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A History of the Discovery of the Hoorweg–Weiss–Lapicque Law

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First quantitative studies of the effect of electricity on excitable biological tissues forming the basis of the Hoorweg–Weiss–Lapicque law are described. The contribution of each researcher to the discovery is delineated and the practical significance of the Hoorweg–Weiss–Lapicque law is explained.

Introduction

Those familiar with electrophysiology know the Weiss–Lapicque strength–duration curve (in Russia, it is more often referred to as the Hoorweg–Weiss–Lapicque strength–duration law). What was the contribution of each of these researchers to the discovery of the law?

Jan Leendert Hoorweg, 1892

Dutch scientist Jan Leendert Hoorweg (Fig. 1) was the first to perform an accurate measurement of the effect of electric current on excitable biological tissue. The results of his studies were published in 1892 in *Pflügers Archiv*, the oldest scientific journal on physiology founded in 1868 in Germany by German physiologist Eduard Friedrich Wilhelm Pflüger [1, 2].

Hoorweg showed that the threshold voltage $V(C)$ of biological tissue excitation is inversely proportional to the capacitance C:

$$V(C) = aR + b/C, \qquad (1)$$

where R is the impedance of the capacitor discharge loop and a and b are constants depending on the object of study.

The experiments were performed in a human subject. The threshold excitation was determined from minimal observable muscle jerk. The paper does not specify the body part to which the electrodes were applied. Presumably, it was an arm. A Gaiffe laboratory capacitor (Paris) with variable capacitance (1-1000 nF) was used in the experiment. The capacitor was charged using a switchable battery with forty 1.5-V Leclanche elements providing the total voltage of 1.5 to 60 V. The minimal threshold energy was found to be 2.025 μJ. The threshold excitation was observed at the threshold voltage of 9 V (capacitance, 50 nF). During the experiment, the inter-electrode impedance remained constant (3200 Ω).

Fig. 1. Dutch scientist Jan Leendert Hoorweg.

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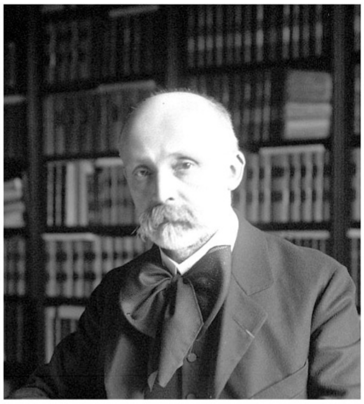

Fig. 2. French scientist Jules Adolphe Georges Weiss.

Georges Weiss, 1901

In 1901, French scientist Jules Adolphe Georges Weiss (Fig. 2) published the results of his experimental studies of pulsed electrical stimulation in *Archives Italiennes de Biologie*, a scientific journal published in Italy (in French). The experiments of Weiss were performed in frogs, a toad, and a tortoise [2-4].

Initially, Weiss also used a Gaiffe laboratory capacitor with variable capacitance of 0.1-10,000 nF. However, then he decided to study the effect of pulse duration on excitation. Attempts had been made before to obtain electrical pulses of given duration, but the methods used by previous researchers did not allow short pulses to be obtained. To solve this problem, Weiss invented a unique technique for generating short current pulses (Fig. 3).

Electrodes E+ and E– are attached to the object under study. The resistor R1 is connected to the electrode E+ via a conducting bridge C-D; the resistor R2 is connected directly to the electrode E–. Voltage V is applied to the terminals V+ and V–. The conducting bridge A-B short-circuits the resistors R1 and R2, so that there is no current through the electrodes E+ and E–. A bullet shot from an air rifle first breaks the bridge A-B. Current $V/(R1 + R2)$ starts to flow through the bridge C-D and the electrodes E+ and E–. As the bullet traverses the distance L between the bridges A-B and C-D and breaks the second bridge, the current through the electrodes E+ and E– ceases to flow. Weiss used an air rifle with a canister of liquid carbon dioxide providing a stable bullet velocity of 130 m/s. The bullet traversed the distance of 1 cm in 0.077 ms. In Weiss' experiments, the distance between the bridges varied from 3 to 40 cm, providing thus the pulse duration of 0.23 to 3.08 ms.

Weiss' experiments required the use of noninductive and noncapacitive resistors. Weiss made such resistors from pencils whose leads had electrolytically applied copper contact rings on their tips. The total resistance of the circuit containing these improvised resistors was 0.45-

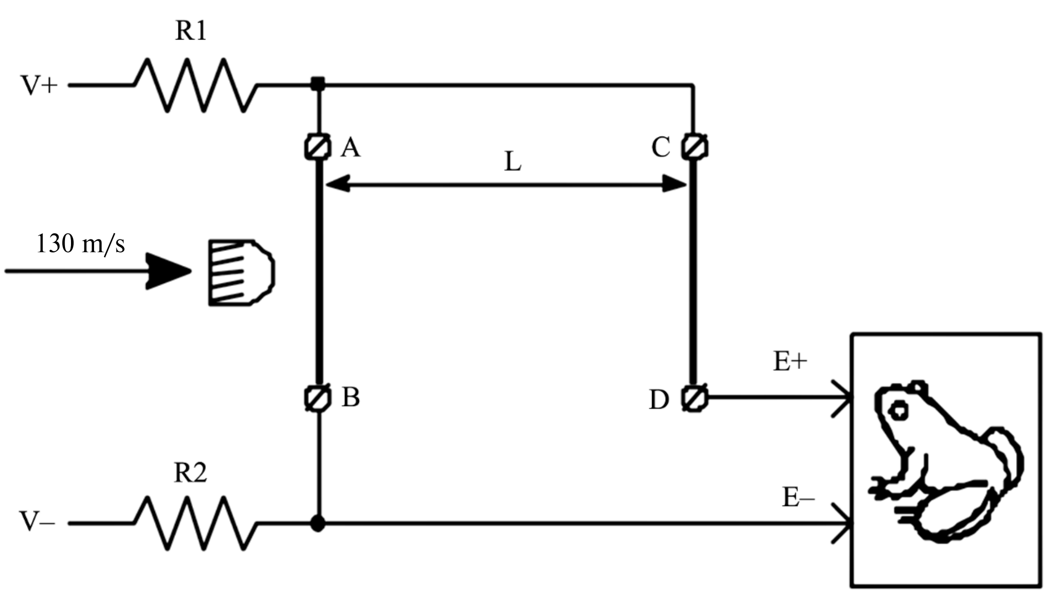

Fig. 3. Circuit used by Weiss to generate short current pulses.

0.59 MΩ. The pulse current was set by varying the voltage V up to the maximum value of ~ 200 V.

Based on the results of his experiments, Weiss suggested the following relationship between the threshold charge Q required to excite biological tissue and the pulse duration t:

$$Q(t) = a + bt, \quad (2)$$

where a and b are constants depending on the object of study.

This equation fits well the experimental data obtained by Weiss, Hoorweg (Fig. 1), and Dubois, a Swiss researcher from Bern who also studied the response of excitable biological tissues to a capacitor discharge.

In the end of his paper, Weiss mentions that he had planned to use in his experiments the oscillograph designed in 1893 by André Blondel [5], but had to abandon this plan because of a delay in manufacture of the oscillograph under supervision of Blondel.

Louis Lapicque, 1907, 1909

French scientist Louis Édouard Lapicque (Fig. 4) used the pulse generation technique invented by Weiss (both scientists were members of the French Biological Society) in his experiments in frogs. The results of these experiments were published in 1907 in *Journal de physiologie et de pathologie générale* [6, 7].

Lapicque modified the ballistic switch of the pulse generator by replacing the air rifle with a firearm (pistol). The bullet velocity was 270 m/s. In tables describing the experimental data, the pulse duration is given in terms of distance (cm) between the bridges (1 cm = 0.37 ms); the voltage is given in millimeters, because it was adjusted using a linear variable resistor (1 mm = 0.5 mV). According to Lapicque, the pulse duration varied from 9 to 81 cm (0.333-3.00 ms); the threshold voltage was 58-380 mm (29-190 mV).

Lapicque used a capacitor and a resistor connected in parallel to simulate a cell membrane. He suggested the following equation to describe the dependence of the threshold electromotive force V on the excitation pulse duration t:

$$V(t) = \frac{\alpha}{1 + e^{-\frac{t}{\beta}}}, \quad (3)$$

where α and β are constants depending on the object of study.

Fig. 4. French scientist Louis Édouard Lapicque.

This equation is generally known as the Lapicque–Blair strength–duration curve, although Henry A. Blair obtained this equation considerably later (in 1932) [8, 9].

Equation (3) does not fit the results of the experiments of Hoorweg, Weiss, and Lapicque as closely as the equation suggested by Weiss.

Further analysis of the experimental results led Lapicque to formulating the following equation, which is now known as the Weiss–Lapicque strength–duration curve or, in Russian scientific literature, as the Hoorweg–Weiss–Lapicque strength–duration law:

$$I(t) = I_R\left(1 + \frac{t_C}{t}\right), \quad (4)$$

where $I(t)$ is the threshold pulse current leading to excitation, t is the pulse duration, I_R is the rheobase (minimal current amplitude of infinite duration leading to excitation), and t_C is the chronaxia [excitation pulse duration for $I(t) = 2I_R$].

On July 24, 1909, Lapicque presented the results of his studies at a meeting of the French Biological Society. In describing Eq. (4), he was the first to use the terms *rheobase* and *chronaxia* [10].

In 2012, the Hoorweg–Weiss–Lapicque model was shown to fit well the results obtained using the Luo–Rudy computer model of a mammalian myocardial cell [11].

Conclusions

Thus, the contributions of the three scientists to the discovery of the strength–duration law are as follows:

1892 – Jan Leendert Hoorweg was the first to perform an accurate measurement of the effect of electric current produced by a capacitor discharge on excitable biological tissue;

1901 – Georges Weiss was the first to study the effect of short current pulses of various durations on excitable biological tissue;

1907 – Louis Lapicque continued Weiss' studies of the effect of short current pulses on biological tissue;

July 24, 1909 – Louis Lapicque presented the strength–duration law at a meeting of the French Biological Society. In his report, Lapicque was the first to use the terms *rheobase* and *chronaxia*.

Specific features of behavior of excitable biological tissue described by the strength–duration law were later taken into account by Gurvich and Yun'ev [12] in animal experiments intended to optimize high-voltage capacitor discharge used for cardiac defibrillation. In his further work, Gurvich improved the circuit suggested in [12] by including an inductor into the capacitor discharge loop [13]. This allowed the effective amplitude of the discharge voltage to be decreased, reducing thus the damage to myocardium. External defibrillation using such pulses began to be used in Russia in 1952.

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REFERENCES

1. Hoorweg, J. L., "Condensatorentladung und Auseinandersetzung mit du Bois-Reymond," Pflügers Archiv, **52**, 87-108 (1892).
2. Irnich, W., "The fundamental law of electrostimulation and its application to defibrillation," Pac. Clin. Electrophysiol., **13**, No. 11, 1433-1447 (1990).
3. Weiss, G., "Sur la possibilité de rendre comparables entre eux les appareils servant a l'excitation électrique," Archives Italiennes de Biologie, **35**, 413-446 (1901).
4. Irnich, W., "Georges Weiss' fundamental law of electrostimulation is 100 years old," Pac. Clin. Electrophysiol., **25**, No. 2, 245-248 (2002).
5. Blondel, A., "Oscillographes; nouveaux appareils pour l'étude des oscillations électriques lentes," Comptes rendus hebdomadaires des séances de l'Académie des sciences, **116**, 502-506 (1893).
6. Lapicque, L., "Recherches quantitatives sur l'excitation électrique des nerfs traitée comme une polarisation," Journal de physiologie et de pathologie générale, **9**, 620-635 (1907).
7. Brunel, N. and van Rossum, M. C., "Lapicque's 1907 paper: From frogs to integrate-and-fire," Biol. Cybern., **97**, No. 5, 337-339 (2007).
8. Blair, H. A., "On the intensity-time relations for stimulation by electric currents. I," J. Gen. Physiol., **15**, 709-729 (1932).
9. Blair, H. A., "On the intensity-time relations for stimulation by electric currents. II," J. Gen. Physiol., **15**, 731-755 (1932).
10. Lapicque, L., "Définition expérimentale de l'excitabilité," Comptes rendus des séances de la Société de biologie et de ses filiales, **67**, 280-283 (1909).
11. Gorbunov, B. B., "A study of the myocardium cell membrane using the Luo–Rudy model," Biomed. Eng., **46**, 117-119 (2012).
12. Gurvich, N. L. and Yun'ev, G. S., "On recovery of normal activity of fibrillating heart in warm-blooded animals by a capacitor discharge," Byul. Eksp. Biol. Med., **8**, No. 1, 55-58 (1939).
13. Gurvich, N. L., "The importance of the physical characteristics of capacitor discharge in recovering normal activity of fibrillating heart," in: Abstracts of Works of Biology Division of the Academy of Sciences of the USSR for 1940, Izd. Akademii Nauk SSSR, Moscow (1941), pp. 375-376.