Instrumentation and the Rise of Modern Physiology

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The rise of experimental physiology has received much attention in the last thirty years from both historians and sociologists of science. Close analysis of the rapid institutionalization and professionalization of this field, as it occurred especially in Germany, has provided an important case study of the social, economic and political factors that enhance the development of autonomous scientific fields.[1] The spread of experimental physiology and its supporting institutions from Continental Europe to Great Britain and North America has also been discussed recently in much detail by historians.[2] However, despite intensive scholarly activity, few have been able to link persuasively the social and intellectual features of this rising discipline.[3]

This paper suggests that laboratory instrumentation can provide important insights into the changing intellectual and social structure of science in the late nineteenth and early twentieth centuries. Instruments have afforded not only new conceptual foci for investigators but also the material culture which has shaped experimental design and laboratory practice as professionalization and institutionalization have occurred. Recording instruments, particularly, have shaped the way scientific data are presented, discussed and accepted. The role of this instrumentation in the intellectual and social changes associated with the rise of experimental physiology and other autonomous sciences has yet to be explored systematically. This paper suggests that close study of research instruments introduced by physiologists in the 1840s and 1850s can provide valuable data with which to discuss social and intellectual linkages in all their richness and depth.

Specifically, the incorporation of the recording drum or "kymograph" into physiology in the late 1840s led immediately to the study and analysis of a wide range of physiological events that had previously been inaccessible to researchers.[4] Emulating the experimental approach of physical scientists, physiologists after 1850 increasingly sought to measure as well as describe physiological processes. This approach was readily assimilated and popularized through the use of recording apparatus, relatively simple instrumentation that made rapid and thus invisible physiological processes visible. Following the path set by the "1847 group" in Germany, experimental physiologists endeavored to formulate general laws and to predict physiological phenomena.[5] In this manner, they achieved a vast extension of the range of events capable of being studied within physiology. Registration instruments effectively opened new physiological events and processes to analysis, particularly those which occurred very rapidly or very slowly. Such instruments both extended the senses of observers allowing them to analyze previously undetected phenomena, and at the same time ostensibly removed the observer from intervening in the measurement of physiological events.[6] As a consequence, researchers could and did claim a new level of objectivity for their science—an important goal in the life sciences at this historic time.

The first physiological events to be recorded were related to blood pressure. Self-registration of changing blood pressure by translation of motion from a mercury manometer to a recording stylus resulted in the autographing of transient events that previously could not be seen or measured. The obvious utility of such analysis led to the rapid incorporation of recording apparatus into research protocols. Investigators modified the recording drum and its accessory apparatus to measure a wide variety of events. They and their successors also adopted this new method of physiological analysis, self-registration, to meet the practical needs of the clinic. The measurement of each heretofore little understood physiological event was explicitly linked to the expectation that such data would prove to be of diagnostic value in detecting and monitoring disease.[7]

Physiology subsequently gained new social authority both in science and in medicine through the application of recording instrumentation. Physiologists could claim objective, quantitative analysis of a given event. They also argued that the data generated by registration instruments could lead to the diagnosis, monitoring and more effective treatment of disease. While such claims

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My appreciation of these issues has been especially enhanced by the comments, criticisms and suggestions of Adele Clarke, Deborah Coon, H. Hughes Evans, Gail Hornstein, Peggy Kidwell, Robert R. Pool, Jr. and John Harley Warner. This research was supported by a grant from the National Science Foundation (RII-8503650) through its Visiting Professorships for Women program.

Science & Technology Studies 5(2):53-62, 1987

were certainly premature in the 1850s and 1860s, the new methodology of physiologists seemed at that time to be applicable both at the laboratory bench and at the bedside. The historian can follow the adaptation of these instruments from their invasive laboratory forms to their non-invasive clinical counterparts and watch in the process the transformation of experimental physiology from a specialized research activity conducted in small ill-equipped rooms to an important teaching and research activity supported by a vast array of apparatus and instruments in medical schools. The claims of both objectivity and utility were fully exploited by advocates of the experimental approach although both of these claims were challenged throughout this period.

By the turn of the twentieth century, kymographic recording apparatus had become the central tool of physiological analysis and the symbol of a new style of pedagogy especially in American medical schools.[8] This style, which can be observed in texts and handbooks produced between 1890 and 1910, was marked by an ever-increasing emphasis on hands-on laboratory experience for introductory students. Students were explicitly trained in an analytical method, as well as in a subject. Registration apparatus thus transformed physiology both intellectually and socially, helping physiologists to secure their place within medical academia. It is the purpose of this paper to explore this transformation, suggesting points of interaction and intersection between cognitive and institutional factors that might in the future be fruitfully studied by sociologists and historians interested in the growth of science.

Introduction of New Instruments

Physiologists traditionally mark the birth of modern physiology with the work of Carl Ludwig (1816-1895), especially his introduction in the winter of 1846-47 of the "kymographion" or revolving drum recorder into physiology.[9] Ludwig's technical innovations in the measurement of blood pressure were to have far-reaching consequences both for the content of physiological data and how physiologists viewed that data. Important conceptual and cognitive changes appeared as a result of the widespread use of registration apparatus in the period 1850-1870, that is, in the period historians usually associate with the rise and institutionalization of Continental physiology.

Ludwig initially wanted to examine the relationship between blood pressure and respiratory movements.[10] This was difficult to do because blood pressure, as read from a manometer attached by catheter to a blood vessel of an experimental animal, was not stable. The level of mercury in the manometer oscillated and could not be read easily; it could only be approximated.[11] By placing a float on top of the mercury and attaching a stylus to the float, Ludwig could use a pen to register on the surface of a revolving drum the changing level of the mercury. The height of the excursion of the stylus bearing the pen indicated maximum pressure. The curves produced in this manner could be measured and compared with other curves, even those made by other investigators, minimizing individual differences. They could also be preserved indefinitely and correlated with other records produced under different experimental conditions. In other words, the experimental set-up could readily be manipulated to study changes in blood pressure under different physiological conditions. Ludwig was specifically interested in determining the effects of respiratory rates and pressures on arterial blood pressure.

Ludwig sought to obtain precise readings from his graphs, yet he recognized the scientific value of the curves themselves, especially when more than one event was recorded. Tübingen physiologist Karl Vierordt (1818-1884) exploited this pictorial presentation further. In order to provide physicians with a visual record of clinical signs that up until then could only be read by touch or palpation, he adapted the kymograph to monitor the external pulse rather than the blood pressure.[12] His instrument, which he called the "sphygmograph" or "pulse writer" was bulky, cumbersome, and poorly adapted for clinical needs. However, this difficulty was overcome by modifications made by a Parisian medical student who took up the problem in the late 1850s; Étienne Jules Marey (1830-1904) adapted Vierordt's device to make it more convenient, reliable and clinically useful.[13] Marey subsequently embarked upon a scientific career devoted to the extension of related research techniques.[14] He referred to these collectively as the "graphic method." In the 1860s and 1870s, he designed numerous registration instruments that produced graphic records of other physiological and pathological processes. These included: the cardiograph for registering movements of the heart (Marey created both internal and external probes for this purpose), the polygraph (to record various physiological processes), the pneumograph (for respiratory movements), the myograph (for neuromuscular events), the thermograph (to measure temperature changes), the electrometer (to monitor electrical changes), and the plethysmograph (to record volume change in limbs or organs). During his career of nearly fifty years, he popularized the use of mechanical, electrical, and photographic recording instruments in physiology, medicine, and biology.[15]

Marey's utilization of registration apparatus coincided with the extension of recording techniques into other physiological problem areas. In 1850, Ludwig's colleague and friend Hermann von Helmholtz (1821-1894) adapted graphic recording apparatus to measure the speed of nervous conduction. Helmholtz used the graphic record produced by contraction of an isolated muscle as an indication of response to a nervous stimulus, the time on the graph between stimulus and response being the period of time required for conduction.[16] Other physiologists and psychologists rapidly adapted Helmholtz's myograph to study nervous conduction,

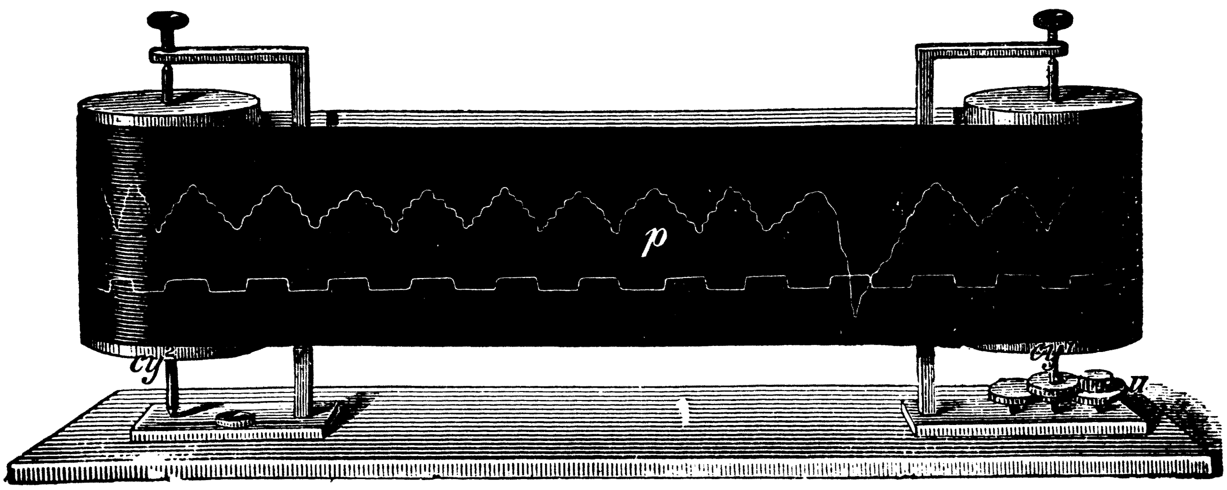

Figure 1. Continuous blood-pressure tracing on a long-paper kymograph [From Stirling, *Outlines of Practical Physiology*, 1902; reproduced courtesy of Charles Griffin & Co., Ltd.]

muscle contraction, muscular work, and reaction time. Marey, too, made many modifications of this apparatus in the 1860s and 1870s.

Thus, the simple act of recording rapidly transformed physiology from a primarily descriptive, vivisectional and anatomically-oriented activity to a quantitative experimental science. Concurring with the goals of physical scientists, physiologists increasingly and explicitly concerned themselves with the determination of biological laws and with the analysis of cause and effect in physiology. Yet, their initial preoccupation with quantification and precise measurement was gradually transformed. By the continued use of these instruments, an expressed desire to understand process and change within complex physiological systems emerged. As investigators recorded and correlated blood pressure, heart rate, nervous and muscular responses, they adapted the instrumentation to monitor these processes simultaneously. An intricate web of discrete events began to be studied using not only one or two but a whole series of levers and styluses. Long papers, held taut between two drums or a drum and roller, allowed for recording multiple phenomena over extended periods of time [Figure 1].[17]

Initially, use of the kymograph or "wave writer" opened up tiny periods of time and fleeting, transient events to measurement and analysis. However, by adjusting the speed of revolution of the drums, instruments could also be adapted to study very slight change over relatively long periods of time, as, for example, that evident in the process of plant growth [Figure 2].[18] This extended the perceptions and senses of observers even further into previously unobservable phenomena. The study of each new process required only slight modification of the transmitting and recording apparatus. The kymograph drum remained unchanged in principle, although Ludwig's drive by a falling weight was gradually replaced by clockwork and then by motor.[19] In the late nineteenth and early twentieth centuries, the possibility for electrical and electronic recording and eventually electronic translation of mechanical events was also realized. Twentieth century recording devices are but electronic transducers playing the same functional roles as their nineteenth-century mechanical ancestors.[20]

This registration technology derived from eighteenth- and nineteenth-century physics and meteorology. In 1878 in *La méthode graphique dans les sciences* *experimentales*, Marey described earlier instruments, including Morin and Poncelet's apparatus for inscribing the positions of a falling body and numerous meteorological instruments used in thermometry, barometry, hygrometry, and the measurement of rainfall and wind. Hoff and Geddes have attempted to define the precise intellectual connections between physiologists and physical scientists at the mid-nineteenth century, yet these cannot be reconstructed entirely, because it is clear that the basic elements of the kymograph (the recording drum or its analogue the recording disc), were in use and available by the 1840s.[21] A set of techniques was borrowed and a category of instruments adapted to meet the specific needs of physiologists. Investigators who sought to measure transient biological events with precision made use of this technology. What was not immediately evident in this process of adaptation of instrumentation from the physical sciences to the biological sciences was the tremendous intellectual and social transformations in laboratory organization and professional practice that would be set in motion by the introduction into physiology of these relatively simple instruments.

Cognitive Effects

The cognitive effects of the introduction of recording apparatus into physiology, and subsequently medicine and biology, were manifold and profound. Many of them were unanticipated. Initially, self-registration apparatus simply extended the senses of observers, making the invisible visible and allowing investigators to measure phenomena precisely. The motivations underlying these innovations in technique were, first, quantification *and*, second, elimination of the subjectivity of the observer from that process. Physiological investigators were explicitly following the experimental method so well developed by physicists and chemists. They wanted to discover the laws of a determined world. Visualization allowed precise measurement and eventual mathematical analysis of rapid, complex, interrelated events.

Registration instruments were remarkably adaptable. They were, in principle, infinitely expandable to the needs of researchers. First, the recording paper was lengthened; then it was replaced by a roll.[22] Drums were enlarged, then stacked one atop another.[23] Pneumatic transmission (of changing pressures) and eventually electrical and electronic transducers replaced direct mechanical connection between the event and the recording stylus.[24] Nonetheless, the principle remained the same: the event self-recorded on a revolving drum, the period of revolution generating the abscissa, plotting the event or position of the stylus against time. Graphic registration, graphic recording, or graphic inscription as Marey later called it, allowed the physiological event to autograph itself. The permanent record was made either by using ink on vellum paper (Ludwig), ink on paper, or most frequently by scratching a line on sooted paper. The curves were generated, measured, and stored for remeasurement. The event was thus quantified.

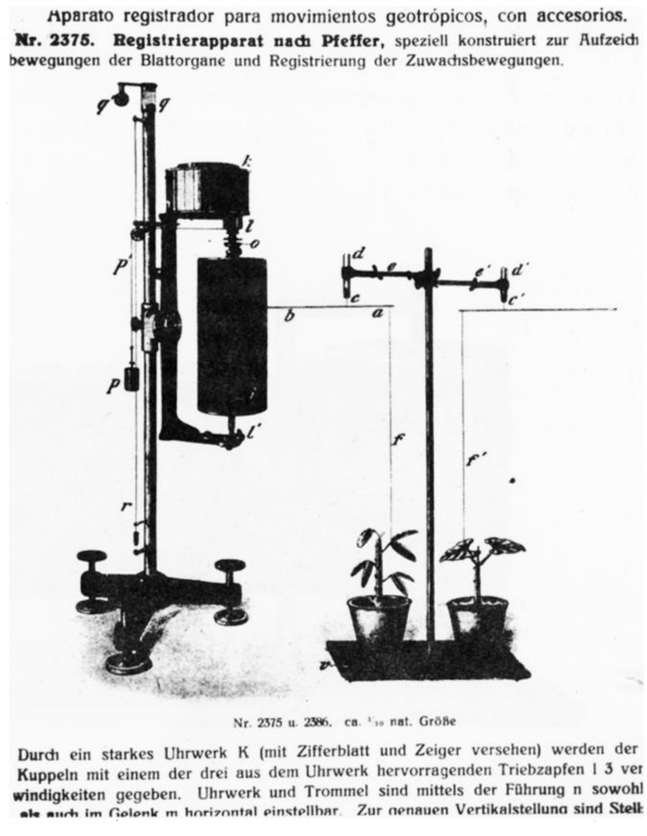

Figure 2. Recording apparatus modified for studying responses of sensitive plants (left) and plant growth (right) [E. Zimmermann catalogue, Leipzig, 1928; Smithsonian Institution Photo No. 86-10018].

Kymographic recording techniques effectively expanded or condensed perceived time frames, depending on the speed of rotation of the drum. All recorded events were timed by the drum's forward motion and by a time marker or chronograph, often a tuning fork in the early investigations. Rapid movement of the drum spread out the event and made minute fluctuations visible; slow movement of the drum condensed the event accentuating rhythm, rate or gradual change. Rapid events and small time intervals were thus brought to the visible range in ways analogous to microscopic enlargement. Slow events and longer time intervals were condensed in ways analogous to the telescope bringing the distant into view. In all cases, the event recorded itself, eliminating the "subjective" intervention of the observer, the "personal equation" that so troubled nineteenth-century astronomers, physicists, physiologists, and psychologists.[25]

In this process the graph itself effectively became the phenomenon to be analyzed.[26] The tracing could be measured and evaluated at leisure, long after the original event was recorded. Marey emphasized, following

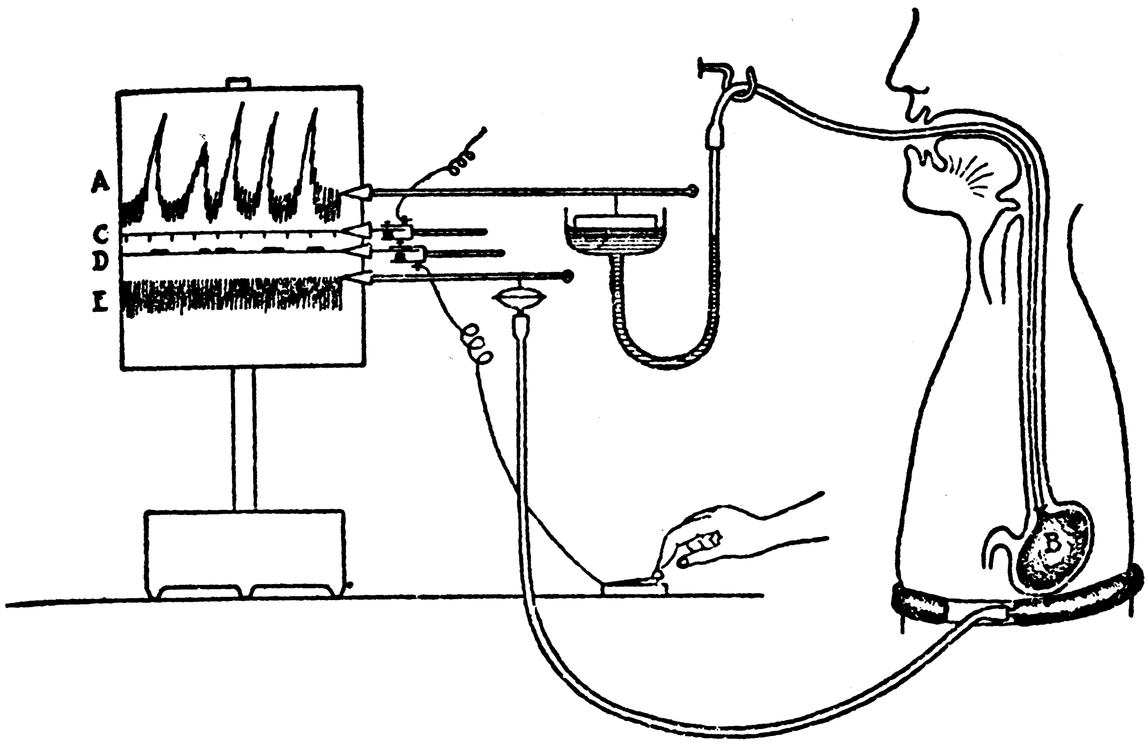

Figure 3. Simple kymograph with various transducers derived from modifications of nineteenth-century instrumentation. Tracing shows simultaneous recording of (A) gastric contractions, (C) time record in minutes, (D) subjective experience of hunger pangs, and (E) pneumograph recording respiratory movements [From W.B. Cannon, *The Wisdom of the Body*, 1932; reproduced courtesy of W. W. Norton & Company, Inc.].

Claude Bernard, that all life was movement and that the graphic method captured this movement.[27] Study of the trajectories of dynamic processes gradually replaced the mere measurement of static events as the primary focus of physiological investigation. The graph both portrayed and symbolized the dynamic process under study. By the end of the nineteenth century, physiologists were studying multiple variables and uncovering complex control mechanisms which operate within the body. The significance of this trend, the study of process and the regulation of that process, was underscored by the introduction in 1926 of the concept of biological homeostasis [Figure 3].[28]

An interesting apparently unanticipated cognitive change accompanied the use of these instruments. Investigators increasingly began to recognize the value of the curve itself. That is, they increasingly displayed their quantitative data (some of it initially derived from kymograph tracings) in graphs rather than in numerical, tabular form.[29] This graphic presentation of data became a significant and conspicuous element of scientific communication in the 1860s during precisely those years in which graphic recording became a routine method of physiological analysis.[30] Indeed, early physiological and medical graphs were often published in white on a black background rather than black on white, apparently imitating the kymographic record inscribed on sooted paper.[31]

Initially, physiologists used the graphic record to obtain precise numbers. They presented these numbers in tabular form in their publications.[32] Gradually, physicians, physiologists, and psychologists began to construct graphs from those numbers, to present even their numerical data graphically. The physiological recording instruments used by nineteenth-century investigators made hidden processes visible and generated numerical data about those processes. Such data was visualized further by systematic mathematical manipulation and subsequent graphic presentation.[33]

The graphic records from instruments subtly encouraged the graphic presentation of all numerical data, even data not originally gathered in graphic form. Routine statistical analysis, graphic recording, and graphic presentation became significant features of the scientific method in the 1860s and ought probably to be viewed as cognitively interrelated and mutually supportive developments.[34] Out of this context emerged the now universally-applied techniques that Tufte has recently called the "visual display of quantitative information."[35] Recording apparatus literally created an awareness of the value of graphs in physiology and medicine and accelerated scientific application of graphic methods, even though graphic presentation of data itself was not a new idea.

Especially interesting in this context is the development by German clinicians of temperature charting in the 1850s and 1860s. Ludwig Traube (1818-1876) utilized the kymograph and extended the application of graphic recording methods to pharmacology early in the 1850s.[36] During these years, he also suggested to Carl Wunderlich (1815-1877) the value of systematically noting human temperature change over time. Wunderlich's landmark book, *Das Verhalten der Eigenwärme in Krankheiten* (The Behavior of Body Heat in Diseases), appeared in 1868, a second edition in 1870. Wunderlich emphasized:

> Whatever the nature of the thermometric observations, if they are to be of any use at all, it is essential that the *results obtained should be continuously recorded*. This can best be done and the course of the disease rendered most evident, by indicating it *on a chart*, or ruled map, as a *continuous curved line* . . . It is convenient to note the frequency of the pulse, and the number of the respirations in a similar manner, but in different colors . . . In this way the entire course of the disease, with all its fluctuations, complications, tendencies, and changes can be seen at a single glance.[37]

Such numerical records presented visually as temperature curves or "charts" proved diagnostically useful in the study of diverse fevers, allowing physicians to distinguish between them and monitor their course. Such visual presentation of data secured the place of thermometry in medical practice from the early 1870s. Graphic recording techniques also affected thermometry directly. The thermometer which measured temperatures, that could themselves be displayed graphically, was supplemented by the thermograph which automatically inscribed its own curve.[38]

These interrelated conceptual themes are evident in the organization of Marey's *La méthode graphique dans les sciences experimentales* (The Graphic Method in the Experimental Sciences) published in 1878. By the 1870s many of the most important accessories to the recording apparatus had been invented or were being perfected. A network of instrument manufacturers was developing. Registration techniques had become an integral part of physiological research as evidenced by the plans of new laboratories. Moreover, graphic presentation of numerical data was an important analytical procedure that had already shown its value in thermometry and was being extended into other problem areas [Figure 4].[39] Marey was then advancing graphic techniques through the use of yet another recording method—photography. He later developed chrono-photography (rapid photography) to record the successive positions of animals during locomotion.[40] For each of these variations on the theme of the graphic method, recording instrumentation provided the drive behind fundamental perceptual, conceptual, and cognitive change in physiology.

Recording apparatus encouraged physiologists to develop analytical techniques that are now firmly identified with the methods of modern science. It also provided the mechanism for translating the expressed experimental ethos of nineteenth-century investigators; i.e., the desire to discover the laws of nature, into common, routine, uniform laboratory experience and practice. Recording instruments not only symbolized a new experimentally-based science to physiologists, they also provided the material basis and heraldry both for transmission of that science and for its institutionalization and standardization in a wide variety of social and cultural contexts. The manufacture, distribution and utilization of these instruments tells us much about the perceived goals of experimental scientists at the end of the nineteenth century.

Social Effects

In following the spread of experimental physiology from Continental Europe to Great Britain, North America and Russia, it is useful to ask how new experimental techniques were transplanted from one context to another. The extensive work on the training of American students abroad in the nineteenth century suggests that in physiology much of this transmission was accomplished between 1860 and 1890 through the training of foreign students in German (and sometimes French or Italian) laboratories.[41] Ludwig's laboratory at Leipzig especially was a focus for the development of skills in experimental design, experimental technique, and experimental analysis. Training by apprenticeship at the laboratory bench has been the primary mode of transmission of research skills. However, this process was changed considerably by the advent of the new nineteenth-century instrumentation of physiology. American students returned home not only with newly acquired research skills, but also with imported German instruments. Laboratories were built to house these important new tools of experimental science.[42]

The physiological laboratory thus became the site for use and storage of instruments, as well as the site for transmission of knowledge made possible by them. From the 1860s in the German states and the 1870s elsewhere, the equipping of physiological laboratories became a major professional activity.[43] Initially, the laboratory was used for the professor's personal research and for the training of a few advanced students or colleagues from other fields. However, by the 1890s, the events which occurred within the laboratory began to acquire increasing pedagogical importance, particularly in the United States. Occasional experimental demonstrations were replaced first by routine demonstrations and finally by

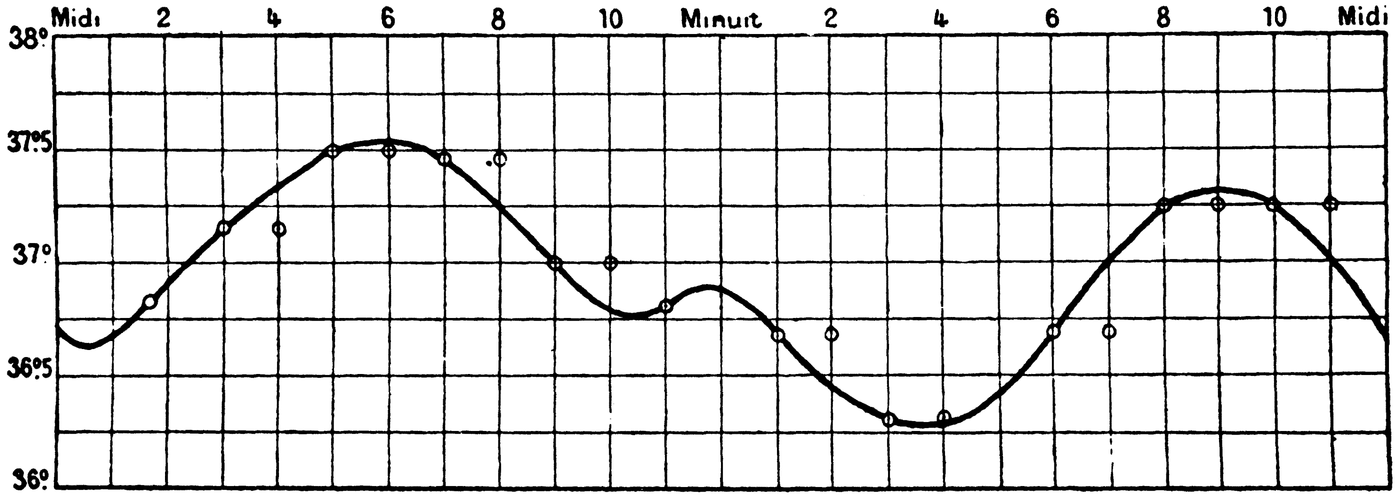

Figure 4. Graphic presentation of pulse data. Prompt's graphing (1867) of Boerensprung's data (1840) [From Marey, *La méthode graphique*, 1878; reproduced courtesy of Masson, Editeur s.a.].

hands-on experiments for all introductory students. The method, the technique, as opposed to the facts, of experimental physiology became increasingly important. All introductory students, not just the advanced students, learned to operate the kymograph and myograph, to record and measure physiological events, to manipulate and modify apparatus. In other words, all students learned to ask questions of nature rather than rely on the authority of didactic lectures. Scientific knowledge was to be gained directly by experience in the laboratory.[44] Students learned to manipulate as well as to observe and describe.

Such a major change in the process of physiological education required that hitherto rare and expensive apparatus be provided for all students. Recording instruments and related apparatus had initially been made by the researcher himself or a skilled mechanic in a university laboratory or nearby industrial shop. As the demand increased, instruments were made and sold by an increasing number of scientific instrument companies.[45] At first made one by one, the availability of these instruments was increased markedly by the introduction of quantity production and the substitution of cheap and durable materials like aluminum (in the case of kymographs) for nineteenth-century brass.[46] The Harvard Apparatus Company, which manufactured physiological apparatus in Boston from 1900, arose from the desire to provide high quality, reliable, inexpensive teaching apparatus to physiology students at the Harvard Medical School. Within five years, it supplied kymographs and myographic equipment world-wide. In America, it transformed kymographic recording from an activity reserved for research investigators to a skill to be learned in introductory courses by all medical students and aspiring life scientists even those at small colleges.[47]

The transformation from research laboratory to teaching laboratory required a major investment of personnel and capital by each college or university. Hands-on laboratory experience became the main emphasis in program building especially in the United States. Recording instrumentation became the centerpiece of these efforts in physiology, but experimental analysis also transformed the methodology of biology and botany and this instrumentation spread into those domains. As a result, laboratory development provided jobs for succeeding generations of American researchers. Quantity production of inexpensive research apparatus allowed even smaller colleges to hire experimentalists to provide hands-on training to introductory students. In the process, chairs, laboratories, and departments were created.

In physiology, the kymograph was the focal instrument of this institutional transformation. It represented both the major tool of experimental physiology and the intellectual power of physiology to transform medicine into a predictive law-bound science of health and disease. Work organization within physiology changed as physiologists built research groups and schools. They constructed their science and their newly-acquired social authority largely on solution of the kinds of problems amenable to analysis by graphic registration.

Conclusions

By the end of the nineteenth century, physiology claimed a role as the foundational subject of scientific medicine and as the epitome of the experimental method in the life sciences. The campaign for creation of journals, societies, separate chairs, laboratories, and departments, so well studied by historians and sociologists, now needs to be correlated with the process of the introduction and application of the registration techniques and instrumentation set in motion by the introduction of the kymograph and other recording apparatus. Physiological journals reproduced kymograph tracings; societies specifically advocated the extension of the experimental and "practical" physiology symbolized by the kymograph; individual scientists pleaded for the creation of chairs, laboratories and departments of experimental physiology. Their European patrons, nineteenth-century governments, saw a role for physiology in the industrialization and modernization of the state and in the improvement of medical practice. American educators spoke of the need to train "for power," that is, to teach methods of scientific reasoning and analysis, rather than facts.[48] Instruments came to represent both the power and the substance of experimental physiology in each of these important discussions.

Continued analysis of these interrelated events will add important dimensions to our understanding of the role of instrumentation in the establishment of modern institutions of science. It will also clarify the intellectual origins of many of the analytical procedures now considered to be integral to the scientific method. Such analysis will connect more persuasively, through the addition both of texture and of fine detail, the intellectual content of science with its underlying and evolving social structure.[49]

NOTES

1. For a review of this literature, see Steven Turner, Edward Kerwin, and David Woolwine, "Careers and Creativity in Nineteenth-Century Physiology: Zloczower 'Redux'," *Isis* 75 (1984): 523-529. Case studies of the development of specific physiological laboratories in German states will soon appear in articles by Arleen Tuchman ("From the Lecture to the Laboratory: The Institutionalization of Scientific Medicine at the University of Heidelberg") and Timothy Lenoir ("Science for the Clinic: Carl Ludwig and the Institutional Revolution in German Science") in William Coleman and F.L. Holmes, eds., volume tentatively titled *The Investigative Enterprise* (University of California Press, forthcoming). I am grateful to these authors for sharing their manuscripts with me. See also Arleen Tuchman, "Science, Medicine and the State: The Institutionalization of Scientific Medicine at the University of Heidelberg" (Ph.D. diss., University of Wisconsin-Madison, 1985).

2. Richard D. French, "Some Problems and Sources in the Foundations of Modern Physiology in Great Britain," *History of Science* 10 (1971): 28-55; Gerald L. Geison, "Social and Institutional Factors in the Stagnancy of English Physiology, 1840-1870," *Bulletin of the History of Medicine* 46 (1972): 30-58; idem, *Michael Foster and the Cambridge School of Physiology: The Scientific Enterprise in Late Victorian Society* (Princeton, N.J.: Princeton University Press, 1978); idem, "Divided We Stand: Physiologists and Clinicians in the American Context" in Morris J. Vogel and Charles E. Rosenberg, eds., *The Therapeutic Revolution: Essays in the Social History of American Medicine* (Philadelphia: University of Pennsylvania Press, 1979), pp. 67-90; and idem, ed., *Physiology in the American Context, 1850-1940* (Bethesda: American Physiological Society, 1987).

3. The standard history of physiology, Karl Rothschuh's *Geschichte der Physiologie* (Springer Verlag, 1953) appeared in English translation in 1973 as *History of Physiology*, trans. and ed. by Guenter B. Risse (Huntington, N.Y.: Robert E. Krieger). On physiology's emergence as an independent experimental science, see J. Schiller, "Physiology's Struggle for Independence in the First Half of the Nineteenth Century," *History of Science* 7 (1968): 64-89. The content of these intellectual histories must yet be integrated with the new social and institutional histories cited above.

4. Merriley Borell, "The Kymograph and the Origins of the Graphic Method," *Electric Quarterly* 7 (Summer, 1985): 2-3.

5. See Paul F. Cranefield, "The Organic Physics of 1847 and the Biophysics of Today," *Journal of the History of Medicine and Allied Sciences* 12 (1957): 407-423; idem, "The Philosophical and Cultural Interests of the Biophysics Movement of 1847," *Journal of the History of Medicine* 21 (1966): 1-7; and idem, ed., *Two Great Scientists of the Nineteenth Century. Correspondence of Emil Du Bois-Reymond and Carl Ludwig*, trans. Sabine Lichter-Ayed (Baltimore: Johns Hopkins University Press, 1982).

6. Merriley Borell, "Extending the Senses: The Graphic Method," *Medical Heritage* 2 (1986): 114-121.

7. Stanley J. Reiser, *Medicine and the Rise of Technology* (Cambridge: Cambridge University Press, 1978): esp. pp. 91-121.

8. Merriley Borell, "Instruments and an Independent Physiology: The Harvard Physiological Laboratory, 1871-1906," in Geison, ed., *Physiology in the American Context*, pp. 293-321.

9. Erich Bauereisen, "Carl Ludwig as the Founder of Modern Physiology," *The Physiologist* 5 (1962): 293-299; Heinz Schrœr, *Carl Ludwig, Begründer der messenden Experimentalphysiologie* (Stuttgart: Wissenschaftliche Verlagsgesellschaft M.B.H., 1967).

10. C. Ludwig, "Beiträge zur Kenntniss des Einflusses der Respirationsbewegungen auf den Blutlauf im Aortensysteme," *Müller's Archiv für Anatomie und Physiologie und wissenschaftliche Medicin* 1847: 242-302.

11. See E.J. Marey, *Du mouvement dans les fonctions de la vie: lecons faites au Collège de France* (Paris: Germer Baillière, 1868), pp. 130-131.

12. Ralph H. Major, "Karl Vierordt," *Annals of Medical History* new ser. 10 (1938): 463-473, esp. pp. 469-473. Vierordt demonstrated his sphygmograph in 1853. On its uses, see Karl Vierordt, *Die Lehre vom Arterienpuls in gesunden und kranken Zustanden gegründet auf eine neue methode der bildlichen Darstellung des menschlichen Pulses* (Braunschweig: Friedrich Vieweg und Sohn, 1855).

13. [E.] J. Marey. "Recherches sur le pouls au moyen d'un nouvel appareil enregistreur le sphygmographe présenté à la Société de Biologie," *Comptes rendus des séances et mémoires de la Société de Biologie* ser. 3, 1(1859): 281-309, and idem, *Physiologie médicale de la circulation du sang basée sur l'étude graphique des mouvements du coeur et du pouls arteriel avec application aux maladies de l'appareil circulatoire* (Paris: Adrien Delahaye, 1863).

14. See E.J. Marey, *La méthode graphique dans les sciences expérimentales et principalement en physiologie et en médecine* (Paris: G. Masson, 1878), esp. pp. 112-113.

15. On Marey's contributions, see Merriley Borell, "Marey and d'Arsonval: Two Visions of the Exact Sciences in Late Nineteenth-Century French Medicine," in J.L. Berggren and Bernard Goldstein, eds., *From Ancient Omens to Statistical Mechanics: Studies on the History of Science in Honor of Asger Aaboe*, volume 39 in the series *Acta historica scientiarum naturalium et medicinalium* (Copenhagen: University Li-

brary, 1987), and H.A. Snellen, *E.J. Marey and Cardiology: Physiologist and Pioneer of Technology 1830-1904—Selected writings in facsimile with comments and summaries, a brief history of life and work and a bibliography* (Rotterdam: Kookyer Scientific Publications, 1980). Robert G. Frank considers Marey's contributions to cardiac physiology in "The Tell-Tale Heart: Physiological Instruments and Clinical Hopes, 1855-1912," forthcoming in Coleman and Holmes, *Investigative Enterprise*.

16. See the translation of this work in Thomas S. Hall, ed., *A Source Book in Animal Biology* (Cambridge: Harvard University Press, 1951), pp. 313-320. On the origins of Helmholtz's techniques in muscle and nerve studies by Theodor Schwann and Emil Du Bois-Reymond, see John Gray M'Kendrick, *Hermann Ludwig Ferdinand von Helmholtz* (New York: Longmans, Green & Co., 1899), pp. 35-38.

17. The figure is taken from William Stirling, *Outlines of Practical Physiology being a Manual for the Physiological Laboratory*, Fourth ed. (London: Charles Griffin, 1902), p. 451. Similar illustrations may be found in most other late nineteenth-century texts. For citation of popular texts, see Borell, "Instruments and an Independent Physiology."

18. A chronology of plant growth registration techniques is found in William F. Ganong, *A Laboratory Course in Plant Physiology*, Second edition (New York: Henry Holt and Company, 1908). Ganong (p. 200) credits Sachs with the invention of the "auxograph" about 1872: "[Sachs' device] consisted of a large vertical excentrically [sic] placed cylinder turned by a weight-and-pendulum clock, and having on one side a smoked paper, which was scratched by a pointer carried on a wheel connected with the plant by a thread." I am grateful to Gene Cittadino for directing me to Ganong's text.

19. The easiest way to follow these changes is through trade catalogues. I have used those found at the Bakken Library, Minneapolis (catalogues of Breguet, Paris; Verdin, Paris; and Boulitte, Paris); the National Museum of American History, Smithsonian Institution, Washington, D.C. (especially the catalogues of Rudolph Koenig, Paris; Cambridge Scientific Instrument Company, England; E. Zimmermann, Leipzig & Berlin; C.H. Stoelting, Chicago; and C.F. Palmer, London); and the Harvard University Medical School, Boston (catalogues of Eugen Albrecht, Tübingen; the Harvard Apparatus Company, Boston; and Baird & Tatlock Ltd., London).

20. See Bauereisen, "Carl Ludwig," p. 297, and Hebbel E. Hoff, L.A. Geddes, and W.A. Spencer, "The Physiograph - An Instrument in Teaching Physiology," *Journal of Medical Education* 32 (1957): 181-198.

21. Marey, *La méthode graphique*, pp. 111-112 and 168; Marey, *Du mouvement*, pp. 111-112; H.E. Hoff and L.A. Geddes, "Graphic Recording before Ludwig: An Historical Summary," *Archives internationales d'histoire des sciences* 12 (1959): 3-25; and idem, "Graphic Registration before Ludwig, the Antecedents of the Kymograph," *Isis* 50 (1959): 5-21. For a critique of Hoff and Geddes' interpretation of Ludwig's innovation, see Schröer, *Carl Ludwig*, pp. 111-113. See also Robert P. Multhauf, "The Introduction of Self-registering Meteorological Instruments," Contributions from the Museum of History and Technology, Paper 23, *United States National Museum Bulletin 228* (Washington, D.C.: Smithsonian Institution, 1961), pp. 95-116. Multhauf's paper shows the ubiquity of related instruments during this period. I am grateful to Deborah Jean Warner for introducing me to this very interesting work.

22. An "endless paper" kymograph is described in the Zimmermann catalogue of 1912 (Psychologische - und Physiologische Apparate. Illustrierte List 25 und Nachtrag), p. 151, item 2220. The paper is fed from a large roll onto the recording drum.

23. The Double Paper Brodie Starling Kymograph listed in the 9th Edition (1953) of the C.F. Palmer (London) Ltd. catalogue (p. 12) was designed by I. de Burgh Daly and described in the *Journal of Physiology* in 1930. The catalogue shows two long paper kymographs stacked on top of one another. I am grateful to Chris Lawrence for sending me photocopies of this apparatus.

24. See Borell, "Extending the Senses."

25. See Edwin Boring, *A History of Experimental Psychology*, Second ed. (New York: Appleton-Century-Crofts, Inc., 1957), Ch. 8, "The Personal Equation," pp. 134-153.

26. I thank Robert R. Pool, Jr. for this observation.

27. Marey, *Du mouvement*, p. vi.

28. The figure is from Walter B. Cannon's classic account *The Wisdom of the Body* (New York: W.W. Norton, 1932), p. 71. In it (p. 24) Cannon defined "homeostasis" as "[t]he coordinated physiological processes which maintain most of the steady states in the organism." For an account of his life and work, see Donald Fleming, "Walter B. Cannon and Homeostasis," *Social Research* 51 (1984): 609-640.

29. See Borell, "Marey and d'Arsonval," and later discussion in this paper.

30. Note correspondence with H.G. Funkhouser, "Historical Development of the Graphical Representation of Statistical Data," *Osiris* 3(1937): 269-404, and Multhauf, "Self-Registering Meteorological Instruments," 106.

31. Hughes Evans made this interesting observation during our joint investigations this past year. See the graphs in C.A. Wunderlich and E. Seguin, *Medical Thermometry and Human Temperature* (New York: William Wood & Co., 1871) and P. Lorain, *De la témperature du corps humain et de ses variations dans les diverses maladies*, 2 vols. (Paris: L'Imprimerie Nationale, 1977). In contrast, the early temperature charts by Wunderlich are displayed on white paper. However, both Ludwig and Traube used ink and paper for kymograph tracings, as discussed later in this paper.

32. See the tabular data of Ludwig in "Einflusses der Respirationsbewegung auf den Blutlauf," 269-302.

33. This transformation can be observed in the early volumes of the *American Journal of Psychology*. I thank Gail Hornstein for this evidence.

34. See Borell, "Marey and d'Arsonval," and Note 30.

35. E.R. Tufte, *The Visual Display of Quantitative Information* (Cheshire, Conn.: Graphics Press, 1983).

36. Traube's investigations are reprinted in L. Traube, *Gesammelte Beiträge zur Pathologie und Physiologie* 3 vols. (Berlin: August Hirschwald, 1871-1878), *Band I: Experimentelle Untersuchungen Band II: Klinische Untersuchungen* and *Band III: Klinische Untersuchungen*. See especially Traube's experiments from 1851-1852, on the effects of digitalis. For these experiments, he used Ludwig's kymograph as modifiedby Volkmann (I, 252-273). Here he presented data from kymograph tracings in tables. In earlier papers from 1850-1851, on the clinical effects of digitalis in fevers, he presented daily pulse, respiration, and temperature data from patients in tabular form (II, 97-204). He used graphic presentation (white on black), however, for similar data from 1851-1852(II, 235-269, on pp. 258-260).

37. C.A. Wunderlich, *On the Temperature of Diseases: A Manual of Medical Thermometry*, translated from the second German edition by W. Bathurst Woodman (London: The New Sydenham Society, 1871), pp. 78-79.

38. Wunderlich did not find Marey's thermograph (1865) clinically useful because it did not fit well on the body. Christopher Lawrence considers physicians' resistance to the introduction of instruments in "Incommunicable Knowledge: Science, Technology and the Clinical Art in Britain 1850-1914," *Journal of Contemporary History* 20 (1985): 503-520, and "Moderns and Ancients: The 'New Cardiology' in Britain 1880-1930" in W.F. Bynum, C. Lawrence and V. Nutton, eds., *The Emergence of Modern Cardiology* Supplement 5 to *Medical History* (London: The Wellcome Institute for the History of Medicine, 1985).

39. Figure 4 shows the value of the graphic method in the study of pulse rate. It is Marey's figure showing P.J. Prompt's 1867 graphic presentation of Boerensprung's data originally published in 1840. The original caption read (*La méthode graphique*, p. 45): "Hourly variations in the rate of the pulse put onto a curve by Dr. Prompt after the numbers published by Boerensprung."

40. See E.J. Marey, "La chronophotographie: nouvelle méthode pour analyser le mouvement dans les sciences physiques et naturelles," *La revue générale des sciences pures et appliquées* 2 (1891): 689-719.

41. For a review of this interesting literature, see Robert G. Frank, Jr., "American Physiologists in German Laboratories, 1850-1900" in Geison, *Physiology in the American Context*, pp. 11-46.

42. For a case study of this process at Harvard, see Borell, "Instruments and an Independent Physiology."

43. On the British response to the rise of German laboratories, see Geison, *Michael Foster*, esp. p. 78.

44. I describe this process fully in "Instruments and an Independent Physiology." This process began earlier in chemistry and physics. On such pedagogical reform, see especially Albert E. Moyer, "Edwin Hall and the Emergence of the Laboratory in Teaching Physics," *The Physics Teacher* 114(1976): 96-103, and Owen Hannaway, "The German model of Chemical Education in America: Ira Remsen at Johns Hopkins (1876-1913)," *Ambix* 23 (1976): 145-164.

45. Hughes Evans and I have compiled a preliminary list of companies supplying major physiological and psychological apparatus in the period c. 1870-1905. Our list includes approximately forty-six in Germany, an additional ten in other German-speaking countries, and sixty more elsewhere. While we have some duplication of companies (their names changed during this thirty-five year period), our list clearly shows the rise of an important instrument manufacturing industry.

46. On the introduction of quantity production by the Harvard Apparatus Company, see Borell, "Instruments and an Independent Physiology."

47. The Harvard Apparatus Company made high-quality precision physiological apparatus available at cost to small colleges and state universities which otherwise could not have afforded the expense of equipping physiological laboratories. See *ibid*. Other American companies (we are aware of about twenty) also produced or supplied related equipment, but not as cheaply.

48. See especially Tuchman, "Science, Medicine and the State" and the articles by Tuchman and Lenoir in Coleman and Holmes, eds., *Investigative Enterprise* for a discussion of the specific goals of the German states in promoting physiology. On the origin and significance of the phrase training "for power," see Borell, "Instruments and an Independent Physiology," p. 300, n. 35, and p. 314, n. 98 and 99. The phrase, attributed to Harvard President Charles W. Eliot, was used by both William Townsend Porter and Henry Pickering Bowditch in their promotion of laboratory physiology. See *ibid*. and Kenneth M. Ludmerer, *Learning to Heal: The Development of American Medical Education* (New York: Basic Books, 1985), p. 52, n. 19.

49. The Boston Working Group, consisting of myself, Deborah Coon, Hughes Evans and Gail Hornstein, is currently examining these important relationships in physiology, psychology, and medicine.

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