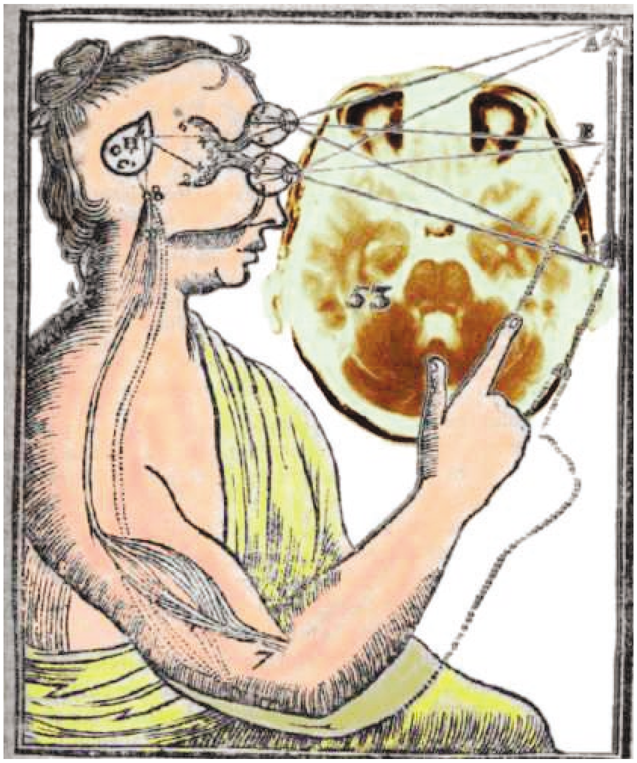

Original engraving: *L'Homme de René Descartes.*

# Bioelectricity and the Origins of Physiology

**BRIAN S. BAIGRIE**

The French scientist and philosopher, René Descartes (1596-1650), is celebrated by historians of science for his contributions to the discrete mathematical sciences (analytic geometry, sine law of refraction, etc.). In his day, however, he was renowned (and, in some quarters, reviled) for the startling thesis that all things, including living creatures, are machines (automata). Descartes (Fig. 1) was not the first to attempt to model biological phenomena on mechanical devices (Johannes Kepler had treated the living eye as far as the surface of the retina as an inanimate optical instrument), but it was Descartes who pioneered the idea that living things are nothing more than mechanical devices, assembled out of lifeless particles that collaborate to produce motion in the whole.

The insistence that there is no line to be drawn between living and nonliving things was the most revolutionary feature of Descartes' mechanistic physiology. It had long been assumed that living things were possessed of a vital entity (separate from their parts) that animated them and explained their characteristic activities—an idea that persists today in such familiar expressions as "scientists will someday create life in the test tube" and "he lost his life." Although nature clearly is not still and lifeless, for Descartes the movement and growth that we intuitively associate with the presence of life was just a mechanical effect, one that differed in no significant way from the propulsion of water through pipes by a pump (Fig. 2).

Although living things seem to be capable of self-initiated movement, Descartes contended that they require the constant attention of some external mover; i.e., like the mainspring of a watch, living things need to be wound up by some external agent. Postulating that God introduced a fixed quantity of motion into the cosmos at the time of creation, Descartes explained the phenomenon of life in terms of the redistribution of motion during the countless collisions between minute particles of matter. He argued that God conserved that fixed quantity of motion, ultimately making possible life.

Descartes' introduction of the conserving influence of God to explain the activities of organisms was unattractive to eighteenth century physiologists, who were increasingly seeking to frame purely naturalistic explanations for biological phenom-

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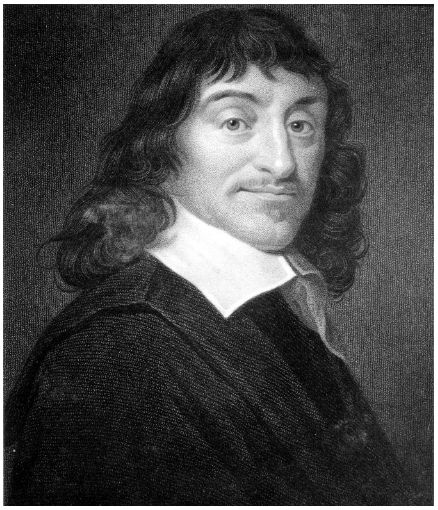

**Figure 1**. Portrait of René Descartes. (*Courtesy AIP Emilio Segrè Visual Archives.)*

ena. Physiologists were also adverse to Descartes' portrait of the central nervous system as a set of hydraulic pipes, the chief purpose of which was to communicate stimulus to the brain and carry fluid back to the muscles, causing a contraction. These misgivings aside, they were held in thrall by Descartes' project of a purely mechanical physiology.

The research program advanced by Descartes received an enormous boost with the rise of studies of electricity during the late eighteenth century. These studies opened the door to the possibility of locating the source of an organism's activity within the organism itself—from muscular contraction to the neural activity of the human brain, electricity within the organism could be exploited to explain its activities, thereby rendering divine intervention completely unnecessary.

The scientist who first attempted to fuse the study of electricity with the science of physiology was Luigi Galvani (1737-1798), for whom the process of electrically plating steel with zinc (galvanizing) is named. An anatomist and physician at the University of Bologna, the world's oldest continuing university, in his *Commentary on the Forces of Electricity in Muscular Motion* (1791), Galvani demonstrated that muscle response depends on the delivery of electricity to the nerve through a conductor.

From very early times, it was known that some marine animals (e.g., electrical eels) are capable of giving shocks. After scientists discovered in 1745 how to generate and accumulate static electrical charges in Leyden jars or rotating static electricity generators (Fig. 3), they began to wonder about the relationship between the physiological effect of its discharge and that of shocks given off by these marine animals. After all, the explosive power of the discharge from a suitably prepared Leyden jar was legendary—it could kill birds and small animals, and even, in a famous demonstration before the King of France, throw an entire company of 180 soldiers simultaneously into the air. It was therefore to be expected that scientists would come to see the Leyden jar as a model for organic phenomena.

In a remarkable series of experiments that commenced around 1780 or so, Galvani found that dissected frog's legs twitched as though in spasm or convulsion on contact with a spark from an electric machine (Fig. 4). What is more, he found that a metal scalpel caused the frog's legs to twitch if the machine was turned on, even if the spark did not actually make contact. If an electrical spark caused this muscle twitching, Galvani reckoned that he could confirm the hypothesis, advanced in 1749 by Benjamin Franklin (1706-1790), that lightning was a form of electricity (as opposed to received opinion which held that lightning was due to exploding gases). To test Franklin's hypothesis, Galvani hung the legs of frogs by their nerves from brass hooks against an iron latticework. The lower tip of the suspended member was connected to a grounded wire. He found that the legs twitched when thunderclouds appeared but they also twitched when there were no thunderstorms. He noticed that twitching could be seen even when the weather was pleasant. The twitching occurred, Galvani discovered, whenever the muscles came into contact with two different metals at the same time.

Since the same twitching was observed when the specimen was moved indoors, Galvani ruled out atmospheric conditions as the root of the muscular contractions. Perhaps the metals were the cause of the twitching—the twitching legs indicating an electric charge generated from outside in the same way that an electroscope signals an electrical charge by the divergence of straws or metallic ribbons. Another possibility was that the frog muscles retained some sort of innate animal electricity even after the frog had expired.

Galvani embraced this latter view. Conceiving a living creature as a fleshy kind of Leyden jar, he argued that the motion was caused by a vital fluid he termed animal electricity. Although Galvani conceived this fluid as having an electric nature, his view was part of a long-standing tradition, which identified life with the breath and the blood, and would influence Mary Shelley's *Frankenstein.* In Galvani's new model of the basic structure of living matter, the nerve and muscle constituted the inner and outer charged surfaces of the jar. When the outer surface of the muscles—like the outer surface of the Leyden Jar—received an electrical charge, the nerve and inner muscular surface became oppositely charged, leading to muscular contraction.

**Figure 2**. Action of the nerves. (Original engraving: *L'Homme de René Descartes*.)

Galvani's paper received a great deal of critical discussion, as one might expect of a new conception of the organism as having an electrical nature. It was circulated among fellow scientists, including Alessandro Volta (1745-1827), who repeated his experiments. A chemist and physicist by trade, Volta was skeptical about the notion of animal electricity. He geared his experiments toward Galvani's model of a Leyden jar. Concentrating the

**Figure 3**. The Leyden jar, the first electrical condensor. In its original form, the Leyden jar was a glass jar or bottle capable of storing a static electric charge that could be released, when grounded, with explosive effect. (*Photo Credit: Coimbra, Portugal.*)

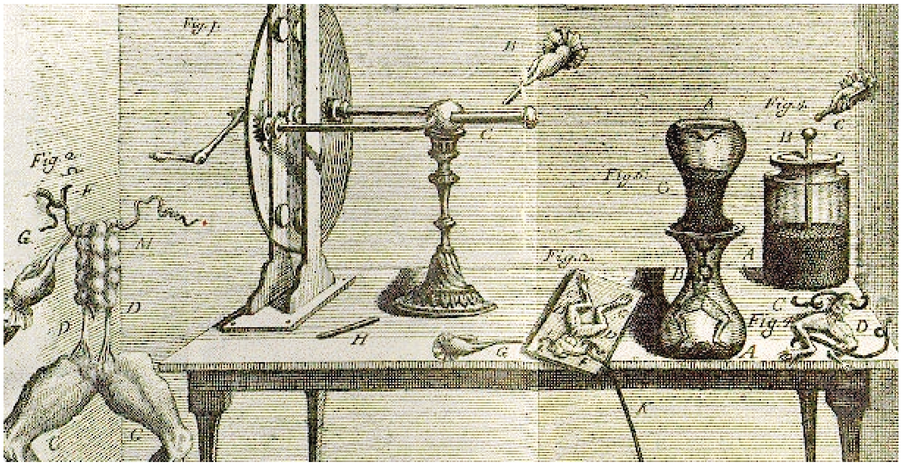

**Figure 4**. Galvani's experiment.

metallic probes on the nerves only, thereby taking the muscles out of the picture, he succeeded in creating an experimental arrangement that no longer functioned like a Leyden jar. This redesigned apparatus, he found, produced the same results.

Volta was struck by the fact that electricity was produced only if two different metals were used. He tried placing a piece of tinfoil and a silver coin in his mouth, one on top of the tongue, the other touching his tongue's lower surface. When the foil was pressed to the coin, a sour taste was produced in his mouth, which Volta interpreted as indicating the presence of an electrical discharge. The taste lasted as long as the tin and silver were in contact with each other, showing that the flow of electricity from one to the other was continuous. A silver spoon was substituted for the coin and a copper wire for the tinfoil, with the same result. The metals, he concluded, were not just conductors but were actually responsible for the production of electricity. The frog's legs had exhibited not animal electricity but metallic electricity.

Continuing his experiments, Volta realized that electrical forces were generated not only when two dissimilar metals touched but also when a metal touched certain kinds of fluid. When he placed disks of silver, tin, or zinc on moist cloth, clay, or wood and then separated them and brought them to the electrometer, a negative electrification resulted. He showed further that improved results were produced when a circuit was formed by two different metals separated by a moist element, and that their effectiveness was added together when such combinations of metals and moist element were stacked in a repeating pattern.

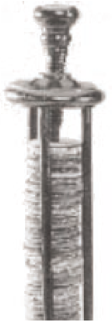

**Figure 5**. Two versions of Volta's pile, or column of electric generating elements. I The first featured a pile of silver and zinc disks, each separated from the adjoining pair by paper or cloth separators soaked in brine; the second featured a ring of cups filled with brine and connected by alternate strips of zinc and silver joined by metallic jumpers. The second form was an improvement over the first because the current tended to weaken as the brine in the separators dried out.

In this way, Volta succeeded in building his famous column or pile of electric generating elements (Fig. 5), which is the basis of all modern wet-cell batteries. He experimented with many solutions, finally settling on brine. He found that if he constructed piles of dissimilar metal disks, sandwiching pieces of cardboard-soaked brine in between them, he had a very effective set of battery cells (each sandwich forming one cell). The invention of the electrical battery was announced in 1800, with Volta demonstrating its action the following year in Paris.

Volta's experiments were immediately replicated by scientists on both sides of the Atlantic, who recognized that a source of constant-current electricity would ultimately transform established disciplines in ways that had been unimaginable. The discipline that reaped the greatest immediate benefit from Volta's battery was chemistry, which now possessed a powerful tool for tracking down new elements and understanding the nature of chemical bonding.

The most ambitious experimenter with the new technology was Humphry Davy (1778-1829), who persuaded himself that the voltaic cell produced electricity through chemical reaction. He conjectured that the reverse might also be true—that the application of electricity to compounds and mixtures might produce chemical reactions. With an extra strong battery, in 1807 Davy extracted potassium from a lump of dampened potash and a week later sodium from caustic soda (now known as sodium hydroxide).

The enormous success that chemists enjoyed with Volta's battery only reinforced Volta's claim that Galvani's interpretation of his experiments had been misguided. Even so, Galvani's underlying conviction that electrical phenomena are involved in life processes was hardly touched by Volta's criticism. The only issue for the science of physiology in the coming years was the nature of this involvement—whether it would be expressed (following Descartes) in purely mechanical terms or would lend credence to Galvani's conviction that living things are animated by animal electricity.

The study of bioelectricity waned in the quarter century following Volta's historic announcement, not because the interest of physiologists was dampened by

Volta's critique of Galvani but because they found that they could make no useful headway on the practical problem of measuring the electrical currents thought to be generated in the nervous and muscular cells—currents that were so weak that they could not be detected with available electroscopes. Thereafter the study of bioelectricity was revived by a new school of physiologists. The central figure in this school was the Swiss scientist Emil Heinrich Du Bois-Reymond (1818-1896), professor of physiology in Berlin. Thanks to the invention of the galvanometer two decades earlier, in 1848-1849 Du Bois-Reymond was able to detect what he called action current in the frog's nerve and was subsequently able to demonstrate that this phenomenon also occurs in striated muscle and is the primary cause of muscular contraction. His contributions, published in his book, *Researches on Animal Electricity* (1848), are the foundation for the field of bioelectricity.

Du Bois-Reymond's research was dictated by the basic principle of mechanical explanation that in a living thing no forces have any effect other than the familiar physiochemical ones—a principle that has since dominated the science of physiology. In the wake of his achievements, nineteenth century physiologists were able to replace Descartes' quaint portrait of nerves as water pipes with the modern view that information within the nervous system is carried by electricity generated directly by organic tissue.

In historical reconstructions, if the focus is on the place of electricity in the construction of modern physiology, Galvani will surely be granted a prominent position, since it was he who championed the idea that electricity is centrally involved in the activities of living things. For Galvani, however, animal electricity was a vital fluid that was similar to ordinary static electricity but a property of living things alone. If our emphasis, instead, is on the mechanization of physiology, it is clear that electricity became a central part of physiology only when the new generation of physiologists found a way to frame purely mechanical interpretations for the action of electricity within living things. The mechanisms that Descartes advanced to explain the activities of living things may be quaint by present standards, but they are closer in spirit to the mechanisms postulated by modern physiologists than we may at first be inclined to believe.

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