± 0.3)	29 (34.3 ± 0.1)
	TDE: 71.1 ± 0.1	INDE: 2.8 ± 0.0	TDE: 94.3 ± 0.2	INDE: 1.9 ± 0.0	TDE: 119.1 ± 0.5	INDE: 1.2 ± 0.0
150	71 (76.0 ± 0.1)	29 (30.2 ± 0.1)	67 (94.9 ± 0.1)	33 (45.6 ± 0.1)	71 (125.0 ± 0.5)	29 (51.2 ± 0.2)
	TDE: 106.8 ± 0.2	INDE: 4.3 ± 0.0	TDE: 141.3 ± 0.1	INDE: 2.8 ± 0.0	TDE: 177.5 ± 0.5	INDE: 1.8 ± 0.0
200	74 (105.1 ± 0.6)	26 (36.7 ± 0.3)	79 (164.1 ± 0.3)	21 (43.2 ± 0.1)	77 (169.4 ± 0.6)	23 (50.1 ± 0.2)
	TDE: 142.3 ± 0.7	INDE: 5.7 ± 0.0	TDE: 208.0 ± 0.2	INDE: 4.2 ± 0.0	TDE: 220.8 ± 0.7	INDE: 2.2 ± 0.0
Shock[b]						
Laerdal Heartstart ForeRunner						
–	88 (124.4 ± 0.6)	12 (17.4 ± 0.0)	82 (119.3 ± 0.6)	18 (26.6 ± 0.0)	87 (129.8 ± 0.3)	13 (19.8 ± 0.1)
	TDE: 142.2 ± 0.9	INDE: 5.7 ± 0.0	TDE: 146.2 ± 0.9	INDE: 2.9 ± 0.0	TDE: 149.6 ± 0.3	INDE: 1.5 ± 0.0
Survivalink FirstSave STAR						
First shock	82 (183.2 ± 8.0)	18 (40.2 ± 0.6)	79 (155.8 ± 2.7)	21 (42.1 ± 0.7)	81 (141.1 ± 5.4)	19 (33.6 ± 0.2)
	TDE: 223.6 ± 8.4	INDE: 8.9 ± 0.3	TDE: 198.8 ± 3.5	INDE: 4.0 ± 0.1	TDE: 174.9 ± 5.7	INDE: 1.7 ± 0.1
Second shock	83 (182.2 ± 2.3)	17 (36.4 ± 0.5)	79 (152.4 ± 0.6)	21 (41.1 ± 0.6)	80 (131.8 ± 0.9)	20 (32.7 ± 0.4)
	TDE: 219.3 ± 2.3	INDE: 8.8 ± 0.1	TDE: 194.2 ± 1.6	INDE: 3.9 ± 0.0	TDE: 165.0 ± 1.1	INDE: 1.7 ± 0.0
Following	83 (258.7 ± 3.4)	17 (52.8 ± 0.3)	79 (218.7 ± 2.6)	21 (59.0 ± 0.6)	80 (187.9 ± 1.8)	20 (46.3 ± 0.4)
	TDE: 311.6 ± 3.5	INDE: 12.5 ± 0.1	TDE: 278.1 ± 3.1	INDE: 5.6 ± 0.1	TDE: 235.0 ± 2.3	INDE: 2.4 ± 0.0

[a] The absolute values are given as mean ± S.D.

[b] Mean ratio of the energies of the positive and negative waveform phase, absolute values, TDE and INDE [% (J), J, J/Ω]]

three combinations of the resistive loads 25, 50 and 100 Ω. Results are given as mean ± S.D. of these three values. The M-Series defibrillator changes its internal resistance and therefore does not conform to the above requirements.

3. Results

The typical discharge waveforms at 25, 50 and 100 Ω are represented graphically in Figs. 1 and 2. The characteristic parameters describing the discharge waveforms are shown in Tables 1–6. In Tables 1–5 the values depend on the various resistive loads and the energy selected for the MCED. For the ForeRunner the values depend only on the various resistive loads. For the FirstSave the values additionally depend on the number of shocks already discharged after turning on the defibrillator. The values in Table 6 were computed by combining the fitted time constants for different combinations of two resistive loads using Eqs. (1) and (2). The values therefore depend on the selected energy regarding the MCED and the number of shocks already discharged for the FirstSave.

3.1. Discharge waveform (Figs. 1 and 2)

The LIFEPAK 12, the ForeRunner and the FirstSave use a biphasic truncated exponential waveform (Fig. 1). The M-Series uses a biphasic truncated exponential waveform with serrated positive waveform phase in all but one energy-impedance configurations (Fig. 1); at a configuration of 100 Ω and 200 J the M-Series has an anomaly using a truncated exponential waveform without the typical serrated positive waveform (Fig. 2).

Table 2
Initial voltage (a) and current (b) given as mean ± S.D.

	Test resistive load		
	25 Ω	50 Ω	100 Ω
(a) Selected energy (J)	Initial voltage (V)		
Medtronic Physio-Control LIFEPAK 12			
100	877.8 ± 0.8	978.0 ± 0.2	1086.0 ± 0.3
150	981.4 ± 1.0	1139.0 ± 3.2	1293.0 ± 3.8
200	1246.0 ± 6.3	1383.0 ± 0.7	1536.0 ± 0.6
Zoll M-Series Biphasic			
100	482.8 ± 1.5	759.3 ± 1.3	1290.0 ± 3.8
150	588.7 ± 0.6	928.4 ± 0.6	1572.0 ± 4.3
200	706.7 ± 7.9	1329.0 ± 9.2	2140.0 ± 11.6
Shock	Initial voltage (V)		
Laerdal Heartstart ForeRunner			
–	1535.0 ± 10.7	1657.0 ± 8.5	1712.0 ± 6.0
Survivalink FirstSave STAR			
First shock	1570.0 ± 36.0	1597.0 ± 10.3	1616.0 ± 23.4
Second shock	1573.0 ± 10.5	1612.0 ± 11.0	1637.0 ± 21.9
Following shocks	1833.0 ± 8.4	1902.0 ± 6.7	1935.0 ± 3.4
(b) Selected energy (J)	Initial current (A)		
Medtronic Physio-Control LIFEPAK 12			
100	35.1 ± 0.0	19.6 ± 0.0	10.9 ± 0.0
150	39.3 ± 0.0	22.8 ± 0.1	12.9 ± 0.0
200	49.8 ± 0.3	27.7 ± 0.0	15.4 ± 0.0
Zoll M-Series Biphasic			
100	19.3 ± 0.1	15.2 ± 0.0	12.9 ± 0.0
150	23.6 ± 0.0	18.6 ± 0.0	15.7 ± 0.0
200	28.3 ± 0.3	26.6 ± 0.2	21.4 ± 0.1
Shock	Initial current (A)		
Laerdal Heartstart ForeRunner			
–	61.4 ± 0.4	33.1 ± 0.2	17.1 ± 0.1
Survivalink FirstSave STAR			
First shock	62.8 ± 1.4	31.9 ± 0.2	16.2 ± 0.2
Second shock	62.9 ± 0.4	32.2 ± 0.2	16.4 ± 0.2
Following shocks	73.3 ± 0.3	38.0 ± 0.1	19.4 ± 0.0

3.2. Discharged energy (Table 1)

Generally, the MCED did not deliver the precise amount of energy that had been selected. The delivered energies deviated from the selected energy by up to +19.1 or −28.9%. The LIFEPAK 12 always delivered less energy than selected, the M-Series less or more depending on the resistive load. The energy delivered by both MCED increased with increasing resistive load. The energy delivered by the FirstSave decreased with increasing resistive load and depended on the number of shocks discharged after turning on the defibrillator. The ForeRunner automatically delivered an energy of approximately 150 J for any test resistor.

In case of the MCED impedance-normalised delivered energy decreased with increasing resistive load and increased with increasing selected energy as expected. Maximum and minimum values were achieved by the LIFEPAK 12 defibrillator at 7.8 and 1.0 J/Ω, respectively. For the SAED impedance-normalised delivered energy decreased with increasing resistive load. The maximum value was achieved by the FirstSave (12.5 J/Ω) and the minimum value by the ForeRunner defibrillator (1.5 J/Ω).

In general, more than 70% of the delivered energy was delivered in the first phase of the shock. The LIFEPAK 12 shows energy splitting into approximately 88% for the positive part and 12% for the negative part at 25 and 50 Ω and into 76 and 24% at 100 Ω independent of the selected energy. The ForeRunner shows energy splitting into approximately 88 and 12%. The two remaining defibrillators show a variety of groupings in the energy splitting.

3.3. Initial voltage (Table 2a)

For all tested defibrillators initial voltage increased with the selected energy or the number of shocks and with the resistive load. The values of the MCED showed a wide range, whereas the values of the SAED

Table 3
Mean ratio of positive and negative waveform phase duration together with the absolute values and the total pulse duration[a]

Selected energy (J)[b]	Test resistive load: 25 Ω Positive	25 Ω Negative	50 Ω Positive	50 Ω Negative	100 Ω Positive	100 Ω Negative
Medtronic Physio-Control LIFEPAK 12						
100	55 (5.7 ± 0.0) Total: 10.4 ± 0.0	38 (3.9 ± 0.0)	56 (7.5 ± 0.0) Total: 13.3 ± 0.0	38 (5.1 ± 0.0)	57 (9.7 ± 0.0) Total: 17.0 ± 0.0	39 (6.6 ± 0.0)
150	55 (5.9 ± 0.1) Total: 10.7 ± 0.1	38 (4.0 ± 0.0)	57 (7.7 ± 0.1) Total: 13.5 ± 0.0	38 (5.2 ± 0.0)	57 (9.8 ± 0.0) Total: 17.1 ± 0.1	39 (6.6 ± 0.0)
200	56 (5.7 ± 0.1) Total: 10.3 ± 0.0	38 (3.9 ± 0.0)	56 (7.5 ± 0.0) Total: 13.3 ± 0.0	38 (5.1 ± 0.0)	57 (9.6 ± 0.0) Total: 16.9 ± 0.0	39 (6.5 ± 0.0)
Zoll M-Series Biphasic						
100	60 (5.9 ± 0.0) Total: 9.9 ± 0.0	40 (4.0 ± 0.0)	60 (5.9 ± 0.0) Total: 9.9 ± 0.0	40 (4.0 ± 0.0)	60 (5.9 ± 0.0) Total: 9.9 ± 0.0	40 (4.0 ± 0.0)
150	60 (5.9 ± 0.0) Total: 9.9 ± 0.0	40 (4.0 ± 0.0)	60 (5.9 ± 0.0) Total: 9.9 ± 0.0	40 (4.0 ± 0.0)	60 (5.9 ± 0.0) Total: 9.9 ± 0.0	40 (4.0 ± 0.0)
200	60 (5.9 ± 0.0) Total: 9.9 ± 0.0	40 (4.0 ± 0.0)	60 (5.9 ± 0.0) Total: 9.9 ± 0.0	40 (4.0 ± 0.0)	60 (5.9 ± 0.0) Total: 9.9 ± 0.0	40 (4.0 ± 0.0)
Shock[b]						
Laerdal Heartstart ForeRunner						
–	48 (3.0 ± 0.0) Total: 6.2 ± 0.0	47 (2.9 ± 0.0)	49 (4.3 ± 0.0) Total: 8.7 ± 0.0	49 (4.3 ± 0.2)	59 (9.2 ± 0.0) Total: 15.5 ± 0.0	39 (6.0 ± 0.0)
Survivalink FirstSave STAR						
First shock	49 (3.6 ± 0.0) Total: 7.3 ± 0.1	45 (3.3 ± 0.1)	57 (4.8 ± 0.1) Total: 8.6 ± 0.1	39 (3.3 ± 0.1)	69 (8.1 ± 0.3) Total: 11.7 ± 0.3	28 (3.3 ± 0.0)
Second shock	48 (3.4 ± 0.1) Total: 7.1 ± 0.1	46 (3.3 ± 0.0)	56 (4.6 ± 0.0) Total: 8.3 ± 0.1	39 (3.3 ± 0.0)	66 (7.1 ± 0.1) Total: 10.8 ± 0.1	31 (3.3 ± 0.0)
Following	48 (3.4 ± 0.0) Total: 7.1 ± 0.1	46 (3.3 ± 0.0)	56 (4.7 ± 0.1) Total: 8.4 ± 0.1	39 (3.3 ± 0.0)	66 (7.2 ± 0.1) Total: 10.8 ± 0.0	31 (3.3 ± 0.0)

[a] The remaining percentage of waveform duration separates positive and negative waveform phases. The absolute values are given as mean ± S.D.

[b] Mean ratio of positive and negative waveform phase duration, absolute values and total pulse duration [% (ms), ms]

Table 4
Mean ratio of the charge flows of the positive and negative waveform phase together with the absolute values and the total charge flow[a]

Selected energy (J)[b]	Test resistive load: 25 Ω Positive	25 Ω Negative	50 Ω Positive	50 Ω Negative	100 Ω Positive	100 Ω Negative
Medtronic Physio-Control LIFEPAK 12						
100	76 (132.9 ± 0.0) Total: 91.0 ± 0.0	24 (−41.7 ± 0.1)	72 (106.9 ± 0.2) Total: 65.4 ± 0.1	28 (−41.5 ± 0.0)	69 (84.3 ± 0.1) Total: 45.3 ± 0.0	31 (−38.8 ± 0.0)
150	76 (154.9 ± 1.2) total: 104.5 ± 0.6	24 (−50.2 ± 0.4)	72 (127.8 ± 0.3) Total: 77.1 ± 0.3	28 (−50.4 ± 0.2)	68 (101.1 ± 0.1) Total: 53.8 ± 0.1	32 (−47.1 ± 0.2)
200	76 (188.9 ± 0.5) Total: 129.0 ± 0.4	24 (−59.4 ± 0.3)	72 (151.9 ± 0.3) Total: 92.9 ± 0.1	28 (−58.8 ± 0.2)	68 (118.6 ± 0.1) Total: 63.9 ± 0.1	32 (−54.7 ± 0.0)
Zoll M-Series Biphasic						
100	67 (108.5 ± 0.2) Total: 54.6 ± 0.3	33 (−54.1 ± 0.3)	64 (85.8 ± 0.2) Total: 37.9 ± 0.2	36 (−48.1 ± 0.2)	66 (69.8 ± 0.1) Total: 33.4 ± 0.1	34 (−36.5 ± 0.1)
150	67 (132.6 ± 0.2) Total: 67.0 ± 0.2	33 (−66.1 ± 0.4)	64 (105.0 ± 0.2) Total: 46.0 ± 0.1	36 (−59.1 ± 0.1)	66 (85.1 ± 0.2) Total: 40.8 ± 0.1	34 (−44.3 ± 0.2)
200	69 (155.9 ±) Total: 85.4 ± 0.3	31 (−71.0 ± 0.4)	71 (137.6 ± 0.2) Total: 80.6 ± 0.2	29 (−57.2 ± 0.2)	69 (98.2 ± 0.2) Total: 54.2 ± 0.1	31 (−44.0 ± 0.2)
Shock[b]						
Laerdal Heartstart ForeRunner						
–	73 (115.9 ± 0.3) Total: 74.0 ± 1.1	27 (−42.5 ± 0.0)	68 (97.4 ± 0.3) Total: 52.3 ± 0.8	32 (−45.4 ± 0.0)	76 (105.3 ± 0.1) Total: 71.4 ± 0.1	24 (−33.8 ± 0.2)
Survivalink FirstSave STAR						
First shock	70 (157.1 ± 3.5) Total: 88.8 ± 3.4	30 (−67.9 ± 0.2)	70 (120.4 ± 1.7) Total: 69.5 ± 1.7	30 (−50.9 ± 0.5)	76 (105.2 ± 3.4) Total: 72.4 ± 3.6	24 (−32.5 ± 0.2)
Second shock	70 (153.0 ± 2.3) Total: 89.0 ± 1.4	30 (−64.6 ± 0.5)	70 (116.4 ± 0.6) Total: 66.0 ± 0.5	30 (−50.2 ± 0.6)	75 (95.2 ± 0.3) Total: 62.9 ± 0.6	25 (−32.2 ± 0.3)
Following	70 (182.2 ± 1.6) Total: 104.2 ± 1.9	30 (−77.7 ± 0.2)	70 (140.2 ± 1.8) Total: 79.6 ± 1.8	30 (−60.4 ± 0.5)	75 (114.1 ± 0.9) Total: 75.7 ± 1.1	25 (−38.2 ± 0.3)

[a] The absolute values are given as mean ± S.D.
[b] Mean ratio of the charge flows of the positive and negative waveform phase, absolute values and total charge flow [% (mC), mC]

showed a narrow range. Maximum and minimum values were achieved by the M-Series defibrillator at 2140.0 and 482.8 V, respectively.

3.4. Initial current (Table 2b)

For all tested defibrillators initial current increased with the selected energy or the number of shocks but decreased with the resistive load. The MCED values showed a narrow range, whereas the SAED values showed a wide range. The maximum value was achieved by the FirstSave (73.3 A) and the minimum value by the LIFEPAK 12 defibrillator (10.9 A).

3.5. Pulse duration (Table 3)

Generally, total pulse duration was independent of the selected energy or the number of shocks. For all but the M-Series defibrillator total pulse duration increased with the resistive load. The M-Series pulse always required 9.9 ms.

The LIFEPAK 12 and the M-Series showed a constant duration splitting of 56–38 and 60–40%, respectively. Duration splitting depended on the resistive load for the SAED. In general, the first positive pulse was longer than the second negative pulse.

3.6. Charge flow (Table 4)

For the MCED total charge flow increased with the selected energy and decreased with the resistive load. No rule could be determined for the SAED. Overall, the total charge flow is positive, i.e. the first phase carries more charge than the second phase of the shock. None of the tested defibrillators therefore showed a balanced charge flow. The maximum value was achieved by the LIFEPAK 12 (129.0 mC) and the minimum value by the M-Series defibrillator (33.4 mC).

Splitting of the charge flow into the first and second phases occurred independently of the selected energy for the LIFEPAK 12 and independently of the number of shocks for the FirstSave and showed different groupings for both defibrillators. Generally, more than 64% of the charge was delivered in the first phase.

Table 5
Tilt given as mean ± S.D.

	Test resistive load		
	25 Ω	50 Ω	100 Ω
Selected energy (J)	Tilt (%)		
Medtronic Physio-Control LIFEPAK 12			
100	59.0 ± 0.1	47.9 ± 0.0	36.1 ± 0.0
150	57.2 ± 0.1	46.5 ± 0.1	35.0 ± 0.1
200	58.6 ± 0.1	47.6 ± 0.1	35.7 ± 0.0
Zoll M-Series Biphasic			
100	−9.4 ± 1.2	−3.9 ± 0.2	15.3 ± 0.5
150	−8.5 ± 0.0	−4.3 ± 0.0	15.0 ± 0.1
200	−13.1 ± 1.8	25.6 ± 0.2	38.1 ± 0.3
Shock	Tilt (%)		
Laerdal Heartstart ForeRunner			
–	61.4 ± 0.4	52.1 ± 0.2	55.5 ± 0.3
Survivalink FirstSave STAR			
First shock	42.2 ± 1.2	33.2 ± 0.4	26.3 ± 0.9
Second shock	45.2 ± 0.2	34.7 ± 0.5	27.9 ± 0.2
Following shocks	43.6 ± 1.1	33.8 ± 0.3	27.8 ± 0.2

3.7. Tilt (Table 5)

Roughly speaking, the tilt did not depend on the selected energy or the number of shocks and varied from 61.4% for the ForeRunner to −13.1% for the M-Series defibrillator. The tilt of the LIFEPAK 12 and the FirstSave decreased with the resistive load, whereas the tilt of the M-Series increased with the resistive load.

3.8. Capacitance and internal resistance (Table 6)

The LIFEPAK 12 showed a capacitance of approximately 200 μF, which demonstrates the slow exponential decay of the waveform pulse (Fig. 1). The two SAED showed a capacitance of approximately 100 μF, resulting in a faster exponential decay of the waveform pulse (Fig. 1). For all three defibrillators the computed internal resistances were not negligible in comparison with the resistive loads.

Table 6
Capacitance and internal resistance given as mean ± S.D.

Selected energy (J)	Capacitance (μF)	Internal resistance [Ω]
Medtronic Physio-Control LIFEPAK 12		
100	201.0 ± 0.6	5.7 ± 0.2
150	199.3 ± 0.7	7.6 ± 0.2
200	202.1 ± 1.1	5.6 ± 0.3
Shock	Capacitance (μF)	Internal resistance (Ω)
Laerdal Heartstart ForeRunner		
–	100.2 ± 0.6	3.1 ± 0.3
Survivalink FirstSave STAR		
First shock	101.3 ± 1.3	2.1 ± 0.7
Second shock	101.3 ± 1.6	2.0 ± 0.7
Following shocks	102.3 ± 1.8	2.1 ± 0.9

4. Discussion

The waveforms of four different biphasic defibrillators were analysed. It was found that there are significant differences in the delivered discharge waveforms. The tested defibrillators use different capacitors and different internal resistors, resulting in a varying time constant of exponential decay. The LIFEPAK 12, the ForeRunner and the FirstSave use a biphasic truncated exponential waveform with a time gap between the first and the second phases, whereas the M-Series defibrillator achieves a serrated positive waveform by adjusting the internal resistor in time and does not show any time gap between the first and the second phase.

In the case of the two defibrillators with manually selectable energy (LIFEPAK 12 and M-Series), the delivered energy deviated substantially from the selected energy. The LIFEPAK 12 always delivered less energy than selected, the M-Series less or more depending on the resistive load. One of the two semi-automated defibrillators (ForeRunner) always delivered approximately the same amount of energy, the other one (FirstSave) discharged different energies depending on the number of shocks discharged after turning on the defibrillator. The energy delivered by both MCED increased with increasing resistive load, whereas the energy delivered by the FirstSave decreased with increasing resistive load.

Impedance-normalised delivered energy of the two SAED varied from 1.5 to 12.5 J/Ω. In comparison, patent US 5111813 proposed a defibrillation protocol with recommended impedance-normalised delivered energy values between 3 and 4.5 J/Ω based on a study of human defibrillation using damped sinusoidal waveform shocks [21].

Generally, the initial voltage increased and the initial current decreased with the resistive load. Apart from the anomaly of the M-Series defibrillator at an energy-impedance configuration of 200 J and 100 Ω, the serrated positive waveform pulse of this defibrillator produced the lowest values for initial voltage and the second lowest value for initial current.

The LIFEPAK 12, the M-Series and the FirstSave adjust the amount of energy stored in the capacitor. The capacitor of the ForeRunner defibrillator always charged to approximately the same value, (Table 2b) taking the internal resistance into account.

The tilt differed considerably among the tested defibrillators varying from −13.1 to 61.4% and depended differently on the resistive load. Negative tilt occurs when the initial voltage of the positive phase is smaller than the absolute value of the initial voltage of the negative phase. All negative values were achieved with the M-Series defibrillator.

Concerning total phase duration, all but the M-Series defibrillator showed impedance-adjusted values.

Generally, biphasic defibrillators split their shock into a positive and a negative phase. All tested defibrillators showed greater values for the characteristic parameters of the first phase. Again, some defibrillators used a constant splitting ratio for certain characteristic parameters. None of the tested defibrillators showed a balanced charge flow.

The defibrillators tested in this study do not comprise all biphasic defibrillators in clinical use. This study was a theoretical lab study, thus the different waveforms or the defibrillators for possible efficacy were not assessed.

The various parameters chosen to describe the defibrillator waveforms are not independent in general. Initial voltage U and initial current I are related by Ohm's law $U = I \cdot R$ to the patient's transthoracic impedance R. On the other hand, charge flow Q and energy E are not proportional because $Q = \int I(t)\mathrm{d}t$ and $E = \int I(t)^2 * R\mathrm{d}t$ are integral quantities over a chosen time interval.

Usually, defibrillation is achieved by successful selection of energy, either manually or automatically. The energy chosen and the patient's individual transthoracic impedance determine the current through the heart. The average adult human impedance is approximately 70–80 Ω [20]. According to the AHA guidelines 'ventricular fibrillation and other cardiac arrhythmias can be terminated by electric shock when sufficient current passes through the myocardium' [1]. A promising alternative approach to defibrillation is therefore the use of electric current and charge flow instead of energy. Current-based therapy would prevent attempts to deliver inappropriately low energies to a patient with high impedance, and would prevent high-energy shocks to patients with low impedance, which result in excessive current flow, myocardial damage and failure to defibrillate [1,20,21].

Furthermore, possible new technical developments must also be considered. Triphasic waveforms and the use of two separate capacitors for biphasic waveforms are interesting approaches in this connection [22–24].

This study illustrates the differences in the waveform design and the varying dependence of the waveform characteristic parameters on the patient's transthoracic impedance. Optimal waveform and optimal impedance compensation for biphasic defibrillation have not yet been determined [1,25].

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