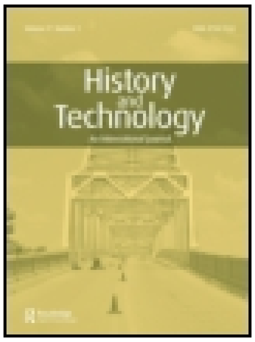

History and Technology

ISSN: 0734-1512 (Print) 1477-2620 (Online) Journal homepage: http://www.tandfonline.com/loi/ghat20

Willem Einthoven and the Development of the String Galvanometer. How an Instrument Escaped the Laboratory

Bart Grob

To cite this article: Bart Grob (2006) Willem Einthoven and the Development of the String Galvanometer. How an Instrument Escaped the Laboratory, History and Technology, 22:4, 369-390, DOI: 10.1080/07341510601003081

To link to this article: http://dx.doi.org/10.1080/07341510601003081

History and Technology
Vol. 22, No. 4, December 2006, pp. 369–390

Willem Einthoven and the Development of the String Galvanometer. How an Instrument Escaped the Laboratory

Bart Grob

In 1901 the Dutch physiologist Willem Einthoven invented the string galvanometer. It was an instrument capable of recording weak electrical pulses in the human body. He used it to investigate the human heartbeat and in 1924 was awarded the Nobel Prize for medicine or physiology for the discovery of the mechanism of the electrocardiogram. Soon after his first publication he contacted a number of Dutch and international instrument makers with a view to persuading them to produce his apparatus. The correspondence between Einthoven and these instrument makers gives us an insight into the process from prototype through to sellable instrument. It also reveals that these instrument makers had an important part to play in the earliest development of the string galvanometer on its way to becoming an electrocardiograph. The first impression that the string galvanometer made on instrument makers appears to have been an important guiding factor in the direction taken by the technological development of the apparatus. Secondary considerations such as financial and legal matters were decisive in whether or not the instrument was actually made.

Keywords: *Willem Einthoven; Siemens & Halske; Cambridge Scientific Instruments Company; Cardiograph*

Introduction

In 1901 Willem Einthoven (1860–1927) published his first article on his newly invented string galvanometer.[1] In this article the Dutch professor of physiology describes the physical features of the string galvanometer. The device was a highly sensitive measuring instrument for the measurement of very small electrical currents. In 1924

Bart Grob is at Museum Boerhaave, National Museum of the History of Science and Medicine, PO Box 11280, 2301 EG Leiden, The Netherlands. E-mail: research@museumboerhaave.nl

ISSN 0734–1512 (print)/ISSN 1477–2620 (online)
DOI: 10.1080/07341510601003081

Einthoven was awarded the Nobel Prize for the discovery of the mechanisms of the electrocardiogram. It is often thought that he was awarded the Prize for his invention of the string galvanometer. This is not the case, however. The Nobel Prize was awarded for his theoretical work on the mechanism of the electrocardiogram (ECG). Even before he constructed the string galvanometer he had predicted, on a mathematical basis, what the shape of the ECG would be. Although it was the theoretical aspects of the ECG that brought Einthoven scientific fame, the instrument itself proved invaluable in demonstrating the validity of his theoretical claims.

Soon after this first publication Einthoven contacted a number of instrument makers to see whether they would be interested in manufacturing his instrument. The correspondence between Einthoven and these manufacturers is preserved in the Einthoven archives, which are kept at the Museum Boerhaave. This paper is largely based on this correspondence. In the letters Einthoven and the manufacturers discuss the possible production of the string galvanometer. This correspondence gives us an insight into the relationship between the inventor of the early cardiograph and its subsequent manufacturers.

Although the invention of the string galvanometer has been crucial in the understanding of the mechanism of the heartbeat, this paper will discuss the initial commercial developments of the instrument rather than the construction of the electrocardiogram or its other medical applications. There is recent literature dealing with the acceptance of graphical methods in clinical practice. This article however focuses on questions such as: How did a physiological research instrument become a clinical diagnostic tool? What expectations did Einthoven have when he invented the string galvanometer? Did he have particular goals that he wanted to achieve? Was he aware that he had invented an instrument with the potential to become the most important clinical tool in cardiology? What were the expectations of the companies Einthoven approached? The Einthoven archives provide a fresh view of the earliest developments of the electrocardiograph.

Authors who have recently written on the history of cardiology have treated the subject in different ways. The concept of a generation gap, a debate between general physicians and 'new cardiologists,' has been developed by Lawrence.[2] In his article the author outlines the emergence of cardiology in Britain over the period 1880–1930. He describes the process of emancipation and specialisation of physiologists in the pre-cardiological scientific climate at the end of the 19th century. By the end of this process Britain was playing a leading role in international cardiological research. Lawrence postulates that a break with the old tradition occurred in the final decades of the 19th century. These 'old-school' physicians were still holding onto physical investigation with the (re)discovered techniques of palpation and auscultation. Followers of this school felt that physical examination could only be learned after years of practice, a honing of the skills. In fact, they felt that practising medicine was an art form, which could never be replaced by instruments. According to Lawrence a new breed of physicians entered internal medicine from the field of experimental physiology. These new-school scientists used a wide range of instrumentation to study the phenomena of life. Apart from using instruments, the experimental physiologists approached the heart in a different way. Where old-school knowledge was based upon findings from post-mortem examinations of the heart, the new school was acquiring knowledge by studying the living heart. According to Lawrence this led to much debate between the two parties, a debate that would linger on well into the 20th century. In the author's opinion, it was Einthoven's electrocardiograph that provided the new cardiologists with enough new information to supersede the old school.

According to Burnett[3] the reason for the slow acceptance of the cardiograph as a diagnostic tool was because the instrument was a research instrument and not yet a clinical tool. To make this point Burnett considers the technical evolution of the cardiograph. He places these developments in the historical context described by Lawrence. Burnett states that the existence of an experimental physiological research environment provided fertile soil for Einthoven's string galvanometer. Apart from this fertile soil, the Cambridge Scientific Instruments Company (CSI) was in Burnett's view a driving force behind the establishment of Einthoven's instrument as a clinical tool.

While the above authors concentrated on British developments in cardiology, Burch,[4] in his article about the technological development of the electrocardiograph, focuses more on developments in the rest of Europe and the USA. In Burch's opinion the origins of the electrocardiograph are to be found in Germany and not in Britain. He describes how the Munich instrument maker Max Edelmann contacted Einthoven and took the string galvanometer into production. According to Burch it was these Edelmann-type cardiographs that first reached the USA, where they were an important factor in the establishment of cardiology as a medical specialism. For legal reasons their business agreement would not last for long. This agreement has also been discussed by Snellen.[5] In his biography of Einthoven, in the chapter on the technical development of the electrocardiograph, Snellen suggests that Edelmann was the first instrument maker Einthoven contacted. When the cooperation between the two men came to an end, Einthoven contacted CSI and, according to Snellen, they were the ones who made the first cardiographs.

Willem Einthoven and his Invention

Although Willem Einthoven is remembered as one of the founding fathers of cardiology, it was a circuitous route by which Einthoven came to this medical profession. On completing his medical studies at the University of Utrecht, he started out as assistant to Professor F. C. Donders (1818–1889) at the Ophthalmological Hospital in Utrecht. Apart from being director of this hospital, Donders was also professor of physiology at the University of Utrecht. Donders was a well-known physiologist and a Dutch exponent of the new experimental physiology. He used his influence to have Einthoven appointed to the vacant chair of physiology at the University of Leiden. Einthoven's inaugural lecture in 1886 was entitled: 'Theory of specific energies.' The initial research performed at his laboratory concerned the physiology of the eye. He was clearly following in the footsteps of his former teacher, F. C. Donders. Einthoven's research programme changed when he saw a demonstration of Lipmann's capillary electrometer at the first International Physiological Congress in Basle in 1889.

The basis of the capillary electrometer was a tiny column of mercury immersed in a phosphate solution. Connected to the human body the column would react to the electrical pulses of the heartbeat. This instrument could be used to produce a graphical representation of the human heartbeat. The drawback of this method was that, owing to the slowness of mass, the column of mercury would not react quickly enough. It was only by using mathematical methods that Einthoven was able to deduce the real shape of the electrocardiogram. However, this was a time-consuming process because every point on the graph required compensation for the methodological error. So he needed another instrument. Einthoven tried out several electrical measuring devices that were available at the time. He performed experiments with an Arsonval galvanometer and a Thomson galvanometer. Both voltmeters were fast enough to record an electrical current correctly, but they were not sensitive enough to record the tiny electrical pulses of the heart.

Einthoven analysed the data resulting from the experiments performed with the Lipmann capillary electrometer, the Arsonval galvanometer and the Thomson galvanometer. This analysis led him to investigate the physical/mathematical characteristics of the instruments. Lipmann's electrometer in particular held his attention. Not being a physicist, Einthoven had to overcome the problems of the mathematical equations. With the help of H. A. Lorentz (1853–1928), the famous Leiden professor of physics, he was able to solve the mathematical calculations that modulated the physical behaviour of the mercury column. This mathematical approach provided him with a sound basis for the development of a new instrument, the string galvanometer. This instrument would combine the best of both worlds: the swiftness of the galvanometers and the sensitivity of the capillary electrometer.

In 1901 Einthoven had a new, working instrument. He named it the string galvanometer because the heart of the instrument was a quartz string. The first time he referred to the string galvanometer was in his article 'Un nouveau galvanomètre.'[6] Written for an audience of physicists, the article does not contain any images of the instrument as a whole. The focus of this article lay on the physical characteristics of the instrument and the apparatus is presented in terms of facts and figures. The first image of the actual instrument was not published until 1906.[7] A schematic drawing shows the interior of his string galvanometer (Figure 1). Einthoven gives a brief explanation of how the instrument was constructed. The core of the instrument was formed by two iron bars, which were the two poles of an electromagnet. A tiny quartz fibre was placed in the small space between these two bars in such a way that the deviations could be seen through holes in the iron bars. In the holes of the bars magnifying lenses were used to condense the light beam and to magnify the shadow image of the string. When an electric current passed the quartz fibre, it swung to the right or the left according to the potential of the current.

The string galvanometer lay at the heart of the research equipment that Einthoven needed in order to produce an ECG. The whole installation consisted of four aligned instruments (Figure 2): a light source, a time-dividing instrument, a detection device (in this case the string galvanometer) and a recording device. A carbon arc lamp was used as light source for projecting the shadow of the string onto a photographic plate.

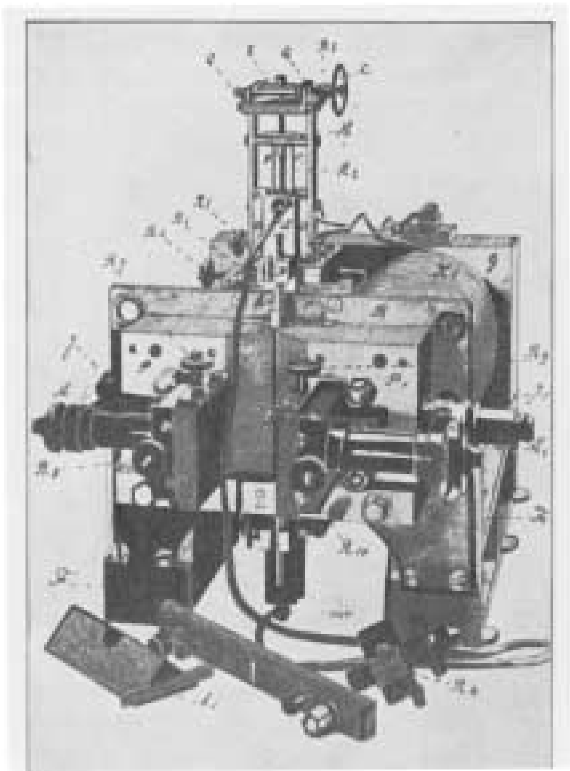

Figure 1 Schematic Drawing of Einthoven's String Galvanometer

The powerful light beam of the carbon arc lamp was ideal for covering the distance between the lamp and the photographic plate in the camera device, more than a metre away. Because the recording of a heartbeat is time-dependent, Einthoven had to use an instrument that would enable him to determine the elapsed time. He used a splitter, a round wheel with small spokes, as his time divider. The spokes would be visible on the ECG as vertical lines and, depending on the velocity of the wheel, would add a time scale to the drawn curves. As the light passed through the lenses of the string galvanometer, the shadow of the string was magnified and projected onto a thin slit in a specially devised camera. The front faced the string galvanometer where the slit was aligned with the magnifying system. At the rear a photographic plate was constructed in such a way that it slid down behind the slit in a constant movement. After processing the photographic plate the characteristic ECG curve could be read.

Using this instrument Einthoven was the first person ever to produce a human electrocardiogram without methodological errors. He spent some time experimenting with it in other fields of electrophysiology, investigating the electrical phenomena of the retina and the nervus vagus, for instance. This established Einthoven as a scientist active in the field of experimental physiology. His experiences with the string galvanometer influenced his intentions and expectations of his instrument. Einthoven's

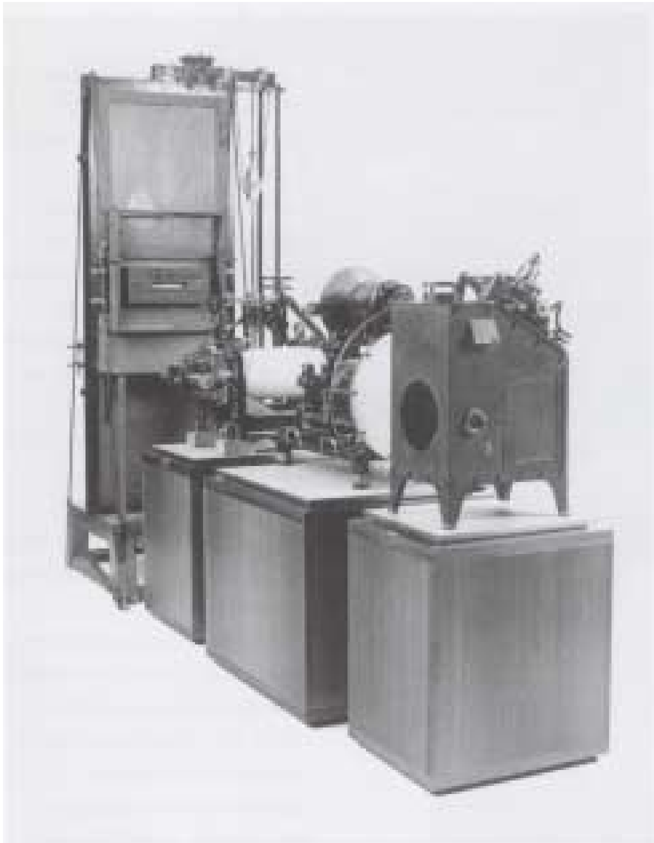

Figure 2 The Complete Constellation of Einthoven's Cardiograph, as Preserved in Museum Boerhaave

expectations were expressed in his first publication on the string galvanometer.[8] In this article he expected this new method to make it possible, better than before, to study all kinds of electrical phenomena of muscles, glands, nerves and senses. This description shows that Einthoven thought that his instrument could be used across the whole experimental field of physiology.

The Correspondence with Dutch Instrument Makers

With the idea of a general physiological apparatus in mind, Willem Einthoven approached a number of instrument makers. In 1902 he first contacted the German instrument maker Siemens & Halske[9] by sending the company a separate print of his article 'Un nouveau galvanomètre.' This was a company that had been founded in 1847 by W. von Siemens and J. G. Halske, starting out as a workshop for telegraphic instruments.[10] At the beginning of the 20th century the company had expanded its business beyond telegraphy into other fields, such as the development of electronic railways, X-ray technology and military equipment.[11]

Einthoven had already been acquainted with this company before developing the string galvanometer. In 1900 he contacted the firm about a sympatic compass.[12] At that time Einthoven had developed an electrical system which enabled a mother compass to control one or several daughter compasses. Why and how Einthoven constructed this device falls outside the scope of this paper. It shows however that from the very start of the development of the string galvanometer Einthoven knew how to make contact with instrument makers.

To Einthoven's regret Siemens was unwilling to become involved in the production of the string galvanometer. In its reply the company gives two reasons for this:

> We are sorry to mention that the string galvanometer does not fit into our production lines nor does it answer to our customer demands so that at this moment we are not in the position to develop the mentioned instrument ….

Furthermore:

> … the specific department, which would be responsible for the further development of the apparatus, is at this moment too much involved with other projects.[13]

Following Siemens's refusal to invest time and money in Einthoven's galvanometer, Einthoven contacted N. G. Van Huffel, director of the Nederlandse Instrumenten Fabriek (Dutch Instrument Factory) (NIF). NIF was founded in Utrecht in 1900. The company specialised in the production and repair of physical, electrotechnical and medical equipment. From the beginning the company had to cope with financial difficulties and with finding and retaining qualified personnel.[14] This paper will show that these difficulties would play an important part in NIF's decision whether or not to produce the string galvanometer.

The correspondence between Einthoven and the director of NIF started in early 1901, but it was not until December 1902 that Einthoven proposed his new invention:

> … Now I should like to describe the apparatus and add to the description that it can be obtained from such and such a company. I am therefore coming back to you and am prepared to accept a reasonable offer on your part, as set out in your letter of 22 April 1901.[15]

Initially Van Huffel showed an interest in Einthoven's invention. However, in his reply Van Huffel did foresee some major difficulties. He wrote to Einthoven that 'if his instrument were to be sold, it would have to come with a great deal of service. When an instrument is sold, the whole set-up needs adjustment on the spot by a technician.[16] Moreover, 'it would be worthwhile if Einthoven himself could demonstrate the instrument.' Not only would this allow the customer to become acquainted with the handling procedures, it would also be a hallmark of the inventor himself. In Van Huffel's opinion this personal approach would have a decisive impact on sales. In addition, he was keen to persuade Einthoven to use his academic network to sell the instrument. For instance, he wanted Einthoven to contact Professor Th. W. Engelmann (1843–1909), a famous physiologist at the University of Berlin. Before he went to Berlin, Engelmann had been appointed successor to F. C. Donders as the chair of physiology in Utrecht. Having been Donders's assistant at the same time, Einthoven was acquainted with

Engelmann, who had also worked with the capillary electrometer, the very instrument that had brought Einthoven into contact with electrophysiology. In Berlin Engelmann occupied an internationally influential position as successor to the legendary E. du Bois-Reymond. If a scholar such as Engelmann were to show enthusiasm for Einthoven's instrument, it would give the instrument legitimacy and as a result a great deal of 'free publicity' for Van Huffel's firm. Van Huffel was simply wanting to reduce his financial risk. A new market would be much easier to capture with Einthoven's contacts, especially as this was such a new and expensive instrument.

For expensive, the instrument certainly would be! According to Van Huffel's calculations, the whole set would cost 2000 guilders (approximately €20,000 today).[17] Einthoven understood that Van Huffel had financial doubts, as is clear from his reply to Van Huffel's letter.

> … It is true that your company is still young and your clients are not numerous, so you see a lot of risk in the supply of 20 instruments, but on the other hand the instrument will in all probability bring you into contact with a number of Dutch and possibly also a few foreign laboratories, which for a young company such as yours is of great importance.[18]

However, Einthoven replied, taking this risk would in the end do his firm more good than harm because it would bring a potentially new clientele to the factory. Even though Van Huffel would have access to an international network of physiologists and Einthoven was willing to help him make contact with these scientists, he considered the financial risks too great and therefore NIF dropped the idea of producing the string galvanometer.

In 1902 Einthoven contacted another Dutch instrument maker, J. W. Giltay. Giltay[19] was head of the company known as 'P. J. Kipp en Zonen, J. W. Giltay Opvolger.' This company was located in Delft and produced electrical measuring and laboratory devices.[20] Under the direction of J. W. Giltay the company also focused on the production of chemical and pharmaceutical products.[21] Einthoven's offer to Giltay of his instrument comes as something of a surprise. A company specialising in chemical and pharmaceutical equipment could not be expected to have much experience of or interest in the production of physiological equipment. For instance, there is no typical physiological equipment, such as respirators or kymographs, to be found in the company's sales catalogue.

When Einthoven first contacted the company, Giltay was positive about the instrument and appeared interested in the production of the string galvanometer. He was however well aware of the technical modifications the string galvanometer would need before becoming a marketable product. Apart from these modifications, another obstacle would be the high price of the instrument. In 1903, the last letter in this correspondence, Giltay stated:

> … I very much regret that I am unable to take this on. It is a very interesting instrument, but I really do not have the time for it. I am working on so many innovations, which will require less thought and probably generate more money, that I can do no more than thank you for the confidence you have shown in me.[22]

Although Giltay made no mention of his expectations of the instrument, we can safely assume that he might have regarded the string galvanometer as an accurate and highly sensitive voltmeter. As a voltmeter it would have made sense for Giltay to be interested in a physiological apparatus in the first place.

The fact that Einthoven contacted Giltay and Van Huffel so soon after he made his first electrocardiogram provides a possible explanation for the hesitant attitude of these Dutch instrument makers. The first ECG made with the string galvanometer is dated November 1902 and the first image of an ECG was printed in a commemorative book for the Dutch Professor S. S. Rosenstein (1831–1906) in 1902.[23] So we cannot assume that Giltay or Van Huffel knew about this publication. Because Einthoven uses expressions such as 'I would like to describe my instrument' in his first letter to these companies, they must first have read about it when Einthoven sent them his article 'Un nouveau galvanomètre.' In this article he describes the apparatus but does not include an image of an ECG. Moreover, at the time Einthoven contacted the Dutch instrument makers, the field of electrophysiology was largely unexplored territory in the Netherlands. Einthoven was one of the few, if not the only one to publish on the subject.[24]

Given the fact that Einthoven had constructed the string galvanometer in rather solitary conditions, it is safe to assume that in 1902 the potential market was not that large. Both instrument makers told Einthoven that it would be very difficult to find customers for his expensive instrument. Only specialists would be interested, only people who had access to and who read Einthoven's articles would be able to understand the potential of his instrument. As mentioned above, the field of electrophysiology was only just beginning to be explored. Even if a buyer were to be found, the prototype needed modification to make it a user-friendly instrument. The letters from Van Huffel show that Einthoven's instrument was considered too complicated. Both directors however seem to have no difficulty in making additional changes to the prototype. They both had a technical background and a workshop to work out the modifications for the further development of the string galvanometer. For instance, in one of the letters from Giltay to Einthoven he suggests the replacement of the electromagnet with a permanent magnet. This would have made the instrument more compact and easier to handle. Einthoven however turned this down because it would have had too much of an impact on the sensitivity of the instrument.

The Correspondence with the Cambridge Scientific Instruments Company

In the meantime Einthoven was determined to find a producer for his instrument. So he contacted the English instrument factory Cambridge Scientific Instruments Company (CSI). CSI was founded by Horace Darwin (1851–1928) and Albert George Dew-Smith (1848–1903) in 1881. It had been Michael Foster, a leading physiologist appointed by Trinity College in 1869, who had encouraged Darwin and Dew-Smith to set up an instrument shop.[25] From the outset CSI was closely associated with Trinity College, Dew-Smith being a pupil of Foster's and Darwin being a fellow at Trinity. Their shop would become a workshop for the development and supply of physiological instrumentation for the Cambridge scientific community. In 1890 the company was split and Horace Darwin assumed sole control.

Even in his younger years Horace had displayed a keen interest in designing instruments. One of the first scientific devices he made was a micrometre system for the 'Worm Stone' at Down House. It was made for an experiment that his father, the renowned naturalist Charles Darwin, conducted to study the rate at which stones are buried by the actions of worms beneath them. Later he undertook an engineering apprenticeship and worked at the world-famous Cavendish laboratory. Horace Darwin would become a highly talented instrument designer who developed a great love for electrical instruments.[26] In 1903 he became a fellow of the Royal Society, an unusual distinction for an instrument maker.

At the beginning of the 20th century Trinity was the centre of experimental science in Cambridge. Under Horace Darwin, CSI probably became even more embedded in the Cambridge academic world. Cambridge's liberal education system, which delivered gentlemen and not businessmen, would influence Darwin[27] strongly. For Darwin, solving a scientific problem with the aid of instrumentation was more important than earning money with it. Sales records show that even the profitable instruments could not cover the losses made from the development of specialised equipment. This paper will show that this attitude would make its mark on the development of the string galvanometer.

When Einthoven contacted Darwin in 1903, the latter had been producing scientific instruments for a number of years. In the archive, the correspondence starts with CSI's reply to a publication Einthoven had sent them. How Einthoven made contact with the company can only be guessed at, although it might be possible that someone in Einthoven's scientific network had pointed him in the direction of CSI.

In reply to Einthoven's letter, CSI wrote:

> … We have read with interest the accounts of your string galvanometer which you have been good enough to send us. We appreciate the beauty and ingenuity of the instrument, & we think it is one which we should like to manufacture if this can be arranged … .[28]

In another letter CSI mentions a copy of 'Un nouveau galvanomètre,'[29] so Einthoven probably used his first publication on the string galvanometer to introduce his machine to manufacturers.

From the start CSI showed an interest in manufacturing Einthoven's string galvanometer. Before they could make the instrument they first needed more specific information from Einthoven. R. S. Whipple, managing director of CSI, asked whether Einthoven could send the instrument to them. This would facilitate a thorough study of the instrument in the workshop and, of course, they could see it working. Einthoven however could not agree to send his prototype. Apart from the fact that it was simply too heavy and bulky, Einthoven could not do without his instrument for a day. Experiments with the string galvanometer had become the central research theme at Einthoven's laboratory. Sending his instrument away would mean a delay in his research. The need for more technical information on the design of the instrument suggests that CSI could see the potential of the instrument but also realised that it had to be changed before it would sell. Before Einthoven and Darwin came to a business agreement, legal difficulties appeared to put the agreement into jeopardy.

At the same time as arranging a business deal with CSI in the United Kingdom, Einthoven was also negotiating an agreement with the firm of Max Edelmann in Germany. Prof. Dr M. Th. Edelmann's physicomechanical institute produced electrical measuring devices at the beginning of the 20th century and was located in Munich. Edelmann was very interested in manufacturing Einthoven's apparatus. It was not long before Einthoven was caught up in the middle of competition between CSI and Edelmann. The next fragment from Einthoven's letter to CSI in 1904 shows that there was a fair amount of competition between Edelmann and CSI concerning the supply of the English and American markets:

> I got a letter from Edelmann and settled the matter with him. I am sorry to say, that he is not willing to leave you the sale for England and America.[30]

CSI was clearly trying to protect its English and American markets. But the company was threatened by Edelmann, who wanted access to the same markets. Edelmann was unwilling to leave the English and American markets to CSI. The matter was made more complicated by the fact that Einthoven did not own the patent rights to the instrument.[31] He did not own these rights because there was no patent law in the Netherlands between 1869 and 1910.[32] It is not clear why Einthoven did not claim the rights to the instrument in England and Germany.

It was Horace Darwin himself who at this point tried to persuade Einthoven to make a business deal with CSI rather than Edelmann. In January 1904 Darwin wrote in a letter to Einthoven that his technician Duddell had heard from A. D. Waller, by then a famous physiologist, who was interested in the string galvanometer. Darwin also mentions that Duddell only wanted to improve the string galvanometer if it could be named after Einthoven.[33] This was one of the demands that Einthoven had made. Each instrument maker could make his instrument only if it was named after him. The second demand was that he wanted 10% of every galvanometer sold. The matter was finally settled in 1905 and both CSI and Edelmann were allowed to make and sell the instrument wherever they wished. Einthoven received 10% of the price of every instrument sold from both parties.

While Einthoven and CSI were building up a fruitful relationship, the association with Edelmann was taking a turn for the worse. After 1907, the agreement was cancelled unilaterally by Edelmann. He accused Einthoven of having copied the operating principle for his string galvanometer. Edelmann referred to the Frenchman C. Ader. In 1897[34] Ader had devised a string instrument for telegraphic purposes. Although Einthoven was aware of this invention—he mentions it in a footnote in his first publication on the string galvanometer[35]—he was convinced that his instrument differed from Ader's. In his opinion not only did his instrument differ in design, it also differed in operating system. In the first place his instrument was more sensitive, owing to the fact that he used a glass fibre and not a metal wire as a detector. Secondly, the physical appearance of the two instruments was so different that there was no reason for Einthoven to think that his instrument would resemble Ader's galvanometer. Einthoven was upset by Edelmann's accusations and wrote a rather angry letter to Edelmann's firm, which cooled the relationship below zero. For Edelmann in turn this letter was reason enough to cancel the agreement. He had in any case made significant changes to Einthoven's design and no longer felt under any obligation to continue paying royalties. One of the main changes he had made was to replace the electromagnet with a permanent magnet, which made it possible to reduce the weight and size of the instrument.[36] He had secured legal protection in 1905 and started to sell the instrument under his own name.[37] After 1907 there was no further contact between the two parties and Einthoven was left disappointed.

It could be said that CSI took advantage of the situation. Although the competition remained, Einthoven was now closely linked with the English company as an adviser. With the approval of Einthoven, William duBois Duddell was appointed to convert the prototype into a marketable instrument. Duddell was a technical engineer working for CSI and during his career he would invent and re-design a number of scientific instruments. The changes Duddell made altered the look of the instrument. In the first place it became lighter and smaller. Einthoven's design contained a heavy electromagnet, which generated a great deal of heat. This heat affected the sensitivity of the string and in turn the measurements. The magnet therefore needed cooling. Einthoven had solved this problem by using a water-cooling device. This made the instrument even bigger and heavier. Duddell however was able to concentrate the magnetic field and to prevent its leakage. He was therefore able to use a smaller electromagnet that generated less heat and that did not need cooling. Second, Duddell invented a new string carrier that made it much easier to replace a broken string. If a string was broken, then the carrier could be taken out of the galvanometer and sent to the shop. A new string would be fixed into the carrier, which was then returned to the customer who could put it back into the galvanometer again. This extra service for the customer meant that the instrument became easier to use and therefore more attractive to purchase. Duddell's changes resulted in the first commercial string galvanometer model.

The first commercial instruments to be sold were marketed as physiological instruments. In 1905 a CSI instrument was sold to a physiological laboratory in Sheffield.[38] The whole system was mounted on a table, so that it was easier to install.

> You will be glad to hear that we have constructed one of your string galvanometers to Mr Duddell's design & the instrument behaves very satisfactorily. We have sold this to one of the leading Physiological Laboratories in this country. At the present time we are constructing a second instrument of the same design. You will observe that Mr Duddell has designed it so that the fibre itself is in a separate brass box & in this way if a fibre becomes [b]roken it is possible for the experimenter to return the vibrator [b]nox to the maker to have a new fibre fitted & returned without difficulty … .[39]

In its first advertisement CSI stressed that the instrument could also be used for purposes other than physiological research alone. The string galvanometer might prove its worth in any job where small, rapidly alternating currents had to be recorded. CSI wanted to reach a wider market than the physiological laboratories alone. Furthermore, a list of the first customers to buy the string galvanometer shows that the first models were not sold exclusively to physiologists or physiological institutions. Examples of such institutions are the Marconi Company, the Japanese Navy and the Institut Océanografique. These organisations probably used the galvanometer for telegraphic purposes. The similarities with Ader's string instrument are still remarkable at this point, especially when we think that Einthoven himself would go on to modify his original instrument and do several experiments with it as a telegraphic receiver during the First World War. Although the string galvanometer was produced and found its way to customers, it was not until the further development of the field of cardiology that the instrument became a predominantly medical instrument.

The above shows that CSI was convinced that Einthoven's prototype needed modification before it could be sold. Technicians were hired to take a closer look at the prototype and modify it into a sellable product. However, the difference between CSI and the Dutch firms was that the English company was able to find the time and the manpower to invest in the development of the prototype. Thanks to Darwin's personal intervention the financial risks involved in the development of the instrument were not an issue. The Cambridge academic climate had influenced Darwin so that inventing and designing were more important to him than making money.

Following the introduction of the first commercial cardiograph Einthoven stayed in touch with the company until 1919. After 1905 most of the letters are from CSI confirming how many cardiographs they had sold. There is hardly any discussion of technical details or innovations. In fact, following the introduction of the first commercial models, it was no longer Einthoven who was responsible for the development of the string galvanometer or cardiograph, as the instrument had now become known. It was another giant in the history of cardiology who would take the cardiograph out of the laboratory and into the hospital, thus taking the development of the cardiograph one step further.

It was Thomas Lewis (1881–1945) who would demonstrate the clinical benefits of the cardiograph as a diagnostic tool. Lewis received his medical education at University College Hospital in London and graduated in 1905. Two years later he was appointed to the staff of the City of London Hospital and worked in the laboratory of Professor E. H. Starling at University College London. A year later he met James Mackenzie, already a well-known specialist in heart disease. He encouraged Lewis to contact Einthoven. In 1909 Lewis visited Einthoven in Leiden and this would mark the beginning of their lifelong friendship. That same year Lewis had purchased an Edelmann galvanometer and had installed it in the basement of University College Hospital in London.

The two men corresponded about technical difficulties they had with the string galvanometer. For instance, they discussed what the right adjustments were for the resistances for the apparatus or they exchanged views about the interpretation of the ECGs they had each obtained. Because Lewis had access to patients, unlike Einthoven, he was able to do more pathological research than Einthoven was able to do, although Einthoven did perform a clinical trial when he connected his laboratory to the academic hospital in Leiden.[40] However, Einthoven would never do such clinical research again once this experiment ended. Lewis, however, was just at the beginning of his cardiological career. Two years after he started to work with the string galvanometer he published his famous monograph on *The Mechanism and Graphic Registration of the Heartbeat*.[41] For decades this publication would be the textbook for young generations of cardiologists. Lewis became most famous for his work on a disease called 'soldier's heart.' During the Great War, many British soldiers suffered from irregular heartbeats. Lewis used the cardiograph to investigate the conditions of these soldiers. Between 1916 and 1918 he produced some 10,000 ECGs,[42] five times more than Einthoven made in his whole career.[43] Lewis was able to make so many ECGs because in 1916 he worked with apparatus that had now been tested and adjusted to clinical practice.

Between 1912 and 1915 Lewis cooperated with CSI technician Bernard A. Robinson.[44] Together they continued the development of the Cambridge cardiograph to make it fit for clinical use. Robinson was sent by Horace Darwin to work with Lewis in the hospital for one day a week. As Robinson had visited Einthoven in his laboratory in 1907, he had technical knowledge of the capabilities of the instrument. Lewis, however, provided the input from clinical practice, so he could make adjustments to the instrument. One of the inventions Robinson applied to the cardiograph was the use of silver-plated glass fibres instead of the quartz fibres Einthoven used. These strings were easier to produce. The production of new strings that were easier to make was a subject that was discussed in detail by Einthoven and Robbert S. Whipple of CSI. In 1915 the cooperation between Lewis and Robinson ended owing to Lewis's wartime activities at the Military Heart Hospital in London. It was during these investigations that the cardiograph established its clinical use for the first time.

The Return to Siemens & Halske

Having initially turned down Einthoven's offer in 1902, Siemens renewed its interest in the instrument when the company read about Einthoven's experiments in the *Nord Deutsche Algemeine Zeitung* No. 153 of 3 July 1907.[45] In this article Einthoven's instrument was described as a machine that enabled doctors to make graphical representations of the human heartbeat. Einthoven's telecardiographic experiment was also mentioned at the end of the article. Einthoven had performed this experiment in 1906 in cooperation with the physician Nolen of the academic hospital in Leiden. A patient at the academic hospital was connected to the string galvanometer in Einthoven's laboratory by means of a telegraphic wire. Readable electrocardiograms were successfully taken. It enabled Einthoven to read an ECG without moving the string galvanometer to the hospital or the patient to his laboratory. Using a telephone connection from his laboratory Einthoven was able to tell Nolen about any heart irregularities as he stood at the patient's bedside feeling his or her pulse. The results were promising and seemed to establish the diagnostic value of the cardiograph as a clinical tool, were it not then for a financial dispute that caused Nolen to pull the plug on the experiment. It is said that Nolen was afraid that all the scientific honour would go to Einthoven and not to him.[46] He refused to pay his half share of the maintenance costs of the telegraphic cable. Einthoven published the results of this experiment in *Archives internationales de physiologie* and that was the end of the experiment.[47]

It was Dr P. Rasehorn, head of Siemens's Wernerwerk, the department for measuring devices, who read the newspaper article and wrote to Einthoven telling him that he knew that the string galvanometer was used for physiological research and that these instruments were manufactured by the firm of Edelmann in Germany. Shortly after this letter Rasehorn visited the Netherlands for business reasons and arranged a meeting in Leiden at which Einthoven showed him around his laboratory. The two men spoke of possible cooperation. Einthoven was still interested but in the light of the experience he had gained from his contacts with CSI and Edelmann he had two demands:

> …
>
> 1. dass Sie das Galvanometer nur unter meinem Namen ankundigen und verkaufen das ist die Hauptsache und,
>
> 2. dass Sie mir für das Galvanometer und eventuell auch für einige der Registrierapparate [Santiomen] bezahlen. Wenn Sie 10% nicht zu hoch finden, so möchte ich diesen Betrag wohl empfangen …[48]

Siemens replied that it welcomed Einthoven's offer, but that a patent on the instrumentation was crucial for the company. It would not be until this matter was resolved that the company would take the string galvanometer into production. Siemens was already involved in manufacturing the photographic part of Einthoven's configuration. It provided the photographic equipment for the string galvanometer for the *Gesellschaft für drahtlose Telegraphie*.[49] The centrepiece of the installation however was an Edelmann string galvanometer. Siemens would clearly have liked to produce the whole set. In this letter the company mentioned that it wanted to develop Einthoven's instrument further as a telegraphic instrument. Although Rasehorn knew that the string galvanometer was used in physiological/medical practice, Siemens was not yet convinced that the way Einthoven had designed the instrument would make it suitable for these applications. The development of the string galvanometer was clearly not the company's priority because it was clear from a letter in 1909[50] Siemens had paid little attention to the further development of the machine. Thus far they had focused only on the peripheral optical devices. After this letter it would be another two years before Einthoven and Siemens corresponded again about the string galvanometer.

In 1911 there was a remarkable change in the company's direction when Rasehorn renewed contact with Einthoven about the string galvanometer. He asked Einthoven if he would be able to send his first German articles in which Einthoven had described the medical applications of the string galvanometer. Einthoven sent Rasehorn the two articles requested.[51] The first article described how the string galvanometer could be applied in physiological research and how it could replace the Lipmann electrometer. The second article contained more electrocardiographic images and had a more clinical/pathological content.

The fact that Rasehorn had asked Einthoven to send these articles suggests that Siemens was no longer developing the string galvanometer for telegraphic purposes: its interest had shifted towards medical/physiological applications. In December 1911 Rasehorn invited Einthoven to visit the Wernerwerk in Berlin. There he was able to see with his own eyes the progress that was being made with the development of the cardiograph. It was the first time in the correspondence that the company did not call its instrument *Saitengalvanometer* (the German for string galvanometer) but cardiograph, an instrument that, as the name implies, is used to make graphical registrations of the heartbeat. This is another indication that Siemens had shifted its focus from telegraphic to medical applications.

After Einthoven's visit to Berlin the two parties discussed legal aspects. For Siemens legal protection for their innovations was a critical factor. Siemens wanted to know from Einthoven if he had any patents. Einthoven had no legal protection owing to the absence of a patent law in the Netherlands at the time he developed the string galvanometer. In 1910 however a new patent law had passed through parliament and Einthoven might well have been keen to find out whether he could still obtain a patent on his instrument. Einthoven had to know if anyone else had obtained legal protection in Europe. It might have been that Einthoven expected Edelmann to own the patent rights and he therefore asked Siemens if a list of all the German patents could be sent to him.[52] Einthoven was sent a list of all the patents on the cardiograph and its peripherals[53] with the comment that patent D.R.P 214165, Treptow/Berlin, owned by August Leib, would be particularly relevant to Einthoven.

> … Von besonderem Interesse für Sie wird das Patent 214165 von Aug. Leib sein. Wie sie aus der in der Aufstellung verzeichnete Notiz ersehen werden, ist es nicht unwahrscheinlich, das dieses Patent garnicht zu Recht besteht. Es kommt lediglich darauf an, von welchem Tage die ersten druckschriftlichen Veröffentlichungen (Abhandlungen, Preisliste, Prospekte) über die bei der Cambridge Scientific Instrument Co. angefertigten Galvanometer datieren. Ich sehe mit grossem Interesse Ihrer diesbezgl; Mitteilung entgegen. Sollte evtl. das Patent nicht zu Recht bestehen, so werde ich über die Persönlichkeit des Patentinhabers, der mir sonst unbekannt ist, nähere Erkundigungen einziehen.[54]

The patent Siemens mentions was taken out on the operating principle of the string galvanometer and the only way to undermine Leib's legal protection was to prove that printed price lists, catalogues and/or descriptions of the string galvanometer had been published in Germany before 29 March 1908. Ironically, the best hand was held by CSI. Becausee the company had been the first to produce the Einthoven string galvanometer, it was not unreasonable to assume that it had distributed printed matter not only in England but also in Germany. As a competitor, Siemens & Halske could not itself find out if CSI had distributed such publications, but it would be very convenient for Siemens if Einthoven could do some research and try to find such publications. If the search proved successful, Leib's patent would no longer be valid. Einthoven used his links with CSI to establish that CSI had indeed sold instruments to Germany before this date:

> Die Cambridge Com (sic) erwittert mir auf meine Anfrage, dass sie schon ihn erstes Exemplar von festen Anschlagen […] Einstellvorrichtung verkauft haben. Dieses erste Exemplar wurde Oktober 1905 abgeliefert. In December 1905 wurde ein anderes Exemplar an der Ausstellung der 'Physical Society' London gezeigt. Weitere Exemplaren wurden dem 6. März 1906 und dem 28 Januar 1908 geliefert. Zwar wurde das erste Preisverzeichnis in Mai 1908 publiziert, aber die Comp. hatte schon vor diesem Datum eine grosse Anzahl von Beschreibungen des Instruments verbreitet. (sic) Abgleich die Comp. mir das nicht nachdrücklich schreibt, so glaube ich doch, das diese Beschreibungen gedruckt waren. Warum daran gezweifelt wird, so kann ich aber (sic) abermals ums Nachricht bitten.[55]

Initially the prospects of Einthoven and Siemens being able to undermine Leib's patent looked good. CSI had distributed descriptions of the cardiograph before March 1908 and had sold a number of instruments. Unfortunately, sold instruments did not count, even if they had been sold before 29 March 1908. At the same time the descriptions distributed in 1906 did not have the legal power to undermine the patent because they were not printed but typed on a typewriter. This meant that Siemens would not be able to undermine Leib's patent:

> Da, wir aus Ihren geschätzten Schreiben ersehen, keine druckschriflichen Veröffentlichungen über das Saitengalvanometer der Cambridge Scientific Instrument Co. vorliegen, die vor dem 29. Märtz 1908 erschienen sind, so werden sie auch nicht in der Lage sein, gegen das deutsche Patent Nr. 214165 Stellung zu nehmen ….[56]

This letter demonstrates that by mid-1913 Siemens had two reasons for abandoning the string galvanometer for a second time. Being able to take out patents on Einthoven's instrument was a cardinal point for them. The seed for this company policy had been planted by Werner von Siemens himself. In his younger years the Siemens founder had experienced the loss of one of his own inventions, the cordite explosive, to another scientist who gained the scientific credit for it. Later in life he would actively try to apply political pressure to establish a more effective legal system for the protection of inventions.[57] This might account for the company's culture being so focused on gaining legal protection for the string galvanometer. The other reason was that, in more recent times, Siemens had developed another type of cardiograph that seemed to be a more marketable product:

> … Wir hatten auf der Kongressausstellung einen Elektrocardiographen ausgestellt und im Betriebe vorgeführt und konnten dabei konstatieren, dass für das Spiegelgalvanometer eine besondere Vorliebe besteht ….[58]

Siemens demonstrated its own cardiograph at the 4th Congress for Physiotherapy. The system Siemens referred to was a mirror galvanometer. Instead of a thin string, a light mirror attached to an electric coil was used as a detector. A light beam was reflected in the mirror and cast onto a scale or photographic paper. This instrument was nothing new: mirror-type galvanometers had been produced and sold in 1907.[59] At the same time Siemens's experience with the production of oscillographs (instruments capable of detecting and recording alternating currents) and the development of photographic equipment supported the development of a new model of cardiograph. Galvanometers of this type had also been tested by Einthoven before he constructed the string galvanometer, but in Einthoven's opinion the mirror galvanometer could not meet his demands for the application of the instrument in his physiological research. It turned out that Einthoven's instrument had lost the competition with this other galvanometer because the mirror type suited Siemens better, since it probably owned the legal rights for the mirror type and it was already producing the peripheral photographic equipment.

This letter brought an end to the correspondence between Einthoven and Siemens on the subject of the string galvanometer. Siemens published a new catalogue for its medical instrument range in 1913 that included its own cardiograph.[60] Einthoven's work on the development of the string galvanometer did merit a mention in the introduction to this catalogue, but there was also reference to the drawbacks of the heavy and bulky design of his type of cardiograph. This first type of cardiograph marked the beginning of Siemens's technological involvement in the field of cardiology.

Conclusion

The process discussed in this paper focuses on how the first stage of the development of the electrocardiograph from prototype to first commercial instrument was shaped. The correspondence between Einthoven and manufacturers shows that two important factors played a major role. Both the expectation of the different parties and the personal decisions of the main players were the key elements responsible for the direction of the technological pathway of the development of the string galvanometer. The Einthoven correspondence demonstrates that instrument makers played an important role in the choices made. It appeared to be important that Einthoven's knowledge of the instrument was coupled to the skills of the technicians. Additionally, Einthoven realised that he needed instrument makers to produce his string galvanometer in large quantities. In the relationship between Einthoven and technicians, communication was a crucial point. It was Einthoven himself who took the string galvanometer out of his laboratory and into the factory. He was able to find manufacturers who might be interested in his instrument and he also spoke the same technical language as the technicians. This was one of Einthoven's unique capabilities: he could combine clinical, experimental physiological and technical knowledge. Although trained as a clinician, he can be placed in the experimental physiological tradition of scientists such as Donders, Du-Bois Reymond and Waller. He received visits from technicians and explained the electrical principles of his instrument in his laboratory. Examples include Rasehorn from Siemens and Robinson from CSI. These technicians brought this new knowledge back home with them and applied it in their own specific settings. This made Einthoven an intermediary between the laboratory and the instrument maker.

In the light of the communication between Einthoven and instrument makers it is interesting to note that the first article he wrote on the invention of the string galvanometer could be read in different ways. When Einthoven approached the company for the first time, Siemens, for instance, saw the instrument as an electronic measuring tool, just another type of galvanometer. CSI immediately acknowledged the physiological possibilities but also foresaw other applications for the instrument. It is not very clear how the Dutch instrument makers saw the string galvanometer. It could be that Van Huffel regarded it as a scientific physiological instrument. This would probably have been because Einthoven pushed Van Huffel into the academic physiological world by mentioning the physiologist Engelmann. These different opinions were decisive in the initial phase of galvanometer development. They were responsible for the direction in which the apparatus was developed. It was not until Einthoven published his article about the *telecardiographic experiment* in 1906 that Siemens saw the telegraphic potential of the string galvanometer. Siemens was looking for a telegraphic instrument because it was in keeping with the company's product range. It would not be until 1911 that, because of a newspaper article, Rasehorn became interested in the medical applications of the instrument.

If the first impression of the instrument was the main reason why a company would or would not be interested in the first place, secondary reasons were in the end decisive for what kind of instrument would be developed. Secondary reasons for Siemens's decision not to produce the string galvanometer were the inability to acquire patents on the string galvanometer and the availability of an alternative instrument. Siemens's unsuccessful attempts to acquire the patent to Einthoven's invention meant that the firm had no protection from plagiarism. Apart from the legal protection, another argument was the in-house development of the mirror-type cardiograph, which resulted in an instrument that was a direct competitor to the string galvanometer. This mirror-type galvanometer was a lighter and smaller product and Siemens was already selling this type of instrument. The time-consuming investments in Einthoven's bulky design to make it into a sellable instrument were probably the reason why Siemens finally chose the mirror galvanometer.

For the Dutch firms there were other secondary reasons why they would not or could not produce the instrument. For Van Huffel of NIF the financial risks were too great. For Giltay the further development from prototype to an actual sellable instrument would have been too time-consuming, and apart from the high start-up costs, there was, according to these Dutch instrument makers, no immediate market for it.

For CSI the financial risks were no reason for dropping the idea of producing the string galvanometer. It was probably Horace Darwin's enthusiasm for Einthoven's design that made him decide to produce it anyway, whether or not it would make money. One reason for this decision might have been that such high-standard laboratory equipment would have added to the prestige of Darwin and his company. At the same time the company's close cooperation and entrenchment in the academic experimental physiological world made the connection to their customers much easier, especially in the second phase, when the string galvanometer escaped the laboratory and found its way into the clinic. The relationship CSI had with Lewis made the company perfectly equipped to meet the demands of daily clinical practice.

Judging by the correspondence between Einthoven and the instrument makers, it is safe to say that even though Einthoven designed a physiological measuring device, resulting from a specific quest for technical solutions for the measurement of bioelectrical phenomena that could not previously be measured, it was not received as such by all instrument makers. With the development and application of this instrument in his research, Einthoven further defined the function of his instrument. Before it became a practical and easy-to-use research instrument, it needed the input of skilled technical instrument makers before physiologists and early cardiologists were able to use it in daily practice in clinical settings. It was not until the string galvanometer escaped from the laboratory into the clinic that the instrument was established as a cardiograph. The work of Thomas Lewis preceded the next phase, the phase in which the cardiograph was accepted as a clinical diagnostic tool, but this status would not be established until after World War II.

Notes

[1] Einthoven, 'Un nouveau galvanomètre.'

[2] Lawrence, 'Moderns and Ancients,' 1–33.
[3] Burnett, 'The Origin of the Electrocardiograph as a Clinical Instrument,' 62.
[4] Burch, 'The Development of the Electrocardiograph,' 31.
[5] Snellen, *Willem Einthoven* (*1860–1927*), 114.
[6] Einthoven, 'Un nouveau galvanomètre.'
[7] Einthoven, 'Le télecardiogramme,' 239–72.
[8] Einthoven, 'Un nouveau galvanomètre.'
[9] Museum Boerhaave Leiden, Arch. 61L (MB61L). Letter from Einthoven to Siemens & Halske, 3 January 1902.
[10] Von Siemens, *Mijn leven*, 48.
[11] Feldenkirchen, *Siemens 1818–1945*, 370.
[12] MB61L. Letter from Einthoven to Siemens & Halske, 13 September 1900.
[13] MB61L. Letter from Siemens & Halske to Willen Einthoven, 21 January 1902.
[14] Mooij, *Instrumenten*, 151.
[15] This is indicated by the fact that Einthoven refers to earlier correspondence between him and Van Huffel: MB61L. Letter from Einthoven to Van Huffel, 4 December 1902. '… Nu wenschte ik den toestel te beschrijven en zou aan de beschrijving gaarne willen toevoegen, dat men het bij die en die firma kan verkrijgen. Ik kom dus weder bij u terug en ben bereid een redelijk voorstel Uwerzijds, zooals in Uw brief van 22 april 1901 vervat aan te nemen.'
[16] MB61L. Letter from Van Huffel to Einthoven, 11 December 1902.
[17] As a matter of reference, Einthoven's honorarium as a professor in physiology at the time was 6000 guilders per annum.
[18] MB61L. Letter from Einthoven to Van Huffel, 24 April 1903. '… Wel is waar is Uw firma nog jong en zijn Uw relaties niet talrijk, zoodat gij wel veel risico ziet in het leveren van 20 exempl. maar daar staat toch tegenover, dat gij door middel van het instrument naar alle waarschijnlijkheid met een aantal Nederlandsche en wellicht ook met enige buitenlandsche laboratoria in relatie komt, wat juist voor een jonge firma als de Uwe van groote betekenis is.'
[19] Van der Spek, 'Jan Willem Giltay.'
[20] Mooij, *Instrumenten*, 112.
[21] Giltay, *Geïllustreerde Prijscourant*.
[22] MB61L. Letter from J. W. Giltay to Einthoven, 23 November 1903. ' … Het spijt me zeer dat ik er niet aan kan beginnen. Ik vind het een zeer interessant instrument, maar ik heb er werkelijk geen tijd voor, ik heb zooveel nieuwigheden onder handen, die minder hoofdbrekens en waarschijnlijk meer geld zullen opleveren, dat ik niet anders kan doen dan u bedanken voor 't in mij gestelde vertrouwen.'
[23] Einthoven, 'Galvannometrische registratie van het menselijk electrocardiogram,' 101.
[24] For instance, Einthoven published in the *Nederlands Tijdschrift voor Geneeskunde*; no other authors can be found on the subject of electrophysiology in this journal at the beginning of the 20th century.
[25] Cattermole, *Horace Darwin's Shop*, 74.
[26] Cattermole, *Horace Darwin's Shop*, 54.
[27] Burnett, 'The Origins of the Electrocardiograph.'
[28] MB61L. Letter from CSIC to Einthoven, 18 December 1903.
[29] MB61L. Letter from CSIC to Einthoven, 25 November 1903.
[30] MB61L. Letter from Einthoven to the Cambridge Scientific Instrument Company, 24 January 1904.
[31] MB61L. Letter from Einthoven to the Cambridge Scientific Instrument Company, 20 January 1904.
[32] Mooij, *Instrumenten*, 38. The Dutch government abolished the patent laws to encourage the free market system. Doorman, 'Het Nederlandsch,' 49.
[33] MB61L. Letter from CSI to Einthoven, 29 January 1904.
[34] MB61L. Letter from Edelmann to Einthoven, 12 February 1907.

[35] Einthoven, 'Un nouveau galvanomètre.'
[36] Edelmann sales catalogue, 1906, Katalog-Samlung, Deutsches Museum.
[37] Snellen, *Willem Einthoven* (*1860–1927*), 116.
[38] MB61L. Letter from CSI to Einthoven, 9 November 1905.
[39] MB61L. Letter from CSI to Einthoven, 30 October 1905.
[40] Einthoven, 'Le télecardiogramme.'
[41] Lewis, *The Mechanism of the Heartbeat*.
[42] Lawrence, 'The New Cardiology,' 31.
[43] Grob, The laboratory equipment of Willem Einthoven. 2000 glass negatives of Einthoven's ECGs are preserved in the Museum Boerhaave collection.
[44] Hollman, *Sir Thomas Lewis*, 43.
[45] Letter from Siemens to Einthoven, 17 September 1907.
[46] Borck, 'Hertzstrom,' 81.
[47] Einthoven, 'Le télecardiogramme.'
[48] MB61L. Letter from Einthoven to Siemens & Halske, 20 September 1907. Einthoven demanded that the string galvanometer be sold under his name and that he be paid a 10% royalty per instrument sold.
[49] MB61L. Letter from Siemens & Halske to Einthoven, 27 November 1908.
[50] MB61L. Letter from Siemens & Halske to Einthoven, 23 December 1909.
[51] Einthoven, 'Die galvanische Registrierung'; Einthoven, 'Weiteres über das Elektrokardiogramm.'
[52] MB61L. Letter from Einthoven to Siemens, 23 January 1913.
[53] MB61L. Letter from Siemens & Halske to Einthoven, 13 February 1913.
[54] MB61L. Letter from Siemens & Halske to Einthoven, 17 February 1913. 'Aug. Leib's Patent 214165 would be of your special interest. As you can read in the note, it is not impossible that that patent is not legal at all. The point is, what is the date of the first printed publications (transactions, price lists, prospectus) dealing with the galvanometers produced by the Cambridge Scientific Instrument Co. I look forward to your answer. If the patent is not legal then I will inform you about the patentee, who so far is unknown to me.'
[55] MB61L. Letter from Einthoven to Siemens & Halske, 7 March 1913. 'The Cambridge Com. informed me that they have sold their first table model. This piece was delivered in October 1905. In December 1905 another model was demonstrated at the exhibition of the "Physical Society" in London. More models were sold on the 6th of May 1906 and the 28th of January 1908. Although the first price list was published in May 1908, the company has spread a large number of descriptions of the instrument before this date. Although the company does not emphasise that these descriptions were printed, I do believe that these were printed. If there are doubts I can ask about it.'
[56] MB61L. Letter from Siemens & Halske to Einthoven, 11 April 1913. 'Because we can make up from your letters that there are no printed publications about the string galvanometer of the Cambridge Scientific Instrument Co., which were printed before 29th of March, we are not in a position to take out legal steps against the German patent no. 214165.'
[57] Von Siemens, *Mijn leven*.
[58] MB61L. Letter from Siemens & Halske to Einthoven, 11 April 1913. 'We have demonstrated a working cardiograph at the conference and observed that there was a special predilection for the mirror galvanometer.'
[59] Smithsonian Museum of American History, Trade catalogue, The Scientific Shop, Siemens & Halske Galvanometers Deprez-d'Arsonval System. Available from http://www.si.edu/digitalcollections/trade-literature/scientific-instruments/files/52568 (accessed 7 June 2005).
[60] Siemens & Halske, *Preisliste*.

References

Borck, C. 'Herzstrom, Zur Dechiffrierung der elektrischen Sprache des menschlichen Herzens und ihrer Übersetzung in klinische Praxis.' In *Die Normierung der Gesundheit: Messende Verfahren der Medizin als kulturelle Praxis. Abhandlungen zur Geschichte der Medizin und der Naturwissenschaft*, no. 82, edited by Volker Hess. Hussum: Matthiesen Verlag, 1997.

Burch, G. E. 'The Development of the Electrocardiograph.' In *A History of Electrocardiology,* edited by G. E. Burch and N. P. De Pasquale. San Francisco: Norman Publishing, 1990.

Burnett, J. 'The Origin of the Electrocardiograph as a Clinical Instrument.' In *The Emergence of Cardiology. Medical History*, Supplement, no. 5. London: Welcome Institute for the History of Medicine, 1985.

Cattermole, M. J. G and Wolfe, A. F. *Horace Darwin's Shop: A History of the Cambridge Scientific Instrument Company.* Bristol: Adam Hilger, 1987.

Doorman, *Het Nederlandsch octrooiwezen en de techniek der 19^{e} eeuw*. The Hague: Martinus Nijhof, 1947.

Einthoven, W. 'Galvannometrische registratie van het menselijk electrocardiogram.' In *Herinneringsbundel Rosentein*. Leiden: IJDO, 1902.

Einthoven, W. 'Die galvanische Registrierung des menschlichen Elektrokardiogramms, zugleich eine Beurtheilung der Anwednung des Capillar-Elektrometers in der Physiologie.' *Archive für gesammte Physiologie* 99 (1903).

Einthoven, W. 'Le télécardiogramme.' *Archives internationales de physiologie,* 4, no. II (1906): 132–64.

Einthoven, W. 'Un nouveau galvanomètre.' *Archives Neerlandaises Des Sciences Exactes et Naturelles,* 6 (1901): 625–33.

Einthoven, W. 'Weiteres über das Elektrokardiogramm.' *Pflügers Archive für gesammte Physiologie* 122 (1908): 517–84.

Feldenkirchen, W. *Siemens: von der Werkstatt zum Weltunternehmen.* Münster: Piper Verlag, 2003.

Giltay, J. W. *Geïllustreerde Prijscourant van chemische en pharmaceutische toestellen: P.J. Kipp & Zonen, J.W. Giltay, Opvolger.* Delft: J.W. Giltay, 1891.

Grob, B. W. J. 'The Laboratory Equipment of Willem Einthoven.' Leiden: Museum Boerhaave, 2004.

Hollman, A. *Sir Thomas Lewis: Pioneer Cardiologist and Clinical Scientist.* London: Springer Verlag, 1997.

Lawrence, C. 'Moderns and Ancients; The New Cardiology in Britain 1880–1930.' In *The Emergence of Cardiology. Medical History,* Supplement, no. 5. London: Welcome Institute for the History of Medicine, 1985.

Lewis, T. *The Mechanism of the Heartbeat.* London: Shaw & Sons, 1911.

Mooij, J. *Instrumenten, wetenschap en samenleving: geschiedenis van de instrumentenfabricage en –handel in Nederland 1840–1940.* Soest, 1988.

Siemens & Halske. *Preisliste 52 elektromedizinische Apparate. 8. Teil Elektrokardiograph.* Berlin: Siemens & Halske, 1913.

Snellen, H. A. *Willem Einthoven (1860–1927). Father of Electrocardiography: Life and Work, Ancestors, and Contemporaries.* Dordrecht: Kluwer Academic, 1995.

Van der Spek, T. 'Jan Willem Giltay: An Instrument Maker at Work in the Early 20th Century.' *Scientific Instrument Society Bulletin,* 70 (2001): 28–32.

Von Siemens, W. *Mijn leven.* 's Gravenhage: Uitgeverij Boot, 1942.