Health Statistics, History of

The field of statistics in the twentieth century (*see* **Statistics, Overview**) encompasses four major areas; (i) the **theory of probability** and mathematical statistics; (ii) the analysis of uncertainty and errors of measurement (*see* **Measurement Error in Epidemiologic Studies**); (iii) design of experiments (*see* **Experimental Design**) and sample surveys; and (iv) the collection, summarization, display, and interpretation of observational data (*see* **Observational Study**). These four areas are clearly interrelated and have evolved interactively over the centuries. The first two areas are well covered in many histories of mathematical statistics while the third area, being essentially a twentieth-century development, has not yet been adequately summarized. Although the fourth area has been going on since man first learned to think inductively, it relies on the state of the art in the first three areas. In this brief survey of health statistics during the past five centuries, emphasis will be given to the development of official health statistics systems in Europe and the US.

Early Interest in Statistics

At the end of the fifteenth century, mathematics was at a rather primitive stage and the threshold of the "scientific revolution" was still two generations away. The mathematics of the Greeks had only re-entered European thinking in the twelfth century, and although some progress had been made in practical applications in navigation and commercial arithmetic, the burgeoning of numeracy was only beginning. Mathematicians still did not recognize the number zero or know how to deal with negative numbers. Except for a few examples of probabilistic thinking such as that in the talmudic literature [10], there was scant evidence of the use of a mathematical approach to probabilities to estimate **risks** or assess the reliability of measurements until the mid-seventeenth century.

Most historians of statistics trace the origins of modern probability theory to the efforts to solve certain gambling problems [e.g. Pacioli (1494), Cardano (1539), and Forestani (1603)] which were first solved definitively by Pierre de Fermat (1601–1665) and Blaise Pascal (1623–1662). These efforts gave rise to the mathematical basis of probability theory, statistical distribution functions (*see* **Sampling Distributions**), and statistical **inference**.

The analysis of uncertainty and errors of measurement had its foundations in the field of astronomy which, from antiquity until the eighteenth century, was the dominant area for use of numerical information based on the most precise measurements that the technologies of the times permitted. The fallibility of their observations was evident to early astronomers, who took the "best" observation when several were taken, the "best" being assessed by such criteria as the quality of observational conditions, the fame of the observer, etc. But, gradually an appreciation for averaging observations developed and various techniques for fitting the observational data to **parametric models** evolved. Many of the founders of modern statistics contributed to the early development of the theory of measurement errors including **Jacob Bernoulli** (1654–1705), **Abraham De Moivre** (1667–1754), **Pierre Simon Laplace** (1749–1827), and **Carl Friedrich Gauss** (1777–1855).

A systematic approach to the collection of data and tabulating observations in a rational manner began with the teachings of Francis Bacon (1561–1626). In his influential treatise *Novum Organum* (1620), he attacked the scholastic philosophy which had developed in the Middle Ages on the basis of the methods of Aristotle. One of the first areas influenced by Bacon's approach was **demography** and **vital statistics** and the social utility of systematic observations is clearly reflected in these early efforts.

The utilitarian nature of statistics is evident in the origins of the word from the Italian *stato* (state), and the original meaning of statistics was a collection of facts of interest to a statesman. Initially such facts were not primarily numerical, but included information on geography, politics, and customs of a region. The compilers of such facts were called statists, a term which survived into the nineteenth century, when the word statistics came to be used for numerical data only, replacing the term "political arithmetic", and the word "statistician" came into vogue.

The Origins of Demography and Vital Statistics

Since ancient times, sporadic surveys of people and property were done to set tax assessments and levies for military service. But after the fall of the Roman empire, regular **censuses** covering an entire state did not occur until the eighteenth century. However, there were intermittent attempts to keep track of the births and deaths in some areas through church records of weddings, christenings, and burials. The City of London was one of the first to regularize the maintenance of such records in 1538, but only within the Church of England. Also at about this time a **surveillance** or early warning system of plague deaths was started in London. To detect the onset of a plague epidemic, parish clerks submitted weekly reports on the numbers and causes of deaths. These weekly *Bills of Mortality* were noted by the authorities who were to take actions if they detected the onset of an epidemic, and by the wealthier citizens for "an indication of when to leave the city for the fresh air of the country" [7]. The weekly bills were published regularly from 1604 until 1842 when they were superseded by reports from the Registrar General.

In 1662, **John Graunt** (1620–1674), a London tradesman who had been active in local politics and intellectual society, published his *Natural and Political Observations Made Upon the Bills of Mortality*, which historians of statistics have referred to as "a remarkable book [12]", "one of the great classics of science [6]", and "a paragon for descriptive statistical analysis of demographic data [7]". Hald summarizes Graunt's contributions to the origins of statistics thus:

> Graunt's critical appraisal of the rather unreliable data, his study of mortality by cause of death, his estimation of the same quantity by several different methods, his demonstration of the stability of statistical ratios, and his life table set up new standards for statistical reasoning. Graunt's work led to three different types of investigations: political arithmetic; testing the stability of statistical ratios; and calculation of expectations of life and survivorship probabilities [7].

At a time when denominator data on the size of the population by age were not available, Graunt used several ingenious lines of reasoning to generate the first **life table** ever published, perhaps his most famous contribution.

Owing to the widespread influence of Graunt's work, bills of mortality similar to the London bills were introduced in Paris in 1667, and soon after in other cities in Europe.

Graunt's life table was brought to the attention of Christiaan Huygens (1629–1695) and his brother Ludwig (1631–1699) who proceeded to develop a probabilistic interpretation of the life table, which was rediscovered independently by **Nicholas Bernoulli** (1687–1759). These investigations, together with the more applied techniques of **Edmond Halley** (1656–1742) based on the births and funerals in the City of Breslau (1693), and the work of Deparcieux (1703–1768) in France who used data from tontines to construct the first correct life tables, formed the foundation of the **actuarial** sciences for life insurance and annuities. These were developed further by Abraham DeMoivre (1667–1754), Thomas Simpson (1710–1761), Benjamin Gompertz (1779–1865), and William Makeham (1826–1891).

It was not until 1766 in Sweden that Per Wargentin (1717–1783) published the first mortality tables for a whole country based on enumerations of the living population as well as on deaths. These mortality tables demonstrated for the first time in a general population that the mortality rate of females was less than that of males.

Graunt's methods of statistical analysis were widely adopted by seventeenth-century statists. **William Petty** (1623–1687), who was a protégé of Graunt, and after Graunt's financial bankruptcy in 1666, his patron, coined the term "political arithmetick" and was one of the founders of the field of political economy. Gregory King (1648–1712) and Charles Davenant (1656–1714) contributed to improvements in the estimates of the population of England. Sebastien de Vauban (1633–1707) described the extent of poverty in France, for which he suffered public disgrace because of its embarrassment of the royal government. Nicholas Struyck (1678–1769) instituted town censuses in the Netherlands and improved the recording of births and deaths. The revelations of statistical data were also used to support religious positions such as the claim of John Arbuthnott (1667–1735), who was a vigorous proponent of political arithmetic, that the stability of the sex ratio "is not the effect of chance but divine providence". Somewhat later, Johann Peter

Suessmilch (1707–1767) in Germany gathered vital statistics from virtually every source then available as evidence of certain tenets of orthodox Lutheran theology. He maintained that the life span (*see* **Life Expectancy**) was constant and that little could be done to improve mortality rates. His work directly influenced the thinking of **Thomas Robert Malthus** (1766–1834). These diverse endeavors eventually led to the establishment of governmental statistical offices in the nineteenth century.

Among the developments in mathematical statistics that occurred during the eighteenth century, two had special relevance for health statistics. **Daniel Bernoulli** (1700–1782), who first developed the **normal** approximation to the **binomial distribution** and used it in studies of the stability of the sex ratio at birth, applied the methods of calculus to mortality rates by treating them as continuous functions. This enabled him to obtain a solution in 1760 to an important public health question of his day: to estimate the impact on life expectancy of eliminating smallpox through a proposed program of mandatory vaccination. His invention of the method of **competing risks**, with some improvement by d'Alembert (1761) and by Makeham (1874), still forms the basic tool for such analyses.

A second development expanded the techniques used by Vauban. Laplace proposed a nonrandom sampling method to estimate the size of the population in 1786. It was based on a notion similar to that of current **ratio estimates**, i.e. that the size of the population of a region was proportional to the annual number of births in that region and that the constant of proportionality could be determined from a purposive sample of subregions. Graunt had used a similar assumption implicitly a century earlier.

Laplace's method was severely criticized, most notably by Baron de Keverberg (1827) [11, p. 164]. These criticisms clearly reflected an appreciation that there were a multitude of factors that could influence any chosen characteristic of a population, that subgroups of the population were not homogeneous with regard to the array of factors influencing the characteristic, and, therefore, purposive samples of the population could not reflect the total population. Only complete censuses of the population would do, and these would have to amass immense amounts of information. At this time there was not yet an appreciation for the power of random sampling methods (*see* **Probability Sampling**).

Applying Statistics to Medical and Social Issues

Just as **demographic** and economic statistics began with the name of "political arithmetic" in the seventeenth century, medical statistics began with the name of "the numerical method" early in the nineteenth century. Although some of his methods were evident in the works of **Phillipe Pinel** (1745–1826) and other French physicians, **Pierre-Charles-Alexandre Louis** (1787–1872) has been described "as the first modern clinician, the man who made bedside medicine a science as well as an art, and who established the principle of learning medicine from thoughtful observation of patients [1]." His studies on the inefficacy of blood letting were the beginning of quantitative medicine and earned him the title of "father of medical statistics" [12]. Louis's hopes for his numerical method were echoed by Giacomo Tommasini (1768–1846) in Italy, and **F. Bisset Hawkins** (1796–1894) in England, who published in 1829 the first English textbook on medical statistics with the rather grand title of *Elements of Medical Statistics; Containing the Substance of the Gulstonian Lectures Delivered at the Royal College of Physicians with Numerous Additions Illustrative of the Comparative Salubrity, Longevity, Mortality, and Prevalence of Diseases in the Principal Countries and Cities of the Civilized World.* Although by later standards Louis's statistical attempts were often inadequate, suffering particularly from sparse numbers, he had a crucial influence on **William Farr** who attended his lectures during his two years in Paris, as did several American physicians who were influential in the early development of public health and epidemiology.

Louis's methods were not immediately accepted for many of the same reasons that Laplace's methods were not: the variability between cases was thought to be highly individualistic and not subject to statistical summarization. For example, **William A. Guy** (1810–1885), who contributed much to public health and occupational statistics, felt "the formulae of the mathematician have a very limited application to the results of observation" [12, p. 151].

The Belgian, **Adolphe Quetelet** (1796–1874), who dominated the field of social statistics for half a century, may have gone too far in the other direction. Impressed by the **central limit theorem** and believing that averages based on large numbers of

observations from a population had remarkable stability, he introduced the concept of the "average man" (*l'homme moyen*) which had considerable popular appeal. He was also enamored of the normal distribution and fitted it to many characteristics, marvelling at the statistical homogeneity of large bodies of data which detracted from further exploration of valid heterogeneities. However, he influenced a large number of statisticians including **Louis Adolphe Bertillon** (1821–1883), Wilhelm Lexis (1837–1914), **Francis Galton** (1822–1911), **Karl Pearson** (1857–1936), and **Ronald A. Fisher** (1890–1962) [11].

Development of Health Statistics in England

During the eighteenth century many physicians and registrars in England recognized the inadequacies of the bills of mortality. There were frequent calls for reforms but because of concerns about personal liberties, religious arguments, and beliefs that population figures were crucial state secrets, it was not until 1800 that Parliament passed a population act that set up the census of 1801. By the 1830s, as in the mid-seventeenth century (with Graunt and Petty), London "witnessed a flash of enthusiasm for vital statistics and political arithmetic" [5, p. 13]. The Statistical Society of London was founded in 1834 by the same group that had founded the statistics section (Section F) of the British Association for the Advancement of Science in 1833, and started publication of its Journal in 1838. These and other early statistical societies in England were greatly concerned with social problems, conducting several surveys to document conditions in England and continuing to push for social reforms long after the surveys proved too expensive to continue. Although they claimed scientific objectivity, these statists were superficial in their use of mathematical methods, paid little attention to the validity or accuracy of their data, but were aware that using numeric data gave credibility to political arguments [5].

A more balanced contribution was made by William Farr (1807–1883) in the area of vital statistics. Starting his career as an unsuccessful London clinician, he quickly became an acknowledged authority on vital and health statistics with a strong interest in medical and social reform. He founded his own weekly journal, *British Annals of Medicine, Pharmacy, Vital Statistics, and General Science*, which lasted only eight months, January to August 1837, but allowed him to write major articles on medical reform and vital statistics. The Births and Deaths Registration Act of 1836 had inaugurated the modern system of civil registration and led to the establishment of the General Register Office in 1837. Farr joined the staff of the General Register Office in 1839, serving forty years, first as compiler of abstracts and then as superintendent of the Statistical Department.

Farr "insisted that the statistician adopt a critical approach, investigating the accuracy of his data, questioning the appropriateness of the units used, and attempting with the help of ratios, logarithms, and the calculus of probabilities to discover relationships and regularity in order to make predictions" [5, p. 29]. Farr's philosophy had an almost immediate impact on improving British statistics. The first four censuses were fraught with many problems. The 1841 census was the first conducted under the supervision of the General Register Office and Farr was one of the key advisors. It was a great improvement over its predecessors and, together with the annual vital statistics data, enabled Farr to put together tables and analyses which placed England at the forefront of this discipline. Between 1836 and the Registration Act of 1874, Farr was largely responsible for establishing the procedures for collecting and analyzing the official mortality statistics. He introduced the standard **death certificate** in 1845 which saw almost no change until 1902. Through Farr's influence the census of 1851 introduced questions on physical disabilities and other medical items which were continued through 1911.

Farr was greatly interested in statistical nosology, introducing his first classification of diseases in 1839. The first International Statistical Congress in 1853 took up the issue, but Farr's nosology did not win the support of other European countries. It was not until 1893 that Jacques Bertillon (1851–1922) proposed a system that became the International List of Causes of Death (*see* **International Classification of Diseases (ICD)**).

Problems noted in the vital registration system in the mid-nineteenth century are still of concern at the end of the twentieth, namely accuracy of diagnoses was not reliable, selection of a single underlying cause of death (*see* **Cause of Death, Underlying and Multiple**) from among several listed

conditions, "the temptation of practitioners to obscure or falsify the cause of death to save respectable families embarrassment in certain sorts of death" [5, p. 62]. Henry Wyldbore Rumsey (1809–1876), one of the chief proponents of sound vital statistics, was vigorous in pointing out statistical fallacies and shortcomings of the existing systems that bear rereading today.

Many of Farr's statistical methods have had a lasting impact: defining mortality rates precisely and basing them on **person-years at risk**, establishing the standard expression of mortality as "deaths per thousand", using the life table and life expectancy as key instruments to assess mortality, using the method of indirect standardization (*see* **Standardization Methods**) to compare mortality rates of localities (although he seems to have made little use of the direct method first demonstrated by F.G.P. Neison in his refutation of the proposal of Edwin Chadwick (1800–1890) to use **average age at death** as a criterion for the health of communities), recommending the establishment of longitudinal **cohort studies** [9], and proposing a paradigm for the estimation of the economic value of human life at each age and social class. Farr's association with **Florence Nightingale** (1820–1910) also resulted in contributions to the use of statistical information for health policy purposes, particularly in respect to the graphic presentation of data (*see* **Graphical Displays**).

Development of Vital Statistics in the United States

As interest in statistical information burgeoned in Europe in the first third of the nineteenth century, a similar phenomenon was occurring on the other side of the Atlantic [4]. Although medicine, statistics, and science generally, in the US lagged behind that in Europe, America had actually preceded other countries in two important respects. Whereas other areas relied on church-maintained records of christenings and burials as the basis for vital statistics, the Massachusetts Bay Colony enacted a law in 1639 requiring the reporting of every birth and death within its jurisdiction, thus establishing the collection of vital statistics as a governmental function covering the entire population. The other colonies gradually adopted similar regulations but for at least the next two hundred years the quality and completeness of the reports were decidedly deficient. The second precedent was when the US became the first nation to establish by constitutional mandate a periodic census requiring complete enumeration of the entire population, conducting its first census in 1790.

At about this time death reports were being used on occasion in port cities to institute quarantine measures in efforts to control epidemics of cholera, yellow fever, and typhus. As the Benthamite social reform interests reached America and evidence for the harmful effects of poverty, industrialization, and unsanitary conditions was sought from vital statistics, the inadequacies of the city and local registration systems became evident. In 1826, Walter Channing (1786–1876) in Boston outlined some of the requirements for valid data on causes of death, including the requisite for medical certification. In 1827 Nathaniel Niles and John D. Russ published the first report on public health statistics in a comparison of mortality data from New York, Philadelphia, Baltimore, and Boston. Other analyses soon followed which became models for the quantitative health reports produced by subsequent generations of health officials which led to increasing pressures for improving the quality of the information. In 1842 Massachusetts again achieved a first by establishing a statewide vital registration system. The effort to establish similar systems in other states marked the beginning of an organized public health movement and contributed to the professionalization of statisticians in this country [2, 3].

Following on the foundation of the Statistical Society of London, statistical societies were started in New York and other American cities. Most did not last very long but the **American Statistical Association**, founded in Boston in 1839, proved to be enduring. It is significant that 14 of the original 54 local members were physicians. But it was a publisher and bookseller, Lemuel Shattuck (1793–1859), who was the Society's key "statist" for health-related issues. He consulted with, among others, Quetelet and was a prime mover for the Massachusetts Registration Act of 1842. He also played a role in the origins of national vital statistics by having mortality queries included in the 1850 census.

In 1846, the first national medical convention (which led to the founding of the American Medical Association) formed two committees relevant to health statistics: (i) a committee on registration

whose report "provided for the convention to formally petition every state government to enact effective registration legislation and to request state and local medical societies to take the lead in lobbying for such laws" [3, p. 201], and (ii) a committee on disease nomenclature which adopted a modification of Farr's classification. Neither of these recommendations was widely adopted for at least 50 years. Although there were many attempts, these efforts were often failures since "the registration movement had moved too far ahead of its base of community support" [3, p. 204]. At the end of the century, no state had a system as good as those in several European countries.

During the last two decades of the nineteenth century, the initiative for improving vital statistics shifted to the Federal government [8]. Under Dr John Shaw Billings (1838–1913), who directed vital statistics in the 1880 and 1890 US censuses, improvements were made in gathering mortality data. The **American Public Health Association** joined with the Census Bureau, which was established in 1902, in drafting a model vital statistics law and standard birth and death certificates that each state could adopt. Because of the early efforts of Cressy L. Wilbur (1865–1928), Chief Statistician for Vital Statistics from 1906 to 1914, the birth- and death-registration areas grew, reaching completeness in 1933, nearly a century after several European countries. The Division of Vital Statistics of the Bureau of the Census was transferred to the Public Health Service in 1946, becoming the National Office of Vital Statistics, with Dr Halbert L. Dunn (1896–1975) as Director. In 1960, NOVS was combined with the National Health Survey to become the **National Center for Health Statistics** with **Forrest E. Linder** (1906–1988) as its first Director.

Development of Health Surveys in the United States

The establishment of the National Health Survey in 1957 marked a milestone in health statistics. With only a few exceptions, previous data relating to health came from vital statistics or from diagnosed diseases seen in hospitals or included in various notifiable **diseases registers**. As public health concerns in the US shifted from the surveillance and control of acute **communicable diseases** to the prevention of chronic diseases, it was necessary to develop data systems that would better describe the current health status of the population (*see* **Quality of Life and Health Status**) and shed some light on health-associated behaviors and use of health care services (*see* **Health Services Organization in the US**). The National Health Survey was the first continuous nationwide survey to gather information from randomly drawn representative samples (*see* **Probability Sampling**) of the noninstitutionalized population of the country to accomplish these aims (*see* **Surveys, Health and Morbidity**). It consists of two distinct surveys: the National Health Interview Survey (NHIS) and the National Health Examination Survey, the latter subsequently expanded to the National Health and Nutrition Examination Survey (NHANES). The NHIS conducts interviews in about 1000 households each week to obtain information on acute illnesses, chronic conditions, health-related knowledge and behaviors, and use of health services. The NHANES involves detailed standardized medical examinations, including laboratory studies and special tests such as ECGs and X-rays, and extensive questionnaires on nutrition and previous health conditions. The NHANES is a periodic survey and NHANES III (actually the sixth cycle of these surveys), being carried out from 1988 to 1994, examined a sample of about 30 000 persons aged 6 months and over. Health interview surveys have now been conducted in many countries and examination surveys have been used effectively in several developing countries to assess the population's health.

These surveys would not have been feasible without the development of survey methodologies which occurred in the twentieth century. Anders N. Kiaer (1838–1919), the first director of the Norwegian Central Bureau of Statistics, reintroduced the idea of a survey sample in what he called the "representative method", in which the sample was to be selected purposively as Laplace had suggested a century earlier, rather than randomly. Arthur Lyon Bowley (1869–1957) is credited with being the first statistician to use random sampling (1906). The seminal breakthrough for sampling methodology came in 1934 when **Jerzy Neyman** (1894–1981) established the theoretical basis for **stratified sampling** with unequal inclusion probabilities. He made another major contribution when he introduced the use of cost functions into survey sampling theory (1938). In the early 1940s, Morris Hansen (1910–1990) and William Hurwitz (1908–1969) at the Bureau of

the Census perfected the methodologies for complex **multistage sampling** designs that are the basis for most modern large-scale surveys.

Conclusion

At the end of the twentieth century, most industrialized countries have effective vital statistics systems in place and many have established periodic interview surveys to assess the health status and needs of their citizens. Much remains to be done in developing countries to institute health services information systems (*see* **Administrative Databases**) that can guide public policies and programs. As the public health burden continues to shift from infectious diseases to problems of an aging population, to concerns about health promotion and disease prevention, and to assuring adequate health care for all citizens, the needs for reliable, relevant, and timely health statistics become ever greater. Fortunately, the methodologies developed over several centuries and the data systems that have been established can, if appropriate resources are provided, meet these needs.

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