

# THE ORIGINS OF THE ELECTROCARDIOGRAPH AS A CLINICAL INSTRUMENT

by

JOHN BURNETT<sup>1</sup>

## INTRODUCTION

In recent years, a significant literature has grown up on the development of the technology of medical diagnosis. Stanley Joel Reiser and Audrey Davis have each written books on the subject,<sup>2</sup> and there have been several shorter studies on individual instruments. The two areas on which attention has been concentrated are the evolution of specific pieces of technology, from a first model with certain practical drawbacks to a more successful one; and the varying reactions of the medical profession to technological change. My focus here is different. I wish to examine not the development of a diagnostic instrument, but the conditions that made possible its creation, and I propose to concentrate not on the physician or the physiologist, but on the instrument-maker.

The introduction of the electrocardiograph—the first commercial model was sold in 1908—marked a change in the nature of the instrumentation of medical diagnosis.<sup>3</sup> It was a much more complicated piece of diagnostic apparatus than had been used before. In the previous century, several important instruments had been placed in the clinician's hands. Most, such as the stethoscope, the thermometer, and the pleximeter, worked on very simple principles, though skill was required to interpret the messages they gave. Others—the sphygmograph is perhaps the clearest example—were mechanically ingenious. The electrocardiograph, however, was qualitatively different. Certainly, it embodied great mechanical and electrical ingenuity. Its most delicate part was the string galvanometer, initially evolved by Willem Einthoven in 1900-03, and probably the most sensitive electrical measuring instrument which had been devised by that time; and it used a form of material—the quartz filament—that had first been made less than twenty years before. In order to make visible the tiny movements of the filament, condensing and projecting microscope lenses were used: the lens design was highly mathematical, and modern

<sup>1</sup> John Burnett, MA, MSc, Department of Physical Sciences, Science Museum, London SW7 2DD, formerly of the Wellcome Museum of the History of Medicine.

<sup>2</sup> Stanley Joel Reiser, *Medicine and the reign of technology*, Cambridge University Press, 1978; Audrey Davis, *Medicine and its technology*, Westport, Conn. Greenwood Press, 1981.

<sup>3</sup> The history and significance of the electrocardiograph are discussed by S.L. Barron, *The development of the electrocardiograph*, London, Cambridge Instrument Company, 1952; George E. Burch and Nicholas P. DePasquale, *A history of electrocardiography*, Chicago, Year Book Medical Publishers, 1964; and Reiser, op. cit., note 1 above, pp. 107-110.

kinds of glass were required. The light source was a carbon arc, the brightest available point source of light, which had become a reliable device only in the previous two decades. Finally, the movements of the filament, after being projected, were recorded on a photographic plate or film which was coated with a recently developed sensitive emulsion. Had any one of these pieces of technology not been available, the electrocardiograph could not have taken shape. But it was not the ingenuity behind its conception which, in itself, separated the electrocardiograph from existing medical technology. It was the combination in one instrument of so many different and new ideas. Twenty years before, so many of its components remained to be invented that the instrument, taken as a whole, was almost unthinkable.

To draw together these various elements of modern technology and fit them into the electrocardiograph was the achievement both of its inventor Willem Einthoven, and of the companies which made and marketed it, notably its sole manufacturers in England, the Cambridge Scientific Instrument Company (CSI). Between 1901 and 1908, Einthoven showed with an unwieldy prototype that the problem of recording the electrical impulses in the heart was soluble. By 1912, the instrument-makers had reduced the size of his apparatus to the point where it was practicable to install one in any hospital or consulting room.

My first intention here, so to speak, is to take the electrocardiograph apart, and examine its various components. If we study each one in turn, and recognize the original reason for developing that piece of technology, and the ends to which it had been used before 1903, we may understand better what Einthoven and CSI actually did: how they drew from a range of sources to solve the particular problem they set themselves. In a way, we are engaged in an exercise in searching for roots, but not in a whig sense. The whig approach might examine the various attempts before Einthoven to detect and measure the electrical currents in the heart. My present aim is to point out how *different* the various applications of technology were from the one they found in the electrocardiograph. This exercise is similar to Hoff and Geddes' discussion of the rheotome, which showed that its role as a physiological instrument had its technical origins in contemporary work on the measurement of electric current.<sup>4</sup> The second part of this essay discusses the relationship between the Cambridge Scientific Instrument Company and its Cambridge environment, and attempts to show how the nature of the Company was shaped by the circumstances under which it was created and grew.

#### PHYSIOLOGICAL INSTRUMENTATION

In 1876, Thomas Henry Huxley surveyed the range of apparatus available for biological research:

Instrumental appliances of simple character have been used by students of the Biological Sciences from the earliest times; but the employment of delicate apparatus, and especially of instruments of precision, for the quantitative admeasurement of the forces exerted by living matter, is of comparatively recent date. In fact, the conception of the problems to the investigation of which such apparatus is applicable was impossible until the physical and chemical sciences had reached a

<sup>4</sup> H.E. Hoff and L.A. Geddes, 'The rheotome and its prehistory: a study in the historical interrelation of electrophysiology and electromechanics', *Bull. Hist. Med.*, 1957, 31: 212-234, 327-347.

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high degree of development, and were ready to furnish not only the principles on which the methods of the physiological experimentalist are based, but the instruments with which such inquiries must be conducted.<sup>5</sup>

Huxley was making an important point: biology had been able to draw not only on the concepts and results of physical science, but also on its instrumentation. In addition to instruments such as the stethoscope, kymograph, and cardiograph, which were invented specifically for diagnostic or physiological work, others, for example the thermometer and various forms of galvanometer, were first devised for use in the physical sciences and were only later applied in biology. In origin, the electrocardiograph belonged to the latter type. At the same time, physics and chemistry were entering other sciences, such as geology, in which stratigraphy and palaeontology were being replaced around 1880 by petrology and mineralogy as the most important disciplines.

Later in the same essay, Huxley said:

The relations of electricity to the properties of contractile and nervous substance have led to the employment of the most delicate apparatus of the electrician, as a means of physiological investigation; while it is not too much to say, that the introduction of various forms of registering apparatus has done for physiology what the microscope has effected for anatomy. It has enabled an apparently instantaneous action to be resolved into its successive constituents, just as the microscope has analyzed an apparent point into its co-existing parts; while the elements of the most complex co-ordinating movements have been separately determined, and their relations to one another accurately defined, in a manner comparable to that in which the microscope renders visible the complex arrangement of the histological elements of a tissue, which to the unassisted eye appears homogeneous. The apparatus by which M. Marey has so successfully investigated the phenomena of animal locomotion, affords an excellent example of physiological appliances of this kind.<sup>6</sup>

Huxley had moved here from an objective assessment of the state of contemporary physiology into propaganda. He clearly believed in the use of advanced instrumentation in physiological research, but in comparing the achievements of Virchow and the young Pasteur with the limited findings of, for example, Marey in high-speed photography, Ludwig with the kymograph, and various workers with the sphygmograph, he was overstating the importance of the results achieved with registering apparatus by 1876. The important concept of cellular pathology had been introduced as a result of researches with the microscope, and it had had an effect on the practice of diagnosis.<sup>7</sup> Electrophysiology, also mentioned with enthusiasm by Huxley, had produced no more than a handful of interesting results. It arrived in clinical medicine only when the electrocardiograph moved from being a physiological instrument to being a diagnostic one, a consequence of the work of Einthoven himself, Thomas Lewis, and others, during the first dozen years of the twentieth century.

Huxley had, however, drawn attention to an important development in instrumentation. Recording instruments had been used by natural philosophers in

<sup>5</sup> Thomas Henry Huxley, 'Biological apparatus', in South Kensington Museum, *Handbook to the Special Loan Collection of Scientific Apparatus*, London, Chapman & Hall, [1876], pp. 312-326, quoting from p. 321.

<sup>6</sup> *Ibid*, p. 325.

<sup>7</sup> Reiser, *op. cit.*, note 2 above, 69-90.

the seventeenth century.<sup>8</sup> In meteorology, Wren in 1663 and Hooke in 1664-79 both constructed “weather clocks” which produced recordings of the simultaneous variations in a number of quantities.<sup>9</sup> The first recording meteorological instrument which was sufficiently mechanically robust to work satisfactorily for a period of years was probably the very complex barograph which the Scots clockmaker Alexander Cumming made for King George III in 1765.<sup>10</sup> Photographic recording was applied to a barograph less than two months after Fox Talbot announced the calotype process in 1839.<sup>11</sup> All these meteorological instruments were useful because they gave continuous recordings of slowly-varying quantities, so that the need for frequent activity by a human observer was avoided. In other fields, there was an independent requirement for the recording of varying quantities, to make possible the study of variations that took place too rapidly for direct human perception to grasp them. Thomas Young produced such an apparatus in 1807, but no one seems to have followed his lead.<sup>12</sup> At the beginning of the nineteenth century, indicator diagrams began to be used to examine the efficiency of steam engines, and they soon became common. In physiology, the history of recording instruments really starts in 1847, with Ludwig’s kymograph.<sup>13</sup>

#### THE OSCILLOGRAPH

The problem of designing an effective oscillograph in the early 1890s was important because of the growth of the electricity industry. If one single event in Britain can characterize this growth, it is perhaps the opening of Deptford Power Station in 1891, the first generating station to serve successfully a wide area,<sup>14</sup> engineered by Sebastian de Ferranti. To electrical engineers, it was particularly important to have a voltage curve for each alternator because they often had odd and widely differing characteristics.<sup>15</sup> CSI later stressed the importance of the oscillograph for attaining efficiency in power stations, and for avoiding resonance effects which could cause a breakdown in high tension cables.<sup>16</sup> There was an alternative to the oscillograph, the “point to point” method in which sample readings were taken from points in the wave, advancing slowly through the waveform so that a cycle was completed in about an hour. This method was successfully applied in the electric power industry,<sup>17</sup> but, as

<sup>8</sup> H.E. Hoff and L.A. Geddes, ‘Graphic monitoring before Ludwig: an historical summary’, *Archs int. Hist. Sci.*, 1959, 12: 1-25; *idem*, ‘The beginnings of graphic recording’, *Isis*, 1962, 53: 287-310; and Laura Tilling, ‘Early experimental graphs’, *Br. J. Hist. Sci.*, 1975, 8: 193-213.

<sup>9</sup> W.E. Knowles Middleton, ‘The first meteorographs’, *Physis*, 1961, 3: 213-222.

<sup>10</sup> W.E. Knowles Middleton, *The history of the barometer*, Baltimore, Md, Johns Hopkins Press, 1964, p. 289.

<sup>11</sup> *Ibid.*, pp. 318-319.

<sup>12</sup> Reiser, *op. cit.*, note 2 above, p. 100.

<sup>13</sup> *Ibid.*, pp. 100-101.

<sup>14</sup> Percy Dunsheath, *A history of electrical engineering*, London, Faber, 1962, pp. 157-177.

<sup>15</sup> *Ibid.*, pp. 169-170; Silvanus P. Thompson, *Polyphase electric currents*, 2nd ed., London, Spon, 1900, pp. 7-8.

<sup>16</sup> *Duddell patent oscillographs: sole makers, Cambridge Scientific Instrument Company, Ltd.*, 1903, pp. 5-6.

<sup>17</sup> V.J. Phillips, ‘Point to point: a method of waveform measurement’, *Papers presented at the Tenth IEE Weekend Meeting on the History of Electrical Engineering, Brighton, 2-4 July 1982*, London, Institution of Electrical Engineers, [1983], pp. 5/1-5/13. An earlier version of the same method had been devised by Sir Charles Wheatstone (Brian Bowers, *A history of electric light and power*, Stevenage, Peter Peregrinus, 1982, p. 80).

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well as being laborious, it depended on the assumption that the waveform would remain stable throughout the period during which it was being studied. Clearly, this assumption could not be made in electrophysiology. Of particular importance in the pre-history of the electrocardiograph was a paper published in 1892 by André Eugene Blondel (1863-1938). Blondel was a graduate of the *École des Ponts et Chaussées*, who worked in the Service Central des Phares et Balises, and from 1893 was professor of electrotechnology jointly at the *École des Ponts et Chaussées* and the *École des Mines*. His paper concerned the design of the first oscillograph,<sup>18</sup> a galvanometer “whose moving part would oscillate following the same law as the variations in the current passing through it,” attached to a means of recording photographically the resulting curves.

Blondel described the properties which such a galvanometer had to have: they were largely the same as the properties required of a string galvanometer in an electrocardiograph. The five properties listed were: (1) The period of the galvanometer should be no more than one-twentieth of the frequency of the alternating current, that is, for A.C. at 100 cycles per second, the galvanometer’s period should be less than a two-thousandth of a second. (2) The damping should be as complete as possible. (3) Self-induction should be minimized so that the variations of the trace obtained were as close as possible to those of the current being studied. (4) Hysteresis and eddy currents should be negligible. (5) The instrument should be sufficiently sensitive.

Blondel then considered three possible solutions to the problem. First, he examined a moving-coil galvanometer. This was a slightly unusual idea, because almost all galvanometers since the 1830s had been moving-magnet ones, with the important exception of the siphon recorder for telegraphy of William Thomson (later Lord Kelvin).<sup>19</sup> Second, he looked at the possibility of adapting the telephone. However, his choice fell on the third possibility: a moving-magnet galvanometer with a tiny magnet, only two or three millimetres across. It proved unsuccessful.

Seven years after Blondel’s paper was published, the first satisfactory oscillograph appeared on the market. The Cambridge Scientific Instrument Company described it in their catalogue as “an entirely new departure in galvanometers, for not only has it the shortest periodic time of any galvanometer yet made, namely about 0.0001 second, but has at the same time extreme sensibility, is dead beat [i.e., is completely damped], has a low resistance and has practically no self induction.”<sup>20</sup> Thus, the Duddell oscillograph fulfilled and bettered the conditions set out by Blondel. It was based on an idea which Blondel had described.<sup>21</sup> Instead of suspending a moving coil, as such, between the poles of a magnet, Duddell used two very thin phosphor bronze strips—the coil reduced to its bare essentials—on which was mounted a tiny mirror, which reflected a beam of light. The reflected beam fell on a photographic plate, and

<sup>18</sup> André Eugene Blondel, ‘Oscillographes; nouveaux appareils pour l’étude des oscillations électriques lentes’, *C.r.hebd. Séanc. Acad. Sci., Paris*, 1893, 116: 502-506.

<sup>19</sup> Dunsheath, *op. cit.*, note 14 above, pp. 294-308.

<sup>20</sup> Quoted by S.L. Barron, *The development of the Duddell oscillograph*, London, Cambridge Instrument Company, 1950, p. 4. The Duddell oscillograph was designed by an Englishman with French blood, William Dubois Duddell

<sup>21</sup> Blondel, *op. cit.*, note 18 above.



thus gave a magnified recording of the movement of the phosphor bronze strips.<sup>22</sup>

The invention of the oscillograph is important in the history of the electrocardiograph, for it solved a very similar problem, the recording of a rapidly alternating voltage. Einthoven required an instrument that combined the sensitivity of the capillary electrometer with the other properties of the oscillograph. As has been made clear above, the oscillograph was devised for the electric power industry. Duddell himself was a consulting electrical engineer, and most of his life was spent in developing instruments for that industry and for wireless telegraphy, such as the thermo-galvanometer, the thermo-voltmeter, the vibration galvanometer, and (with Thomas Mather) the Duddell-Mather standard wattmeter.<sup>23</sup> Thus, although the precursor of the electrocardiograph, a physiological instrument, the oscillograph was developed by electrical engineers for the power supply industry.

#### THE ADER GALVANOMETER

The single-string galvanometer was first described in 1897 by Clement Ader.<sup>24</sup> Ader's instrument was based on a very fine metal wire, 0.02 mm in diameter, vibrating between the poles of a large magnet. A beam of light was projected through a small hole in one pole of the magnet, so that it fell on the wire, and then through a corresponding hole in the other pole. There was no optical system, so a tiny piece of quill from a feather had to be stuck to the wire to make it clearly visible. The shadow of the wire fell on a sensitized length of telegraph tape, which passed immediately into baths of fixer. To Ader, the instrument was a success. He had intended it to speed up the rate of telegraphic transmission, and it raised the rate from 400 to 600 signals per minute on the long cable from Brest to Saint-Pierre, off Newfoundland, and from 600 to 1100 on the shorter one from Marseilles to Algiers.

However, Ader's galvanometer was very different from Einthoven's. In particular, it was less sensitive. After all, it was not a measuring instrument but a device for recording a signal in an intelligible form. Its particular advantage was that because the moving part was so small and light, it had a short periodic time and a small moment of inertia: these important characteristics were shared by the Einthoven galvanometer.<sup>25</sup> It might have been possible to use mathematical methods to reduce the trace it produced to moment-by-moment measurements of voltage, as Einthoven and Burch had done with the capillary electrometer, but this was not necessary to fulfil its purpose.

#### THE OPTICAL SYSTEM

An optical system was required in the Cambridge electrocardiograph since the galvanometer string, only 0.003 mm in diameter, moved only 0.05 mm when the

<sup>22</sup> Duddell's original instrument, which he made in 1897, is in the Science Museum, inventory 1926-1014.

<sup>23</sup> Barron, *op. cit.*, note 20 above, pp. 9-12.

<sup>24</sup> Clement Ader, 'Sur un nouvel appareil enregistreur pour cables sous-marins', *C.r. hebd. Séanc. Acad. Sci., Paris*, 1897, **124**: 1440-1442. The principle of the string galvanometer had first been suggested by James Cumming, professor of chemistry at Cambridge, in 1827. (John T. Stock and Denys Vaughan, *The development of instruments to measure electric current*, London, Science Museum, 1983, p. 31.)

<sup>25</sup> F. Rossel, 'Télégraphie sous-marine', *L'éclairage électrique*, 1897, **12**: 295-298.

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maximum potential of 3 millivolts was applied across it. There were three parts to the optical system: the condenser, and objective and eyepiece lenses. The condenser was an achromatic, with two components, each of a different glass; the objective was an apochromat, with three components.<sup>26</sup> The achromatic lens had originally been invented in 1729, to reduce chromatic aberration in telescopes;<sup>27</sup> after repeated attempts, one was successfully made for a microscope objective only in 1826, when Joseph Jackson Lister applied mathematics to what had hitherto been regarded as a purely empirical problem.<sup>28</sup>

The optical system in the electrocardiograph normally gave a very large magnification (600 times), and, since it used a white light source, chromatic aberration was a severe problem, and the expensive solution had to be adopted of using an apochromatic objective lens, which reduced chromatic aberration even further than the achromat. The demand for this kind of lens was clearly perceived by Ernst Abbe, partner of Carl Zeiss, in Jena.<sup>29</sup> He realized that types of glass with optical properties substantially different from the crown and flint glass then in use were needed, and persuaded Otto Schott, a Westphalian glass manufacturer, to undertake experiments. Schott began to produce useful new optical glasses in 1881. The apochromat was eventually unveiled to the public in 1886. To make a final correction of the chromatic aberration at the edge of field, a multicomponent “compensating eyepiece” was needed, and the Cambridge instrument had one. Abbe’s lenses were originally designed for conventional microscopes, but could be applied to any magnifying system.

The idea of projecting a microscopic image had been common in the eighteenth century, when “solar” microscopes (i.e., ones using direct sunlight for illumination) were used to give spectacularly large but indistinct images of natural history specimens.<sup>30</sup> The electrocardiograph contained, in effect, a projecting microscope made by Zeiss. It had to be specially designed in Jena with lenses only 12 mm in diameter, so that the holes through the poles of the electromagnet could be as small as possible.<sup>31</sup> It was not unusual for CSI to go to Zeiss for optical parts, since they made none themselves. At least as early as 1885, they were using optical parts from Jena in reading microscopes.<sup>32</sup> Zeiss optics were also used in various electrometers invented by C.T.R. Wilson<sup>33</sup> and T.H. Laby.<sup>34</sup> The CSI acted as agents in Britain for Zeiss microscopes and saccharometers.<sup>35</sup> CSI made only the mounting of a large

<sup>26</sup> Robert Stewart Whipple, ‘Some notes on the electro-cardiograph’, *J. Inst. Electrical Engrs*, 1919, 57: supplement 13-26, p. 25.

<sup>27</sup> Henry C. King, *The history of the telescope*, London, Charles Griffin, 1955, pp. 144-145.

<sup>28</sup> Savile Bradbury, *The evolution of the microscope*, Oxford, Pergamon Press, 1967, pp. 191-196.

<sup>29</sup> *Ibid.*, pp. 153-156.

<sup>30</sup> *Ibid.*, pp. 256-269.

<sup>31</sup> Whipple, *op. cit.*, note 26 above.

<sup>32</sup> An example in the Science Museum, which was lent by CSI in 1885 (Inventory 1885-2) is signed CAMBRIDGE SCIENTIFIC INSTRUMENT COMPANY on the frame, and C. ZEISS on the microscope objective mounting.

<sup>33</sup> *Electrometers including electroscopes, Weston normal cell, silver voltmeter, etc. [made by] the Cambridge Scientific Instrument Company Ltd.*, 1911, pp. 5, 10.

<sup>34</sup> *Ibid.*, p. 15

<sup>35</sup> *A descriptive list of instruments manufactured and sold by the Cambridge Scientific Instrument Company*, 1891, pp. 46, 114.

spectrograph supplied to Cambridge Observatory in 1905: the glass came from Jena, and was cut by Adam Hilger in London.<sup>36</sup> When Professors George Downing Liveing and James Dewar made various innovations in spectroscopic apparatus in the 1880s, they also had their instruments made by Hilger, not CSI.<sup>37</sup> Zeiss were also involved in the manufacture of optical components for other diagnostic equipment, such as the Ringleb optical system for cystoscopes, first used about 1907.<sup>38</sup>

#### MEASURING ELECTRICAL CURRENTS IN THE HEART

In the studies of electrical currents in the heart made before the invention of the string galvanometer, instruments initially invented for the telegraphic and power industries—the technology of the latter having to some extent evolved from that of the former<sup>39</sup>—played a large part, as well as instruments developed in pure physics laboratories.

The first successful attempt to record a human electrocardiogram seems to have been made at St Bartholomew's Hospital, London, by Alexander Muirhead, in 1869 or 1870.<sup>40</sup> He used a Thomson siphon recorder, devised by William Thomson to record signals passing through the Atlantic cable, which had been laid in 1866.<sup>41</sup> Muirhead himself later became a successful telegraph engineer. He did not carry out any other physiological work.

Before the invention of the string galvanometer, the most satisfactory method of studying the electrical reactions of the human heart was to use the Lippmann capillary electrometer, as pioneered by Augustus Waller at St Mary's Hospital, Paddington, in the 1880s,<sup>42</sup> though Marey had demonstrated earlier that it was possible to use a capillary electrometer for this purpose, without attempting investigations with it.<sup>43</sup> Gabriel Lippmann invented his electrometer whilst working in G.R. Kirchhoff's physical Laboratory in Berlin.<sup>44</sup> He was engaged on a study of the relationships between capillarity and electrical effects at the boundary between

<sup>36</sup> H.F. Newall, 'Description of a four-prism spectrograph attached to the 25-inch visual refractor (the Newall Telescope) of the Cambridge Observatory', *Mhly Not. R. Astronomical Soc.*, 1905, **65**: 636-650.

<sup>37</sup> For example, a direct vision spectroscope incorporating a micrometer (Whipple Museum, Cambridge, inventory 1253, illustrated by G. L'E. Turner, *Nineteenth-century scientific instruments*, London, Sotheby Publications, 1983, p. 161), and a collimating eyepiece for a spectroscope (George D. Liveing and James Dewar, 'On the use of a collimating eyepiece in spectroscopy', *Proc. Camb. Phil. Soc.*, 1880-83, **4**: 336-342).

<sup>38</sup> *From lighthouse to fibre optics: a history of the treatment of bladder stones and cystoscopy*, Leiden, National Museum for the History of Science, 1973, p. 22.

<sup>39</sup> Bowers, op. cit., note 17 above, p. 39; Burch and DePasquale, op. cit., note 3 above, pp. 23-27.

<sup>40</sup> [Mary Elizabeth Muirhead], *Alexander Muirhead*, Oxford, [privately printed], 1926, pp. 28-29. I am indebted to Mr. W. Lister for this reference.

<sup>41</sup> George Green and John T. Lloyd, *Kelvin's instruments and the Kelvin Museum*, University of Glasgow, 1970, p. 34; William Thomson, 'On signalling through submarine cables', *Trans. Inst. Engrs and Shipbuilders in Scotland*, 1873, **16**: 119-120; and his *Mathematical and physical papers*, 6 vols., Cambridge University Press, 1882-1911, vol. 2 (1884), pp. 168-172.

<sup>42</sup> Zachary Cope, 'Augustus Desiré Waller (1856-1922)', *Med. Hist.*, 1973, **17**: 380-385; Augustus Desiré Waller 'A demonstration on man of electromotive changes accompanying the heart's beat', *J. Physiol.*, 1887, **8**: 229-234.

<sup>43</sup> E.J. Marey, *La circulation du sang*, Paris, G. Masson, 1881, p. 26.

<sup>44</sup> Gabriel Lippmann, 'Beziehungen zwischen den capillaren und elektrischen Erscheinungen' *Ann. Phys. Chem.*, 1873, **149**: 546-551; translated as 'Connexion between capillary and electrical phenomena', *Phil. Mag.*, 1874, **47**: 281-291.



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mercury and a solution of potassium bichromate in dilute sulphuric acid. The measuring instrument was the accidental result of a purely physical investigation.

In addition to the Lippmann electrometer, Waller employed a Thomson mirror galvanometer.<sup>45</sup> This instrument had been invented to receive signals from the first—unsuccessful—Atlantic cable, in 1858.<sup>46</sup> For telegraphic purposes it was superseded by the siphon recorder, though it is still in use in physics laboratories today.

Einthoven, similarly, began his electrophysiological researches with the Lippmann electrometer. Before inventing the string galvanometer, he also used another instrument, the Deprez-d'Arsonval galvanometer. Like Einthoven, Arsène d'Arsonval (1851-1940) was medically trained and had a flair for designing scientific instruments. For his studies of animal heat, he devised a double-chambered calorimeter, and, as soon as he learnt of Alexander Graham Bell's invention of the telephone, he adopted it for electrical studies of muscle contraction.<sup>47</sup> Marcel Deprez (1843-1918) was a pioneer of the electric power industry in France. In 1880, he had invented a low-sensitivity galvanometer which responded rapidly to fluctuations in current; d'Arsonval, in effect, crossed this instrument with the galvanometer in the Thomson siphon recorder, to create a sensitive moving-coil instrument, which could detect 0.1 microamp.<sup>48</sup> It was used by several physiologists engaged in research on skeletal muscle,<sup>49</sup> though its origins lay in the fields of electric power and electric telegraphy.

Despite the fact that many of the instruments used in early studies of the electrical behaviour of the heart were derived from industrial instruments, the activities performed with them remained laboratory experiments. The string galvanometer, too, was initially no more than a device for physiological experimentation; only when it was developed into an integral part of a small, robust unit, could electrocardiography become a diagnostic tool in the hands of individuals who were physicians first and physiologists second.

#### THE DEVELOPMENT OF A PRACTICAL ELECTROCARDIOGRAPH

Einthoven first described the string galvanometer in 1901.<sup>50</sup> He had been interested in the electrophysiology of the heart since about 1890, and for some years he had, like Waller, used the Lippmann capillary electrometer. Einthoven made extensive attempts to deduce the real variations in current from the traces produced by the capillary electrometer. Rather than devising an instrument which might mechanize this process, as Lucas was to do later, Einthoven developed a new form of

<sup>45</sup> Augustus Desiré Waller and E. Waymouth Reid, 'On the action of the excised mammalian heart', *Phil. Trans. R. Soc. Lond.*, series B, 1887, **178**: 215-255, especially p. 232.

<sup>46</sup> Green and Lloyd, *op. cit.*, note 41 above, pp. 30-31.

<sup>47</sup> Arsène d'Arsonval, 'Téléphone employé comme galvanoscope', *C. r. hebdomadaire des séances de l'Académie des Sciences, Paris*, 1878, **86**: 832-833.

<sup>48</sup> Arsène d'Arsonval and Marcel Deprez, 'Galvanomètre aperiódique', *ibid.*, 1882, **94**: 1347-1350; Stock and Vaughan, *op. cit.*, note 24 above, pp. 18-20.

<sup>49</sup> Burch and DePasquale, *op. cit.*, note 3 above, pp. 59-60.

<sup>50</sup> Willem Einthoven, 'Un nouveau galvanomètre', *Archives néerlandaises des sciences exactes et naturelles*, Série 2, 1901, **6**: 625-633. For the development of Einthoven's work on electrocardiography, see Barron, *op. cit.*, note 3 above; Burch and DePasquale, *op. cit.*, note 3 above, pp. 29-35, 56-65, 109-131; Marian Fournier, 'Willem Einthoven—the electrophysiology of the heart', *Medicamundi*, 1976, **21**: 65-70.

galvanometer in 1900-01. Einthoven had an unusual combination of talents. A contemporary explained, "Although Einthoven by training and inclination is a physiologist, yet he proceeded to develop the theory and construction of the string galvanometer in a way which must arouse the admiration of all physicists and those who have been engaged in the design and construction of scientific instruments."<sup>50a</sup> A full description of the string galvanometer was published in 1903,<sup>51</sup> and was followed by an even more important paper in which he described the advantages of the string galvanometer over the capillary electrometer.<sup>52</sup> It established that the string galvanometer was easier to use, free from damping, and more sensitive. In 1903, however, there was still a major difficulty: building the instrument in a practicable form. The apparatus in Leiden filled two rooms, included an enormous water-cooled electromagnet, and required five people to operate it. The problem of over-heating seems to have continued until the introduction of amplifiers using thermionic valves in the mid-1930s, when it became possible to substitute for the string galvanometer a less sensitive Ader galvanometer with a smaller magnet.<sup>53</sup> A surviving set of instructions for using the string galvanometer, dating from 1919-23, says that, "If . . . it is desired to keep the sensitivity of the instrument constant while a series of tests is being made, precautions must be taken to keep its temperature as steady as possible, and to do this it is important that the field should only be switched on at the time of taking a reading, as the heating effect of the current through the magnet coils is appreciable." By this date it was possible to add, "For ordinary cardiographic work this heating effect may be ignored."<sup>54</sup> Whilst Einthoven's work was attracting worldwide attention, it was difficult for other physiologists to follow his example. The early instruments built in Germany, France, and Austria seem to have been just as cumbersome as Einthoven's. Before 1910, the electrocardiograph was definitely still an instrument for physiological research, rather than a diagnostic tool.

Einthoven, however, continued his researches, and with the publication in 1908 of a long paper<sup>55</sup> it became clear that if the electrocardiograph could be reduced to a practicable size, it could be used widely in the diagnosis of heart disease. Before this point, however, CSI had become seriously interested in it. By 1901, in addition to the Duddell oscillograph, they were also manufacturing an adaptation of the d'Arsonval galvanometer to measure resistances, and were clearly very much concerned with the problems of making very sensitive electrical instruments.<sup>56</sup>

<sup>50a</sup> 'The science of electro-cardiography', *Electrician*, 1914, 73: 485-487.

<sup>51</sup> Willem Einthoven, 'Ein neues Galvanometer', *Ann. Pys.*, Series A, 1903, 12: 1059-1071.

<sup>52</sup> Willem Einthoven, 'Enregistreur galvanométrique de l'électrocardiogramme humain et controle des resultats obtenus par l'emploi de l'électromètre capillaire en physiologie', *Archives néerlandaises des sciences exactes et naturelles*, Série 2, 1904, 9: 202-209.

<sup>53</sup> Burch and DePasquale, op. cit., note 3 above, p. 50.

<sup>54</sup> The Cambridge and Paul Instrument Co., *Instructions for using the Einthoven string galvanometer*, [1919-1923], 1.3. Typescript in the Technische Hogeschool, Delft. I am indebted to Jan Deiman for a copy of this item. A contemporary piece of advertising literature avoids the problem of overheating in its discussion of galvanometer performance: Cambridge and Paul Instrument Company, *Cambridge electro-cardiographic apparatus*, London, [1920], pp. 8-9.

<sup>55</sup> Willem Einthoven, 'Weiteres über das Elektrocardiogramm', *Arch. ges. Physiol.*, 1908, 122: 517-584.

<sup>56</sup> *Callendar electric recorders, platinum thermometers, and apparatus for the measurement of small resistances manufactured by the Cambridge Scientific Instrument Company, Ltd.*, 1901, p. 39.

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Fortunately, most of the letters from CSI to Einthoven survive in the Museum Boerhaave in Leiden, along with copies of Einthoven's replies. From examining them, it becomes clear that it was Einthoven who first approached the company concerning the possibility of their making and selling the string galvanometer, towards the end of 1903. On 18 December, CSI expressed enthusiasm for the idea, and offered a royalty of ten per cent on net sales.<sup>57</sup> Einthoven hesitated before committing himself, because he felt that he was under some form of obligation to the firm of Edelmann of Munich.<sup>58</sup> Edelmann told Einthoven that he would not be happy if CSI were to make string galvanometers.<sup>59</sup> Horace Darwin now took control of the situation. He explained to Einthoven that:

Since writing to you we have seen Mr Duddell & have heard from him that Prof: Waller is most anxious to obtain one of your galvanometers & that he thinks that there would be demand for them; he however thinks they should be as simple as possible, & we believe he wishes us to make one for him. We think therefore that it would be to your & to our advantage if you allowed us to make them on the terms suggested in our former letter, anyhow as regards the English market; the American market is of less importance. Mr Duddell is willing to help us, he has worked at a similar instrument, &, as you know, is a man of exceptional ability & great powers of designing new instruments. He would only help us on condition that the instrument was called after your name, but not otherwise.<sup>60</sup>

Darwin also pointed out that because none of Einthoven's work on the string galvanometer had been patented, he would feel free to build one if a customer asked him to do so. Since his letter had begun by stating that Waller already wanted one, Darwin clearly felt that he was in a strong position. Einthoven's reply suggests that he was more concerned with his reputation than with money. He quoted Darwin's remark that Duddell "would only help us on condition that the instrument was called after your [Einthoven's] name," and added, "That for me is the cardinal point."<sup>61</sup> It is known that it was as early as 1905 that Duddell designed, on the geometrical principles so much favoured by Horace Darwin, a casing for the galvanometer string. This was airtight, to prevent completely interference from draughts, and was said to be one of the reasons for the superiority of CSI's electrocardiographs over those of other manufacturers.<sup>62</sup>

There were, however, delays in placing the string galvanometer on the market. CSI were busy with other instruments. Also, there were difficulties in silvering the quartz fibre.<sup>63</sup> The method initially used was to dip the fibres into a silver solution, and then to polish them with 0.1 mm diameter copper wire.<sup>64</sup> It was not until 1910 that Einthoven began to develop the method of cathodic bombardment.<sup>65</sup> In 1914, the company were still unable to bombard their own fibres because of the cost of the equipment needed, and negotiated unsuccessfully with Einthoven for the supply of

<sup>57</sup> Letter from R.S. Whipple to W. Einthoven, 18 December 1903. MS in Museum Boerhaave, Leiden. I am indebted to Marian Fournier for drawing my attention to this correspondence.

<sup>58</sup> Letter from Einthoven to the CSI, 20 January 1904. Copy in Museum Boerhaave.

<sup>59</sup> Letter from Einthoven to the CSI, 24 January 1904. Copy in Museum Boerhaave.

<sup>60</sup> Letter from H. Darwin to Einthoven, 29 January 1904. MS in Museum Boerhaave.

<sup>61</sup> Letter from Einthoven to the CSI, 1 February 1904. Copy in Museum Boerhaave.

<sup>62</sup> Whipple, *op. cit.*, note 26 above.

<sup>63</sup> Letter from Darwin to Einthoven, 21 July 1905. MS in Museum Boerhaave.

<sup>64</sup> Letter from Einthoven to the CSI, 9 March 1904. Copy in Museum Boerhaave.

<sup>65</sup> Barron, *op. cit.*, note 3 above, p. 9.

them.<sup>66</sup> Some years later, the American firm of Charles Hindle developed the method as a practical proposition, and CSI subsequently adapted it to produce more robust fibres by bombarding glass with gold ions.<sup>67</sup> The fibres themselves were made by a method devised some fifteen years before by the English physicist, Charles Vernon Boys. A blob of quartz was heated in an oxyhydrogen flame, and drawn out by attaching part of the blob to an arrow fired by a crossbow. Boys produced filaments about one hundred thousandth of an inch in diameter.<sup>67a</sup>

Cambridge Scientific Instrument Company completed their first Einthoven string galvanometer between July and October 1905. Whipple told Einthoven that it had been sold “to one of the leading Physiological Laboratories in this country”.<sup>68</sup> It transpired that this was MacDonald’s laboratory in Sheffield.<sup>69</sup> In March 1906, the second instrument went to J.C. Bose at Presidency College, Calcutta, and in 1907, the third one was bought by Keith Lucas in Cambridge.<sup>70</sup>

The first complete electrocardiograph was supplied to E.A. Schafer of Edinburgh University on 27 January 1908. The photographs published by Burch and DePasquale<sup>71</sup> show that the string galvanometer had already been reduced to a small size by Duddell, and that the camera was present in the form later sold regularly. The rotary time marker must have been added at some time in the next three years. The form used was the one originated by Bull of the Marey Institute at Boulogne-sur-Seine, which ran synchronously with a tuning fork.<sup>72</sup> Sales began to increase, until 140 had been sold by the end of 1914 (see Appendix I). Along with his royalty payments, Einthoven was sent lists of the purchasers of string galvanometers. The purchasers of the fifty-seven instruments sold by the end of 1912 are given in Appendix II. Although most of the instruments were bought for physiological research, several were bought for wireless telegraphy. These included four galvanometers which went to the Marconi Telegraph Company, and other instruments supplied to the Ministry of Posts and Telegraphs in Rome, the Marine Telegraphy Commission in St Petersburg, and the Institut Océanographique in Paris. Those purchased by the Imperial Japanese Navy and the Bureau of Weights and Measures at St Petersburg may also have been used for the same purpose. In addition, a number of string galvanometers were bought by other instrument-makers, such as Elliott Brothers of London, the Taylor Instrument Company of New York, and G. Boullitte of Paris. These were presumably re-sold, but we do not know to whom.

The initial royalty paid to Einthoven was ten per cent on net sales.<sup>73</sup> As CSI continued to develop the string galvanometer—in particular, once Duddell had made his alterations to the design—it was reasonable that Einthoven’s royalties should fall.

<sup>66</sup> Letter from Whipple to Einthoven, 1 January 1914. MS Museum Boerhaave.

<sup>67</sup> Barron, *op. cit.*, note 3 above, p. 9.

<sup>67a</sup> Charles Vernon Boys, ‘On the production, properties and some suggested uses of the finest threads’, *Proc. Phys. Soc.*, 1887, 9: 8-19.

<sup>68</sup> Letter from Whipple to Einthoven, 31 October 1905. MS in Museum Boerhaave.

<sup>69</sup> Letter from Whipple to Einthoven, 9 November 1905. MS in Museum Boerhaave.

<sup>70</sup> Letter from Whipple to Einthoven, 3 February 1908, MS in Museum Boerhaave.

<sup>71</sup> Burch and DePasquale, *op. cit.*, note 3 above, p. 33.

<sup>72</sup> *Ibid.*, p. 16.

<sup>73</sup> Letter from Whipple to Einthoven, 18 November 1903. MS in Museum Boerhaave.

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On 18 December 1908, he signed an agreement that he would be paid 7½ per cent on instruments built with electromagnets, unless an instrument-maker other than CSI, Edelmann, or Kohl of Chemnitz began to sell them, in which case the royalty would fall to five per cent. The payment on instruments with permanent magnets was to be 2½ per cent, but it appears that none of these was sold before the agreement expired at the end of 1914.<sup>74</sup> They had almost certainly been developed in response to Edelmann's having produced one.<sup>74a</sup> Only three months after the agreement had been signed, CSI discovered that Kunsch und Jaeger of Rixdorf were selling string galvanometers "all the details of which are worked out admirably", so the royalty was reduced to five per cent.<sup>75</sup>

#### CAMBRIDGE

The importance of physical science in the University of Cambridge increased greatly during the last third of the nineteenth century. In the eighteenth and early nineteenth centuries, the Mathematics Tripos had been an effective teaching institution, and produced a large number of eminent mathematicians and astronomers. Every Astronomer Royal from 1765 until well into the twentieth century had studied in the Mathematical Tripos.<sup>76</sup> In 1850, all of the nine Cambridge science professors had read the same Tripos.<sup>77</sup> The Natural Sciences Tripos was instituted in 1884, and slowly grew in strength over the following eighty years.<sup>78</sup> Sviedrys has described the mechanism of the growth in the importance of physical science in the three cases of the chemistry, Cavendish, and engineering laboratories.<sup>79</sup> Practical classes began to be taught in chemistry in Cambridge in 1865, some thirty years behind the most advanced universities in Britain. The Cavendish Laboratory, founded in 1870, began to teach physics in 1874, and the chair of engineering (or more accurately the professorship of Mechanism and Applied Mechanics) was established in 1875, though the professor had to pay for its workshops himself. It is significant that the mechanism that obstructed the establishment of scientific chairs and the creation of laboratories was the collegiate system, which offered innovators no body that they could seek to dominate. Even when the University set up scientific institutions, it was by no means liberal in its supply of money, and the laboratories had to rely on their own sources of funds. The Cavendish had to save student fees to pay for the new wing which was added to its building in 1894, and the engineering workshops had to make

<sup>74</sup> Letter from Einthoven to Whipple, 18 December 1908. Copy in Museum Boerhaave.

<sup>74a</sup> Max Edelmann, 'Ein kleines Satiengalvanometer mit photographischen Registrier-Apparat', *Physikal. Zt.*, 1906, 7: 115-130.

<sup>75</sup> Letter from Whipple to Einthoven 17 March 1909. MS in Museum Boerhaave.

<sup>76</sup> They all *studied*, but one of them cannot be said to have taken the tripos since he did not sit the examinations. He was John Pond, Astronomer Royal from 1811 to 1835.

<sup>77</sup> J.B. Morrell, 'Science and the universities', *Hist. Sci.*, 1977, 15: 145-152, p. 149.

<sup>78</sup> Gerrylynn K. Roberts, 'The liberally-educated chemist: chemistry in the Cambridge Natural Science tripos, 1851-1914', *Historical Studies in the Physical Sciences*, 1980, 11: 157-183; Roy Porter, 'The Natural Sciences Tripos and the "Cambridge School of Geology", 1850-1914', *History of Universities*, 1982, 2: 193-216; Roy Macleod and Russell Moseley, 'Breadth, depth and excellence: sources and problems in the history of university science education in England, 1850-1914', *Studies in Science Education*, 1978, 5: 85-106.

<sup>79</sup> Romuladas Sviedrys, 'The rise of physical science at Victorian Cambridge', *Historical Studies in the Physical Sciences*, 1970, 2: 127-145.



fittings for other university laboratories in an attempt to raise their income.<sup>80</sup> The colleges, in general, were suffering from a slump in income from the land during the agricultural depression between 1870 and 1910, and reformers had to look to sources of money outside the University—private patronage, subscription, and, ultimately, the government—to fund their projects.<sup>81</sup> One result was that when instruments were required for the University's physiological laboratories, a private partnership had to be created to fulfil the need.

As Geison has pointed out, the one college that gave continued support to teaching and research in science was Trinity, the largest and wealthiest.<sup>82</sup> In the first half of the nineteenth century, it had been the most important node of the "Cambridge network" of mathematicians and scientists (a word which, of course, one of their number had invented),<sup>83</sup> and was a notable home of men who hoped to reform the University. From its establishment, the Cavendish chair was held by a succession of Trinity men: James Clerk-Maxwell, Lord Rayleigh, Sir Joseph John Thomson, Lord Rutherford, and Sir (William) Lawrence Bragg. When Thomson looked back over his first quarter-century as Cavendish professor, he gave a list of those of his research students who had been elected fellows of their colleges: ten out of twenty had become fellows of Trinity.<sup>84</sup> Charles Darwin and brother Erasmus Alvey Darwin were both undergraduates at Christ's, as was Charles's eldest son, who became a banker. But Charles's younger sons, George, Francis, and Horace, were all sent to Trinity, and in later life they were active scientists.<sup>85</sup> All the Astronomers Royal mentioned above were Trinity men. The first professor of engineering, James Stewart, was a fellow of Trinity, and when the Engineering Department was recognized in 1889-90, the committee appointed to examine its future, the Mechanical Workshop Enquiry Syndicate, included eight Trinity men and five others.<sup>86</sup> In physiology, too, Trinity led the way, appointing Michael Foster to his praelectorship in physiology in 1869, and giving fellowships to the most important members of the Cambridge school in this period, W.H. Gaskell and J.N. Langley. Trinity also awarded a fellowship to C.S. Roy, a pupil of Virchow, Koch, and DuBois-Reymond, though his work on the physiology of the mammalian heart owed little to the Cambridge tradition.<sup>87</sup>

<sup>80</sup> They may also have made some scientific instruments, e.g. a gas burner whose flame was highly sensitive to sound waves (Lord Rayleigh, 'On a new arrangement for sensitive flames', *Proc. Camb. Phil. Soc.*, 1880-83, 4: 17-18).

<sup>81</sup> J.P.D. Dunbabin, 'Oxford and Cambridge college finances, 1871-1913', *Econ. Hist. Rev.*, 1975, 28: 631-647.

<sup>82</sup> Gerald L. Geison, *Michael Foster and the Cambridge School of Physiology*, Princeton University Press, 1978, pp. 102-111. Geology, however, flourished at St John's (Porter, op. cit., note 78 above).

<sup>83</sup> Susan B. Cannon, *Science in culture: the early Victorian period*, New York, Science History Publications, 1978, pp. 29-71.

<sup>84</sup> J.J. Thompson, 'Survey of the last twenty-five years', in *A history of the Cavendish Laboratory 1885-1910*, London, Longmans Green, 1910, pp. 75-101, especially p. 99.

<sup>85</sup> J.A. Venn, *Alumni Cantabrigienses: Part II: from 1752 to 1900*, 6 vols, Cambridge University Press, 1940-54, vol.2 (1944), pp. 228-229.

<sup>86</sup> T.J.N. Hilken, *Engineering at Cambridge University 1783-1965*, Cambridge University Press, 1967, p. 93.

<sup>87</sup> Raymond Williamson, 'The early history of the Department of Pathology at Cambridge', in Arthur Rook (editor), *Cambridge and its contribution to medicine*, London, Wellcome Institute for the History of Medicine, 1971, pp. 119-138.

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### CAMBRIDGE SCIENTIFIC INSTRUMENT COMPANY

Given that Trinity College was for some years the main centre of scientific activity in Cambridge, it is hardly surprising that the CSI was a product of it. With the encouragement of Foster, the company was founded by two members of the college, Albert George Dew-Smith and Horace Darwin.<sup>88</sup> Its founding was the product motivation similar to that which caused Maxwell to bring to Cambridge a scientific instrument-maker to work permanently in the Cavendish Laboratory, Maxwell wrote:

It has been felt that the experimental investigations were carried on at a disadvantage in Cambridge, because the apparatus had to be constructed in London. The experimenter had only occasional opportunities of seeing the instrument maker, and was perhaps not fully acquainted with the resources of the workshop, so that his instructions were imperfectly understood by the workman. On the other hand the workman had no opportunity of seeing the apparatus at work, so any improvements in construction which his practical skill might suggest were either lost or misdirected.<sup>89</sup>

The motives behind the establishment of a workshop to make physiological instruments were the same, but since the funds for making physiological apparatus were even scarcer than for making physical instruments, the result was the creation of a private partnership. In reality, it can only be regarded as a well-directed act of patronage on the part of Dew-Smith.

The case of physiology may be compared with experimental physics and geology. The Cavendish Laboratory had such a large need for apparatus that it was able to employ its own full-time instrument-makers. The thriving geology department required comparatively little apparatus—its expenditure on petrological microscopes must have constituted most of its spending on equipment—all of which could have been easily bought ready-made from established suppliers. The Physiology Department needed newly developed instruments, but not sufficiently regularly to justify the employment of its own workman. So the solution was the private partnership, which was able to enter other markets at the same time as supplying the needs of the Physiology Department.

Dew-Smith (1848-1903) was a pupil of Foster. He was wealthy, and although not a fellow of Trinity, he was allowed to have rooms in college. Between 1874 and 1876, he carried out, with Foster, research into the mechanism of the heartbeat.<sup>90</sup> He gave a number of instruments to the Cambridge physiological laboratories, financed the production of the *Journal of Physiology* when it began under Foster's editorship,<sup>91</sup> and paid part of Langley's salary as demonstrator to Foster.<sup>92</sup> At some time between 1875 and 1878, Dew-Smith brought to Cambridge Robert Fulcher, a scientific instrument-maker, and took him into partnership. Dew-Smith supplied all the capital. At first, Fulcher used the workshop in the newly-established school of mechanics, but in 1878 he moved into premises of his own. As in the case of Professor

<sup>88</sup> The main printed sources for the history of CSI are '50 years of scientific instrument manufacture', *Engineering*, 1945, 159: 316-363, 401-403, 461-463, 501-502; and Cambridge Instrument Company, *75 years of successful endeavour 1881-1956*, London, [1956].

<sup>89</sup> James Clerk-Maxwell, 'Cavendish Laboratory', *Cambridge University Reporter*, 15 May 1877, p. VII, reproduced in Dennis Moralee, 'The first ten years', in *A hundred years of Cambridge physics*, 2nd ed., Cambridge University Physics Society, 1980, pp. 8-20, p. 19.

<sup>90</sup> Geison, op. cit., note 82 above, pp. 222-238.

<sup>91</sup> *Ibid.*, p. 187.

<sup>92</sup> *Ibid.*, pp. 106-107.

Stewart's workshop, it is not known exactly what range of instruments he made, but he certainly constructed a "sphygmotonometer" (later called a tonosphygmograph)<sup>93</sup> and a mercury manometer,<sup>94</sup> both for C.S. Roy. At the end of 1880, the partnership between Fulcher and Dew-Smith was terminated.

Horace Darwin (1851-1928) was the seventh and youngest child of Charles Darwin.<sup>95</sup> After studying under a tutor, he was sent to Clapham Grammar School, which had been founded by the Reverend Charles Pritchard. Pritchard was an unusual Victorian schoolmaster in that he taught practical natural philosophy to his pupils. "I proposed to introduce a systematic course of instruction relating to physical phenomena in the midst of which we live and have our being", he wrote, "I laid it down as a maxim, that the main intention of early education should be the development of the habit of thinking."<sup>96</sup> Horace appears to have benefited from his time at Clapham, though Pritchard himself had left before Horace had arrived. He read the Mathematics Tripos at Cambridge, graduating in 1874. After an engineering apprenticeship, he returned to Cambridge. Early in his life, Horace Darwin carried out a limited amount of original research. When Lord Rayleigh took up the Cavendish chair in 1879, Darwin helped him at the beginning of his studies on electrical standards.<sup>97</sup> With his brother George, Darwin worked in the Cavendish in 1880-81 on an attempt to detect tides in the solid earth caused by the moon.<sup>98</sup> As a result of his work as an instrument designer, Darwin was elected a fellow of the Royal Society in 1903. It was an unusual distinction for an instrument-maker: the last who had been so honoured was William Simms in 1853.

The new partnership was set up between Dew-Smith and Darwin on 1 January 1881: they called themselves the Cambridge Scientific Instrument Company. Up to 1884, the company acted as publishers of the *Journal of Physiology*, and they also made lithographic plates. When the partnership was dissolved in 1891, Darwin took full control of the instrument-making, whilst the Cambridge Engraving Company had a separate existence under Dew-Smith; it was absorbed in 1913 by the Cambridge University Press. CSI became a limited company in 1895, and Horace Darwin appears to have remained the majority shareholder until 1919, when it amalgamated with R.W. Paul Ltd, to form the Cambridge and Paul Instrument Company. It changed its name to the Cambridge Instrument Company (CIC) in 1924.

The company's oldest surviving catalogue, number 2 of 1882, is almost entirely concerned with physiological apparatus. Such evidence as there is of their earliest products points to an almost exclusive interest in physiology. Roy said in 1881 that

<sup>93</sup> Charles Smart Roy, 'The form of the pulse-wave', *J. Physiol.*, 1879, 2: 66-81.

4OR Charles Smart Roy and J. Graham Brown, 'The blood-pressure and its variations in the arterioles, capillaries, and smaller veins', *ibid.*, 1880, 2: 323-359.

<sup>95</sup> The biographical sources for Horace Darwin are Robert Stewart Whipple, 'A tribute to Sir Horace Darwin', *Journal of Scientific Instruments*, 1929, 6: 10-16; the obituary by R.T. Glazebrook, *Nature*, 1928, 122: 580; and the unsigned obituary in *Proc. R. Soc. Lond.*, 1929, 122A: v-vi.

<sup>96</sup> Quoted by Ada Pritchard, *Charles Pritchard*, London, Seeley, 1897, pp. 47-48. See also James R. Moore, 'On the education of Charles Darwin's sons', *Notes Rec. R. Soc. Lond.*, 1977, 32: 51-70.

<sup>97</sup> Robert John Strutt, fourth Baron Rayleigh, *John William Strutt, third Baron Rayleigh*, London, Edward Arnold, 1924, p. 109.

<sup>98</sup> Richard Tetley Glazebrook, 'Lord Rayleigh's professorship', in *op. cit.*, note 84 above, pp. 40-74, especially p. 72.

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they made onkometers and onkographs,<sup>99</sup> and the company's advertisements imply that physiology was its chief concern.<sup>100</sup> By 1891, its catalogue contained some 200 instruments, only a quarter of which were physiological. The success of the company was partly due to Darwin's understanding of the principles of the geometrical or kinematic design of instruments.<sup>100a</sup> These principles had been set out very clearly by Clerk-Maxwell in 1876,<sup>101</sup> though he admitted that they had earlier been applied, in a limited way, by Lord Kelvin.<sup>102</sup>

### CSI AND TRINITY

Many of the instruments made and sold by the company had been devised by Trinity men. For example, the company's 1899 catalogue listed a freezing microtome invented by C.S. Roy,<sup>103</sup> as well as the better-known Caldwell-Threlfall microtome, for which two fellows of another college, Gonville and Caius, were responsible.<sup>104</sup> The section of the catalogue entitled 'Blood Circulation' described many of the cardiological instruments devised by Roy and Walter Holbrook Gaskell. There was Gaskell's frog heart clamp and frog heart forceps, and his modification of Roy's frog cardiograph.<sup>105</sup> Roy contributed mercury and torsion manometers, a tonosphygmograph (for recording changes in the volume of a short length of unopened artery or changes in pressure of the blood within an artery), a pulse tonograph, an onkometer (for measuring the variation in volume of a living organ), an onkograph and a plethysmograph (for recording changes in the volume of a dog's foot),<sup>106</sup> and electrodes for neurological work.<sup>107</sup> Gaskell also produced a modification of Roy's tonometer.<sup>108</sup> In collaboration with one of his pupils, John George Adami (1862-1926), a fellow of Jesus College from 1891, Roy also constructed a cardiometer and a myocardiograph.<sup>109</sup>

In the early years of the twentieth century, Keith Lucas (1879-1916), who was elected a fellow of Trinity in 1904, invented a wide range of ingenious instruments in the course of his work on muscle contraction. CSI published a short catalogue, which

<sup>99</sup> Charles Smart Roy, 'The physiology and pathology of the spleen', *J. Physiol.*, 1881, 3: 206-228.

<sup>100</sup> Inside the back covers of *J. Physiol.* supplements 1 and 2 to vol. 3. 1881-2.

<sup>100a</sup> Horace Darwin, 'Scientific instruments: their design and use in aeronautics', *Aeronautical Journal*, 1913, 17: 170-185; and S.L. Barron's contribution (pp. 80-82) to 'Discussion on kinematic design applied to instruments', *Transactions of the Society of Instrument Technology*, 1954, 6: 66-82.

<sup>101</sup> James Clerk-Maxwell, 'General considerations concerning scientific apparatus', in South Kensington Museum, op. cit., note 5 above, pp. 1-21; reprinted in D. Niven (editor), *The scientific papers of James Clerk Maxwell*, 2 vols., Cambridge University Press, 1890, vol. 2, pp. 505-522.

<sup>102</sup> *Ibid.*, p. 5.

<sup>103</sup> *Physiological instruments manufactured by the Cambridge Scientific Instrument Company Ltd.*, 1899, pp. 85-86; Charles Smart Roy, 'Neues schnellgefrierer-Microtom', *Arch. mikr. Anat.*, 1881, 19: 137-143. Roy also devised a simpler microtome: the original of this instrument was constructed by Gardner of Edinburgh (Charles Smart Roy, 'A new microtome', *J. Physiol.*, 1879, 2: 19-23), emphasizing the fact that inventors prefer to work with scientific instrument-makers who trade nearby.

<sup>104</sup> *Physiological instruments*, op. cit., note 103 above, pp. 82-83; Brian Bracegirdle, *A history of microtechnique*, London, Heinemann, 1978, pp. 236-265.

<sup>105</sup> *Physiological instruments*, op. cit., note 103 above, pp. 49,66.

<sup>106</sup> *Ibid.*, pp. 52-54, 64, 67, 69-70, 71.

<sup>107</sup> *A descriptive list of instruments manufactured and sold the Cambridge Scientific Instrument Company*, 1891, p. 100.

<sup>108</sup> *Ibid.*, p. 93.

<sup>109</sup> *Physiological instruments*, op. cit., note 103 above, pp. 61-62.

was almost entirely devoted to Lucas's instruments.<sup>110</sup> It included basic apparatus, such as the Lucas muscle trough; apparatus for making other laboratory apparatus, for example, a capillary draw-tube which drew out glass capillary tubing to a standard size; and measuring instruments that used electrical methods. Two of the latter are particularly to be mentioned: an electromagnetic time signal, which gave accurate regular markings of time intervals on the continuous photographic record of another signal,<sup>111</sup> and the Lucas analyser for capillary electrometer records,<sup>112</sup> which deduced from records produced by the instrument, in which the actual trace of the signal had been masked by the slow response time of the capillary electrometer and the high inertia caused by its large mass of moving mercury.<sup>113</sup> Lucas devised the analyser for use in his studies of action potentials from nerves, rather than for cardiological work. He was a director of CSI from 1904 to 1914.

The list of non-physiological instruments made to the designs both of Trinity men and of other Cambridge men is even longer. The same physiological catalogue of 1899 lists as an appendix some apparatus for other purposes, including a micrometer pressure gauge invented by Napier Shaw, demonstrator in physics at the Cavendish Laboratory, fellow of Emmanuel, and subsequently director of the Meteorological Office.<sup>114</sup> Shaw was also interested in anthropometry, and CSI, as well as listing a wide selection of Galton's instruments,<sup>115</sup> also advertised Shaw's apparatus for measuring the highest note audible to the human ear.<sup>116</sup> Alfred Ewing, Stewart's successor as professor of engineering, invented a wide variety of instruments, including a seismograph, an extensometer, and as one of the discoverers of magnetic hysteresis, a hysteresis tester. C.T.R. Wilson, a fellow of Sidney Sussex from 1900, invented a variety of electrometers and electroscopes during his researches into atmospheric electricity, and CSI sold them.<sup>117</sup> In 1911, Wilson was able for the first time to use his cloud chamber to make tracks of ionizing particles visible by photographing the drops of water which condensed on the ions formed along its track.<sup>118</sup> The following year CSI sold their first batch of six cloud chambers.<sup>119</sup> The company also made instruments for botanists who had taken up the study of plant growth under the influence of Julius von Sachs. Francis Darwin, Sidney Vines, and Marshall Ward, leading figures in Cambridge, had all studied under him at Wüzburg.<sup>120</sup> CSI produced a variety of klinostats for Vines, as well as a cup micrometer, an auxanometer which measured plant growth, and a slowly rotating

<sup>110</sup> *Some physiological apparatus [made by] the Cambridge Scientific Instrument Company, Ltd.*, 1913.

<sup>111</sup> *Ibid.*, pp. 14-16.

<sup>112</sup> *Ibid.*, pp. 2-7.

<sup>113</sup> Burch and DePasquale, *op. cit.*, note 3 above, p. 97-101.

<sup>114</sup> *Physiological instruments*, *op. cit.*, note 103 above, p. 100.

<sup>115</sup> *Ibid.*, pp. 106-113.

<sup>116</sup> *Ibid.*, p. 110.

<sup>117</sup> *Electrometers*, *op. cit.*, note 33 above, pp. 3-10.

<sup>118</sup> P.M.S. Blackett, 'Charles Thomas Rees Wilson 1869-1959', *Biogr. Mem. Fellows R. Soc. Lond.*, 1960, 6: 269-295.

<sup>119</sup> Of this batch two are preserved. One is in the Science Museum, inventory 1981-2175. Its C.S.I. serial number is 15551: it came to the Museum from the University College London. Serial 15553, supplied to the Department of Natural Philosophy at Edinburgh University, is now in the Royal Scottish Museum. Wilson's original apparatus is still in the Cavendish Laboratory.

<sup>120</sup> S.M. Walters, *The shaping of Cambridge botany*, Cambridge University Press, 1981, pp. 70-72.



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recording cylinder for use with it.<sup>121</sup> This last instrument was designed by Horace Darwin for his brother Francis; Francis and Horace together also designed apparatus for studying the transpiration of water through the stomata of leaves.

#### CSI AND THE ACADEMIC WORLD

Although the CSI traded as a commercial concern, its attitudes for its first twenty years were those of the university rather than those of the commercial world. It was not intended to make a financial profit—Darwin's main concern seems to have been that it should not make too great a loss. The company was keen to use its ingenuity to create novel instruments, but not to seek markets which its skills might have made them able to penetrate.

The concern for “traditional” values which was so deeply held by sections of the English middle classes, and which caused them to regard manufacturing industry with hostility, has recently been described by Wiener.<sup>122</sup> He stresses the fact that well into the twentieth century, both Oxford and Cambridge universities conceived their task as the production of gentlemen with a liberal education. “Business men were objects of scorn and moral reproof, and industry was noted directly as a destroyer of country beauty . . . undergraduates were regularly discouraged from pursuing their commercial careers, and alarms were sounded against the infection of these rarified precincts by vulgar influences from without.”<sup>123</sup> The CSI during the first twenty years of its existence, was engaged in invention rather than in production: this was acceptable to the university community. The Darwin family thought Horace brilliant with machines, but lacking in commercial judgement:<sup>124</sup> yet this failing enabled him to remain in ideological contact with the academic world in which he sold his instruments.

The sales literature produced by the company did not mention the usefulness of its instruments or the number of them which had been sold, but stressed rather their intellectual content. The preface to the 1899 catalogue of physiological instruments stated: “We are prepared to make any of the instruments described in recent scientific papers or in advanced Text Books, in many cases instruments required for original investigation have been supplied by us; either these were made from the designs of the experimenter, or the company designed the instrument to suit the case. We think we are in an exceptionally good position to carry out this class of work.”<sup>125</sup> Seventeen years earlier, the foreword to the catalogue had said, “The Company is . . . anxious . . . to strike out or adopt and improve new forms of instruments [rather] than to direct its energies to the reproduction in a dealer's spirit of familiar and more or less stereotyped models.”<sup>126</sup> The most conspicuous symbol of the Victorian enthusiasm for industrial capitalism had perhaps been the Crystal Palace. Wiener quotes Ruskin's opinion of it: “The quantity of thought . . . it expresses is I suppose, a

<sup>121</sup> *A descriptive list*, op. cit., note 107 above, pp. 23-24, 37-38.

<sup>122</sup> Martin J. Wiener, *English culture and the decline of the industrial spirit 1850-1980*, Cambridge University Press, 1981.

<sup>123</sup> *Ibid.*, p. 23.

<sup>124</sup> Gwen Raverat, *Period piece: a Cambridge childhood*, London, Faber, 1960, p. 203.

<sup>125</sup> *Physiological instruments*, op. cit., note 103 above.

<sup>126</sup> 1882 catalogue, foreword.

single and admirable thought . . . that it might be possible to build a greenhouse larger than one greenhouse was built before. This thought and some very ordinary algebra are as much as all that glass can represent of human intellect.”<sup>127</sup> Ruskin’s emphasis on thinking as a prerequisite for the creation of a worthwhile artefact was shared by Horace Darwin (though, ironically, as an anti-vivisectionist, Ruskin would have disapproved of many of CSI’s products). CSI emphasized the thought and craftsmanship that went into the making of their instruments, as well as their design. The preface to a general catalogue of instruments stated that: “Great care is taken to ensure first-rate workmanship; our staff of instrument makers is highly skilled, and the machine tools are suited to the production of work requiring great accuracy. Many of the instruments are new; in their design care was taken to ensure accuracy of movement, convenience in use, and general simplicity.”<sup>128</sup>

That the company’s attitudes were acceptable to the university community was shown when the whole of the foreword quoted above was set as a translation with Greek in a tripos examination. A Greek version was later published by a distinguished classical scholar and fellow of Trinity.<sup>129</sup> With the exception of some of the electrical temperature measuring equipment, the instruments that CSI made before 1900 were of no use to industry. Cambridge was traditionally suspicious of applied science: witness Sir George Airy’s long struggle to introduce applied mathematics into the Mathematics Tripos.<sup>130</sup> One famous mathematics teacher even refused to let Clerk-Maxwell show him simple demonstrations of optics, which he had never seen, on the ground that the phenomena could be satisfactorily understood without ever having witnessed them.<sup>131</sup>

In 1925, the CIC published a twelve-page pamphlet, which suggests that although they by then supplied many instruments to industry, they still thought of themselves as a part of the university world.<sup>132</sup> It purported to contain translations of three ancient Egyptian papyri: in fact, one described the use of the Féry pyrometer, another the visit of CIC staff to the British Empire Exhibition at Wembley in 1924-25, and the third the use of the electrocardiograph. A stylized drawing of an Egyptian electrocardiograph was printed, along with an explanation:

The holy day of the cult was called KLINIK . . . THE NAME (written in hieroglyphics on the panel), RA-LALL,<sup>133</sup> very freely translated means ‘One who knows the number of combinations of three things taken two at time’ and denotes infinite wisdom . . . THE PLEHT. This was a small tablet of translucent stone, obtained from a locality called KO-DAX. At the end of the sacrifice this was sometimes found to be covered with mystic writings (quite untranslatable). THE FYBA. A small harp-like instrument. The priests spent a good deal of their lives putting new strings in these

<sup>127</sup> Wiener, *op. cit.*, note 22 above, p. 29.

<sup>128</sup> *A descriptive list*, *op. cit.*, note 107 above, p. [iii].

<sup>129</sup> R.D. Archer-Hind, *Translation into Greek verse and prose*, Cambridge University Press, 1905, pp. 146-147.

<sup>130</sup> J.G. Crowther, *Scientific types*, London, Cresset Press, 1968, pp. 366-367.

<sup>131</sup> This was Isaac Todhunter (1820-84). Arthur Schuster, *The progress of physics during 33 years (1875-1908)*, Cambridge University Press, 1911, pp. 25-27.

<sup>132</sup> [R.F. Clark], *Proceedings of the Egyptological Society: a report on the discovery of ancient papyri in Egypt and Babylon by Mr Carrier, F.O.B., communicated by Professor Peter Splinters, D.Sc., M.E.S.*, London, Cambridge Instrument Company, 1925. Clark was in charge of the Company’s Manchester office.

<sup>133</sup> I.e., Right Arm—Left Arm, Left Leg.

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instruments . . . The great enemy of the cult ANTIVIV, an evil spirit in the shape of a small brown dog, is depicted as reduced to a proper state of servitude by holding the god's discarded sandal.<sup>134</sup>

According to the title-page it was "a report by Mr Carrier . . . communicated by Professor Peter Splinters." Mr Carrier is presumably intended to represent Howard Carter, whose excavation of the tomb of Tutankamun at Thebes had made sensational news when his colleague, the Earl of Carnarvon, died during the explorations, thus becoming part of the myth of "the curse of the pharaoh". Professor Peter Splinters represents Sir Flinders Petrie, who occupied the chair of Egyptology at University College London from 1892 to 1933. In associating themselves with Carter and Petrie, CIC can be seen to be expressing the belief that they had a place in academic society.

Sanderson has linked CSI with manufacturing companies which were among the leaders in the movement towards industrial research in Britain between 1870 and the First World War, such as Nobel's, Burroughs Wellcome, and Firth Brown.<sup>135</sup> This is misleading. These companies were initially manufacturers, who subsequently found benefit in carrying out their own research. In its early years, CSI produced only a small number of specialist instruments, and developed them themselves. To Horace Darwin, research was more important than production.

Originality; concern for detail; interest in quality rather than quantity: these are the features which link the thinking of CSI to that of the academic world. The change when Robert Stewart Whipple (1871-1953) took up the commercial guidance of CSI is clear.<sup>136</sup> His father was George Mathews Whipple (1842-93) superintendent of Kew Observatory, where a wide range of scientific instruments were tested for the government. G.M. Whipple married the daughter of Robert Beckley, the chief instrument-maker at the Observatory. R.S. Whipple worked briefly at Kew. Despite the great interest in instrumentation that was present in the environment in which he was brought up, Whipple also understood modern business methods. These he learned in 1894-97, while working for the firm L.P. Casella of Holborn Bars, London, one of the most successful of Victorian instrument-makers.<sup>137</sup> Whipple came to Cambridge to be Darwin's assistant in 1897. The number of CSI employees at that time is not known. In 1901, it was thirty-six, in 1913, about 180. The factory had to be enlarged in 1900, 1906, 1912, 1913, and 1914. Whipple himself devised a portable indicating instrument for use with industrial resistance pyrometers: it consisted of a potentiometer attached to a d'Arsonval galvanometer.<sup>138</sup> Whipple did not loosen CSI's ties with the university, but he exploited the new markets for temperature-measuring instruments in the kiln and metal industries, and in the handling of refrigerated food.<sup>139</sup> Perhaps it was because he was not himself a

<sup>134</sup> [Clark], *op. cit.*, note 132 above, p. [5].

<sup>135</sup> Michael Sanderson, *The universities and British industry 1850-1970*, London, Routledge & Kegan Paul, 1970, pp. 20-21.

<sup>136</sup> For the life and work of Whipple, see his 'Reminiscences of an instrument maker', *Journal of Scientific Instruments*, 1942, 19: 178-183; and the obituary by A.C. Menzies, *Proc. Phys. Soc., Series A*, 1954, 67: 1129-1130.

<sup>137</sup> *Quart. J.R. Meteorol. Soc.*, 1898, 24: 99-100.

<sup>138</sup> J.A. Chaldecott, *Temperature measurement and control*, 2nd ed., London, Science Museum, 1976, part II (Catalogue of the collection in the Science Museum), p. 32.

<sup>139</sup> *Ibid.*, pp. 29-32, 38-40; *Technical thermometry: electrical resistance thermometers . . . manufactured and supplied by the Cambridge Scientific Instrument Company Ltd.*, 1906, pp. iii-iv.

university graduate that he was able to accept freely the idea of commercial profit-making, and to guide CSI away from craftsmanship towards new markets and large-scale production.

#### CONCLUDING REMARKS

The electrocardiograph was probably the most sophisticated scientific instrument in existence when it was first invented, combining as it did technical ingenuity in a number of fields. Only a few earlier instruments approached its complexity, notably the Kew photographic barograph of 1867, which was mostly the work of Robert Beckley, R.S. Whipple's grandfather.<sup>140</sup>

In examining the history of scientific instruments, it is difficult to point to examples of close co-operation between the instrument-maker and the natural philosopher before the last thirty years of the nineteenth century. Even instances such as the collaboration between J.J. Lister and Andrew Ross in the production of the first completely successful achromatic microscope tend to show a one-way flow of ideas, from the natural philosopher to the instrument-maker. What emerges from the study of the electrocardiograph is a clear picture of the way in which, in the era of increasingly complex electrical measurement, the instrument-maker was able to incorporate in the finished, saleable instrument the solutions to a variety of technical problems, drawn from a range of other technologies and applications. He was able to have a general view of science and engineering—albeit from a rather unusual standpoint—which was denied to the research scientist in the seclusion of his speciality.

S.L. Barron of the CSI was the go-between between Sir Thomas Lewis and the company. He had a particularly close view of the interaction between physiologists, clinicians, and manufacturers during the development of electrocardiography. Barron fully understood the importance of these interactions, and concluded his essay on the history of electrocardiography thus:

Possibly no other twentieth-century medico-scientific invention has had more far-reaching results than the electrocardiograph, or has become so universally used in every hospital and by all practising cardiologists throughout the world. It has been the product of close co-operation between the medical scientists and manufacturers; hardly has a need been expressed than it has found its response in a piece of practical equipment. Laboratory extemporisation has been examined by the manufacturers, and put into a practical and marketable form.<sup>141</sup>

#### ACKNOWLEDGEMENTS

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<sup>140</sup> Knowles Middleton, *op. cit.*, note 10 above, pp. 322-323.

<sup>141</sup> Barron, *op. cit.*, note 3 above, p. 21.

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### APPENDIX I: SALES OF STRING GALVANOMETERS, 1905–15

Listed below are the number of string galvanometers sold by the Cambridge Scientific Instrument Company, and the royalties paid on them to Willem Einthoven. These figures are derived from the sales records which were sent to Einthoven at the end of every half year, except that the royalty for the whole of 1909 was paid at once, and that for the instruments which had been ordered, but not delivered by the end of 1914, which was paid after the end of 1915. The royalties were depleted by income tax, which CSI were obliged to deduct on a sliding scale starting at one shilling in the pound, under section 25(1) of the Finance Act of 1907.

To		£	s.	d.	royalty.
To 31 Dec. 1907	3 instruments	12	5s.		
30 June 1908	2	9	19	6	
31 Dec. 1908	1	7	4	5	
31 Dec. 1909	8	26	11	7	
30 June 1910	4	10	7	2	
31 Dec. 1910	4	10	5	11	
30 June 1911	7	14	8	5	
31 Dec. 1911	6	15	12	3	
30 June 1912	11	26	19	8	
31 Dec. 1912	11	30	14	9	
30 June 1913	10	25	9	0	
31 Dec. 1913	29	72	1	3	
30 June 1914	16	40	11	5	
31 Dec. 1914	22	47	17	0	
31 Dec. 1915	6	13	9	8	
TOTAL	140	363	17	1	

### APPENDIX II: BUYERS OF STRING GALVANOMETERS, 1905–12

By the end of 1912, fifty-seven string galvanometers had been sold. Their purchasers are listed below, along with the dates on which the instruments were sent out from Cambridge. As in Appendix I, this information is extracted from the sales records sent by CSI to Einthoven.

1. .05 Professor MacDonald, Physiological Laboratory, Sheffield (sold between July and October).
2. 16.03.06 Professor J.C. Bose, Presidency College, Calcutta.
3. .07 Keith Lucas, Cambridge.
4. 28.01.08 Professor Stiasonie, Paris.
5. .08 Professor Schafer, Edinburgh (sold between January and June).
6. .08 University of Kazan (sold between July and December).
7. 26.01.09 Bureau of Weights and Measures, St Petersburg.
8. 03.02.09 University of Birmingham.
9. 15.02.09 Marey Institute, Paris.
10. 16.03.09 University of Strassburg.
11. 28.05.09 University of Naples.
12. 07.05.09 Marconi's Wireless Telegraph Company.
13. 08.10.09 University of Manchester.



*J. Burnett*

14. 01.12.09 Elliott Brothers, London.
15. 04.01.10 Sanger, Shepherd and Co., London.
16. 26.01.10 University of Sendai, Japan.
17. 24.02.10 University of Lyons.
18. 14.06.10 Ministry of Posts and Telegraphs, Rome.
19. 30.07.10 Royal Infirmary, Edinburgh.
20. 09.09.10 B.S. Lloyd & Co.
21. 31.10.10 H.B. Silberberg & Co.
22. 09.10.11 Pathological Laboratory, Cambridge.
23. 09.01.11 J.W. Lowdon.
24. 18.01.11 Taylor Instrument Co.
25. 29.03.11 Speidel & Co.
26. 17.05.11 Marine Technical Commission, St Petersburg.
27. 26.05.11 Dr. R.W. Mitchell.
28. 12.06.11 G. Fontaine.
29. 19.09.11 University of Kyoto.
30. 20.09.11 Imperial Japanese Navy.
31. 02.11.11 Takata & Co.
32. 22.11.11 University of Utrecht.
33. 13.12.11 New York Postgraduate Medical School.
34. 27.12.11 Seebohm and Dieckstahl [?]
35. 01.01.12 Professor William Osler.
36. 11.01.12 Taylor Instrument Company.
37. 11.01.12 G. Boullitte.
38. 09.02.12 J.G. Biddle.
39. 02.04.12 Institut Océanographique.
40. 03.04.12 Marconi's Wireless Telegraph Company.
41. 17.04.12 Professor Willem Einthoven [This is probably the oldest surviving CSI string galvanometer. It is now in the Universiteits Museum, Utrecht.]
42. 01.05.12 St Bartholomew's Hospital, London.
43. 25.05.12 Dr E. Avery Newton.
44. 08.06.12 University of Groningen.
45. 26.06.12 Jarré et Cie.
46. 22.07.12 University of Rome.
47. 30.07.12 Marconi's Wireless Telegraph Company.
48. 30.07.12 Marconi's Wireless Telegraph Company.
49. 07.08.12 G. Boullitte.
50. 12.08.12 Dacca College.
51. 02.09.12 Dr M.D.D. Gilder.
52. 02.11.12 Carnegie Institute, Washington D.C.
53. 13.11.12 Westinghouse Electric Company.
54. 14.11.12 Pein & Co.
55. 14.11.12 G. Boullitte.
56. 05.12.12 Guy's Hospital, London.
57. 23.12.12 J.G. Biddle.