The bicentennial of the Voltaic battery (1800–2000): the artificial electric organ

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Alessandro Volta invented the electric battery at the end of 1799 and communicated his invention to the Royal Society of London in 1800. The studies that led him to develop this revolutionary device began in 1792, after Volta read the work of Luigi Galvani on the existence of an intrinsic electricity in living organisms. During these studies, Volta obtained a series of results of great physiological relevance, which led him to anticipate some important ideas that marked the inception of modern neuroscience. These results have been obscured by a cultural tradition that has seen Volta exclusively as a physicist, lacking interest for biological problems and opposed in an irreversible way to the physiologist, Luigi Galvani.

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TWO CENTURIES AGO, on 20 March 1800, Alessandro Volta, a professor at the University of Pavia and Fellow of the Royal Society of London, sent a letter from Come, his native town, to Sir Joseph Banks, President of the Royal Society, announcing the invention of a device capable of producing electricity 'by the mere contact of conducting substances of different species'[1] (see Fig. 1). This device, the 'Voltaic battery', marked the birth of a new era in the development of modern physics and important changes in our lifestyle.

One year later, Volta was disappointed that the studies prompted by his invention were devoted almost exclusively to determining the chemical effects of the new device, and, in addition, that scientists, he said, 'seem to pay little attention to those other effects referred to as electrical–physiological effects, which are nevertheless unique and surprising, as I will explain to you. On the contrary, I myself became largely involved with these effects since the beginning'[2]. In a memoir written in 1802, after discussing the physiological effects of variable-duration electrical stimuli brought about using his battery, Volta remarked that the results obtained from these and other experiments had many interesting applications that, if used correctly, might benefit the fields of both physiology and practical medicine[2].

Volta–Galvani: physics versus physiology

Volta's interest in the medical and physiological problems connected to the study of electricity has been obscured by a historical tradition that tends to view him as a champion of physics who was opposed to the champion of physiology and medicine, Luigi Galvani. The well-known controversy between these two scientists concerned the origin of the electricity involved in the muscle contractions brought about by metallic conductors in frog preparations: Volta the physicist asserting that this electricity was produced by metals, and Galvani the physiologist, claiming that it was intrinsic to the organism. According to this tradition, we are led to believe that Volta had no genuine interest in animal physiology and considered the problem of muscle contraction exclusively from a physical viewpoint. The invention of the electrical battery was thus considered to be the conclusive event in the controversy, sanctioning the victory of Volta and, consequently, the dominance of a physical viewpoint over a physiological interpretation[3].

There is no doubt that the invention of the battery was a landmark. The research wave set into motion in 1791 by the first publication of Galvani's experiments on muscle contraction became oriented almost exclusively in a physico–chemical direction. As Volta noted, after he had made his invention public, there had initially been an outburst of studies concerned with the chemical effects of his battery. Among these effects, the decomposition of water first observed by Nicholson and Carlisle in England was particularly notable. At the beginning of the 19th century, the most-exciting phase of progress of electrical science was marked by the study of the chemical effects of the Voltaic battery and of the chemical phenomena involved in the functioning of the battery itself. Particularly important was the research of Davy and then of Faraday, Davy's successor at the Royal Institution of London. It was here that a huge Voltaic battery became available. However, Volta's interest in the physiological aspects of electrical influence in animal organisms was genuine, and the results he obtained are of great importance, not only because they led to the invention of the battery, but also because of their intrinsic biological relevance.

Natural and artificial electric organs

Volta started his experimental studies on the effects of electricity in muscle contraction in 1792, after reading the recently published account of Galvani's experiments[4]. However, his interest in the involvement of electricity in 'animal economy' (that is, 'physiology' in a broad sense) pre-dated the publication of Galvani's work, as documented by a letter he addressed ten years earlier to Mme de Nanteuil[5].

In this letter, Volta discussed the possibility of the existence of a genuine 'animal electricity', an electricity that, as he clearly stated, 'would be essentially linked to life, which would depend on some of the functions of animal economy'. In his opinion, this expression was not suited to those forms of electricity that could be produced 'by rubbing the back of a cat, by currying

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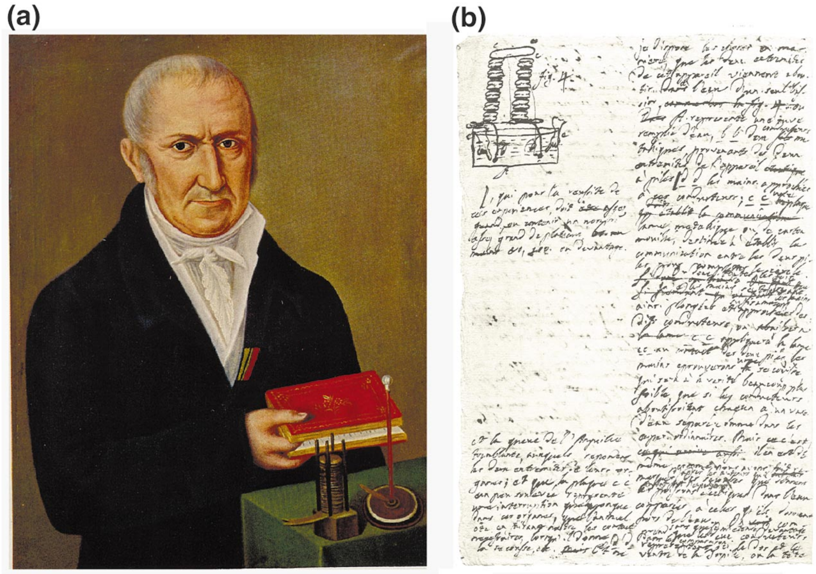

Fig. 1. ***Volta and his electric battery.*** **(a)** *Contemporary portrait of Volta in his old age with two of the most important instruments he invented, the battery and the electrophore.* **(b)** *Draft of Volta's letter to Banks, announcing the invention of the battery.* Courtesy of the Istituto Lombardo – Accademia di Scienze e Lettere, Milan, Italy.

a horse', nor to the electricity 'that has been observed arising spontaneously from the feathers of a living parrot'. According to Volta, however, the existence of a genuine animal electricity had now been discovered in the 'electric fish' by Walsh, who had succeeded in verifying the hypothesis of the electrical nature of their shock. In particular, after confirming that the electric shock of a *Torpedo* could propagate through conductive materials and was arrested by insulating matters, Walsh succeeded in obtaining sparks from an electric eel[6]. Despite these experiments, it was difficult to understand, Volta noticed, how an animal could manage to accumulate a large quantity of electrical fluid and move it at will, and, moreover, how it could bring about the electrical discharge in the water (a conductive material itself) and direct it towards its prey. As to these last difficulties, Volta remarked, they could be explained by taking into account that water is a relatively poor conductor: the discharge would affect prey because it would be directed preferentially towards its body, which is a better conductor than water. Volta was alluding to the explanation of electric-fish discharge given by Cavendish[7], an explanation that led Cavendish to build up an artificial *Torpedo* that was capable of producing an electrical shock when immersed in water (see Fig. 2). Volta concluded his letter by saying that he shared with Cavendish and Walsh the idea that the discharge of *Torpedo* involves a large quantity of electrical fluid that is, however, endowed with low tension.

This was an important aspect of the argument. The discharge of electric fish did not correspond in a simple way to the electric discharges achieved using electrical machines and Leyden jars (the first capacitors), to which 18th-century scientists were accustomed. Unlike the discharges of physical devices, fish could provoke strong contraction and other physiological effects (electric eels can even kill large animals), and yet they were not normally capable of producing the signs considered typical of strong electricity, such as sparks, sounds and electric wind. Until Walsh, these differences made the idea of the electrical nature of this fish discharge purely hypothetical. However, it had been shown that a 'battery' consisting of a large number of Leyden jars, weakly charged and connected in parallel, could produce a discharge resembling that produced by *Torpedo*, in both strength of physiological effects and absence of typical electrical signs. Volta was well prepared to accept this view, as he had previously developed the idea that the efficacy of electrical effects depended on two factors: a quantitative factor (electrical fluid) and an intensive one, which he called 'tension' (and we now refer to as potential or 'voltage'). Electrical machines produced relatively weak effects because, in spite of their high tension, their discharge involved a very small quantity of electric fluid. The discharge of electric fish, on the other hand, was powerful because of the huge amount of electric fluid moved, even though, owing to the relatively low tension involved, the typical electrical signs were absent.

Some themes dealt with in the letter to Mme de Nanteuil resurfaced in the letter to Joseph Banks that Volta wrote after eight years of extremely intense and fruitful research[5]. In this last letter, Volta referred to his new apparatus as the 'organe électrique artificiel' (a denomination reminiscent of the 'artificial *Torpedo*' of Cavendish). Volta said that he did this 'in order to acknowledge that it was similar at bottom', as he constructed it, 'in its form to the natural electric organ of the *Torpedo* or electric eel'. As it was made by an alternation of disks of two different metals (copper and tin, or silver and zinc) with interposed humid disks, the battery bore an obvious visual resemblance to the natural electrical organ of fish, which is also made up of stacked disks. In order to make the resemblance with the electric eel more evident, Volta suggested that the stacked disks of the artificial organ 'might be joined together by pliable metallic wires or screw-springs, and then covered with a skin terminated by a head and tail properly formed, etc.'

From the constructional point of view there was, according to Volta, another more-fundamental similarity. Unlike any other physical electric device, and similar only to the natural electric organ, his new apparatus was capable of producing and maintaining a flow of electric fluid without the need of interior insulating materials. It is worth remembering that the possibility illustrated by his physical device of an 'electricity excited by the mere contact of conductive substances' removed an important conceptual difficulty in envisioning how the natural electricity of electric fish could be produced and accumulated by animal tissues, which were known to be composed exclusively of conductive tissues.

The artificial electric organ shared important operational similarities with the natural organ: although particularly effective in producing physiological effects, it was poor at producing the typical electrical signs of electrical machines. This was an indication, according to Volta, that in both cases, large amounts of electric fluid were moved at a relatively low tension. Moreover, the artificial apparatus could 'act incessantly and without intermission…without any previous charge', similar to the fish that can produce shocks repeatedly without exhausting their electricity.

The way Volta pushed the similarity between natural and artificial electric organ has been interpreted as evidence that he aimed to reduce the biological mechanism to the domain of physics, by showing the basic similarities between biological and physical phenomena. Accordingly, his purpose would have been to show that the electricity of *Torpedo* and electric eels is also, in some way, a type of physical electricity, to which it would be inappropriate to assign the phrase of 'animal electricity', something that he had considered fully pertinent about 20 years earlier[8].

It is perhaps appropriate to recall what Volta wrote in 1802 (Ref. 5). By discussing the different ways conductive materials can be arranged in order to obtain a current, Volta noted the effectiveness of an assembly of one metal (conductor of the first class in his classification) with two different liquids (second-class conductors), in addition to the usual combination of two different metals with a liquid. Afterwards, he wondered whether an electromotive force could also be obtained by putting together three different conductors of the same class (for example, three different metals or three different liquids). He had not yet been able to produce any relevant electric sign by such combinations in his experiments. 'But', he added, 'if not art, nature has found the way to succeed with this in the electric organs of *Torpedo* and trembling eel (*Gymnotus electricus*), etc., which are built up exclusively of conductors of this second class, that is, humid ones, without anyone of the first class, without any metal. And perhaps we are not far from the possibility that also art could imitate them.' Thus, nature (in this specific case the animal kingdom) might open to the physicist unsuspected possibilities that he should try to imitate with his art.

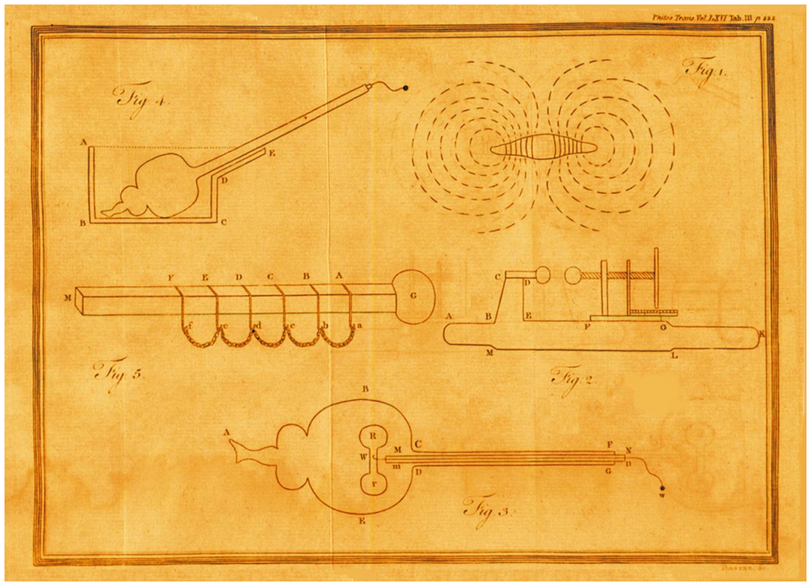

Fig. 2. ***The 'artificial Torpedo' of Cavendish capable of delivering electric shocks even when immersed in water.*** *The graphical illustration of current flow first used here anticipates the representation of the 'lines of force' of electrical field suggested by Faraday in the 19th century. This is one of the first successful applications of physical modelling to biology.* Reproduced from Ref. 7.

Volta's electro–physiological experiments

In the work of Volta, 'electrical–physiological' does not only allude to the possibility of reproducing in a physical device the electric phenomena of living organisms. In the course of the studies that led to the invention of electric battery, Volta made a series of important observations of proper physiological relevance that have been largely ignored by the scientific tradition. This is perhaps also the consequence of the artificial limits that exists between physics and physiology, erected by a certain culture that was scarcely aware of the objective difficulty of tracing the boundaries between sectors of science in the 18th century.

Volta anticipated, by about half a century, the fundamental idea of the functional organization of nervous system, the doctrine of 'specific nervous energies' of Johannes Müller[9]. As it is well known, this doctrine stipulates that the physiological effects of nerve stimulation depend on the type of nerve stimulated and not on the type of stimulus used to achieve the stimulation. If different stimuli are used for stimulating the eye or optic nerve, such as mechanical or chemical irritations, or light or electricity, the result will be, in any case, a luminous sensation. The same holds true for most other types of sensation, such as taste, hearing and somatic sensations. In Volta's formulation, this law of the constancy of nerve stimulation effects also encompasses motor nerves. In his second memoir on animal electricity, published in May 1792, during the initial period of his electrophysiological investigations, Volta wrote,

> It, therefore, becomes manifest that according to which nerve is stimulated and to what is its natural function, such is the effect that ensues correspondingly, that is to say as regards sensation and motion, when that nervous virtue is activated on subjecting it to the influx of electrical fluid.

He had just mentioned the experiment of electrical stimulation of his tongue with a bi-metallic arc, an experiment that, varied in a multiplicity of forms, was reported repeatedly in future publications and private letters[5].

From a communication that he sent a few months later for publication to Tiberius Cavallo, a Fellow of the Royal Society, we learn that Volta carried out this experiment with the initial purpose of eliciting muscle contraction in living humans. The tongue seemed particularly appropriate because of its muscular nature, its accessibility and the low electrical resistance of its mucous surface. Contrary to his expectations, however, he did not obtain any contraction by using a tin–silver arc, but perceived instead a clear acid taste[5]. Volta interpreted this effect correctly as being caused by the stimulation of nerve fibres coming from the gustatory papillae. Next, he tried a similar experiment on the eye, and he found that the bi-metallic contact induced a light sensation there[5].

He also endeavoured to stimulate the acoustic and olfactory systems. At the beginning he did not succeed in producing any acoustic sensation with a bi-metallic arc, but, after the invention of the battery, he was able to produce a noise by applying two probes connected to a battery of 30–40 silver–zinc elements into both ears. Volta never succeeded in producing an odour sensation by applying the electrical stimulus into the interior of nose, not even by using the powerful electricity of a battery of many elements. However, he succeeded in eliciting somatic sensations by applying his 'metallic electricity' to skin or to a mucous surface. Although initially he referred to these sensations as tactile, afterwards he decided that they were more akin to pain. The sensations were particularly acute and hard to tolerate if the stimulus was applied to a sore surface. After the invention of the battery he discovered that the painful sensation grew when the power of battery was increased, and with batteries of 20 elements it could not be endured even for a few seconds.

In his electro–physiological experiments, Volta showed a particular ability to obtain important information by using simple devices. Taste sensation can be elicited, he said, by using a silver and copper coin. A

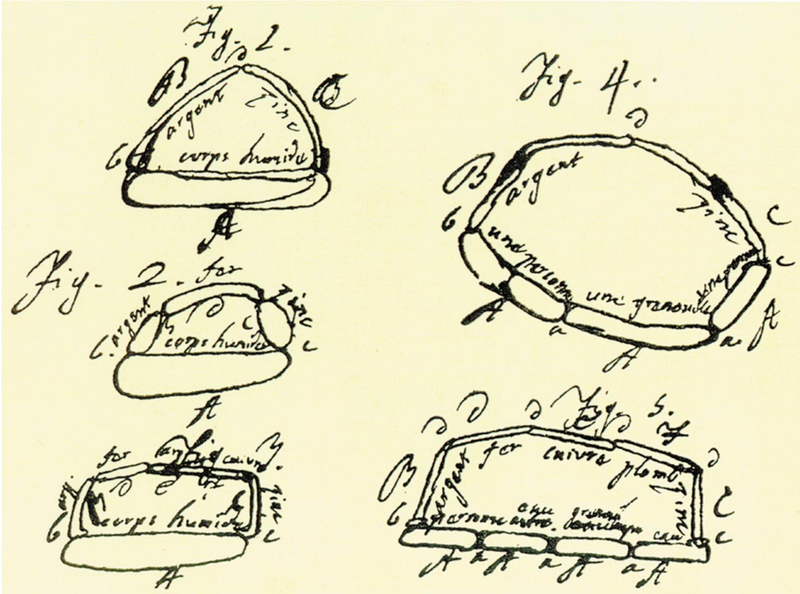

Fig. 3. ***Schemes of the connections between various metals, humid conductors, animal preparations and human bodies, similar to those used by Volta to illustrate his multifaceted experiments on the electricity produced by metallic contacts.*** Courtesy of the Istituto Lombardo – Accademia di Scienze e Lettere, Milan, Italy.

visual sensation can be elicited by using a blunt tinfoil (or a zinc lamina) and a silver spoon: the tinfoil is put into contact with the conjunctiva of the eye corner and the spoon used to contact the interior of mouth.

Volta liked to combine different physiological effects in a single experiment; for example, putting one of the two metals in contact with the tip of his tongue and the other with conjunctiva. As the two metals were connected together, he experienced both a light and a taste sensation. The experiment could be further complicated by forming a chain that included, besides the experimenter's eye and tongue, a frog preparation[5]. Closing the circuit also elicited, in addition to the double sensation, contraction of the frog's leg. By using other arrangements, Volta could produce a taste sensation in one subject and a visual sensation in another, besides eliciting the contraction of a frog (see Fig. 3).

This way of combining different effects in a single experiment might apparently represent the tendency of the 18th-century science towards stage effects. In Volta, however, it reflected more the tendency to capture the essentials in a scientific result, making it easy to show and to reproduce. In the communication of the invention of the battery he invites the reader to repeat one of his multifaceted experiments by exploiting the strong electrical power of the new apparatus.

> But the most curious of all these experiments is, to hold the metallic plate between the lips and in contact with the tip of tongue; since, when you afterwards complete the circle in the proper manner, you excite at once, if the apparatus is sufficiently large and in good order, and the electric current sufficiently strong and in good course, a sensation of light in the eyes, a convulsion in the lips, and even in the tongue, and a painful prick at the tip of it, followed by a sensation of taste.[1]

Far from adopting exclusively an 'electro–physical' viewpoint, as it has been claimed, Volta operated a continuous and fruitful exchange between an electro–physical and an electro–biological perspective in his investigations. From the tongue experiment, first performed in 1792, he was able to determine the polarity of metallic current, four years before he could measure it with a physical instrument. He noticed that the acid sensation produced by application of the tin pole of the bi-metallic arc to the tongue could be reproduced by discharging a positively charged Leyden jar on the tip of the tongue. Moreover, from the maintained character of the acid sensation perceived, Volta concluded that a bi-metallic contact produced a continuous flow of electricity. Having established the continuous (potentially 'perpetual', as he liked to say) character of metallic current, he could then conclude that the transient appearance of contractions in frog legs, which occurred only at the making and breaking of circuit, was not due to an intermittent character of the current produced by metals, but to a physiological property of nerve excitability.

In his experiment on vision, he initially noticed that light sensation occurred only at the onset and at the offset of the electrical stimulus. However, aware of the continuous character of the metallic current, he endeavoured to produce a maintained sensation, and eventually was able to perceive a steady dim light when one of the poles of the bi-metallic circuit was applied close to the eye and the experimental room was completely darkened[5]. However, as this continuous light was very faint, he concluded that, in order to stimulate effectively, it was necessary to make and break the circuit in rapid alternation. This method, which he also used for obtaining tetanic contraction in frogs, precedes the method of impulse trains used in modern times. Volta was particularly skilful in these experiments: with the ability to break and make alternatively, 'and with more or less rapidity', the contact between the two metals he was able, in 1793, to produce a 'sensation of a undulating, and, as it were, sparking light, and eventually of an almost continuous light'. A flicker-fusion experiment with an electrical stimulus provided by only a tinfoil and a silver spoon!

Volta noticed that the effect of electrical stimulation often depended on stimulus polarity, thus anticipating somewhat the 'law of polar excitation' developed fully by Pflüger more than 50 years later[10]. In his tongue experiment he noticed that the taste changed from 'acid' to 'alkaline' when the polarity of the stimulus was inverted. Moreover, he noticed that sensation of pain upon stimulation of skin or of a mucous surface was excited by a smaller intensity current with stimuli of negative polarity. He also anticipated Pflüger, at least partially, by noting that stimuli of a given polarity were more effective at the onset of current application, whereas opposite polarity stimuli were usually more effective at current offset. In 1795, he could produce both onset and offset contractions in a single experiment. A bi-metallic arc was used for connecting two frog preparations through two glasses filled with a saline solutions. One preparation was plunged with its spinal cord on the side of the negative electricity and with its legs on the positive electricity side, while the other frog was arranged in the opposite way. One frog contracted at the moment when the circuit was established, the other when it was broken[5].

In particular, Volta was able to counteract experimentally possible objections to his conclusions. It could be surmised that the acid taste perceived in tongue experiment was merely due to the metals themselves and not to the passage of current. In order to address this objection, he first showed that the acid sensation did not appear when the metals were in contact with tongue, but not in contact with each other. Furthermore, he showed that the acid taste could be perceived even when there was no direct contact of tongue with metal: for example, when tongue tip was plunged in a glass filled with water that, in turn, was in contact with the positive electrode. He also performed a striking experiment, in which the solution used for the contact with the tip of the tongue was alkaline. Immediately as he plunged his tongue tip, he perceived an acid taste (which he attributed to current passage) that was subsequently followed by an 'alkaline' sensation, as the solution diffused and reached the tongue surface[5].

Although Volta did not write works that dealt exclusively with physiological and medical themes, the interest for the physiological and medical relevance of his discoveries appears clearly in his writings. In 1793, he discussed different arrangements suitable for electric stimulation of the visual system. Among other possibilities, he remarked that the experiment also succeeded when the tips of the bi-metallic arc were placed inside mouth; for example, in the opposite sides of mouth vestibule. This experiment is easy to reproduce, because it does not involve the rather heroic procedure of putting one of the metallic tips on the eyeball (it can be conveniently performed in modern times by using a 4.5 V battery, for example). Volta wrote[5],

> On the other hand I am persuaded that the experiment would succeed even in persons blind for cataract, or any other fault, except for insensibility or paralysis of optic nerves.
>
> Therefore, these trials could be of some utility, allowing one to discover if such fault exists. Moreover, who knows if, being well administered, they could be of some help in this same paralysis, both initial, or more or less advanced.

In 1802, Volta indeed used the electricity of his battery for therapeutic purposes, although, in this case, to treat deafness rather than blindness.

Concluding remarks

It is interesting to note that the communication to the Royal Society in 1800 on the invention of the battery is to a large extent concerned with results and discussions of physiological relevance. In the final pages, after discussing at length the effects of the electricity of the battery in promoting sensations and movements, Volta wrote[1],

> All the facts which I have related in this long paper in regard to the action which the electric fluid, when excited and when moved by my apparatus, exercises on the different parts of our bodies which the current attacks and passes through – a current which is not momentaneous, but which lasts, and is maintained during the whole time that this current can follow the chain not interrupted in its communication; in a word, an action, the effects of which vary according the different degrees of excitability of the parts, as has been seen – all these facts, sufficiently numerous, and others which may be still discovered by multiplying and varying the experiments of this kind, will open a very wide field of reflection, and of view, not only curious, but particularly interesting to medicine. There will be a great deal to occupy the anatomist, the physiologist, and the practitioner.

Two centuries later, we can consider how prophetic these words were, by considering the immense development of electrophysiology, and the tremendous importance reached by electricity in its diagnostic and therapeutic application to medicine.

The 18th century, an 'electrical century' *par excellence*, ended with the invention of the battery, and a new epoch began. In the science of enlightenment, the barriers between different disciplines were much less defined than in modern times, mainly because of the revolutionary phase of scientific progress. This imposed a great interchange of scientific ideas and methods. The tradition that has seen Volta exclusively as the physicist, in modern acceptance, opposed to the physiologist, Galvani, was developed mostly in the 19th century. It has been revived in modern times as a 'case history' for some philosophies that aim to exalt the importance of external influences and a priori conceptions on the activity of scientists[3]. Besides contributing to the neglect of the electro–physiological work of Volta, it risks under evaluating some important aspects of the controversy between Galvani and Volta (see Refs 11,12).

How could we apply to old epochs those categories used to distinguish sectors of science in modern times? It would be difficult to assign many of the 17th- and 18th-century scientists to physics, or to medicine, or to philosophy, and this is particular for the study of electricity. In 1600, more than a century before Volta, the word 'electricity', in its modern sense, first appeared in *De Magnete*, a milestone in the historical development of electrology, written by William Gilbert[13]. Gilbert was the physician of Queen Elizabeth I.

Instead of relying on distinctions that are more or less artificial, and particularly inappropriate for the understanding of science history, we could perhaps apply to the scientific work of Volta what Niels Bohr said in 1937, when commemorating the bicentennial of the birth of Galvani[14]:

> [this] immortal work…which inaugurated a new epoch in the whole field of science, is a most brilliant illustration of the extreme fruitfulness of an intimate combination of the exploration of the laws of inanimate nature with the study of the properties of living organisms.

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