ART. XIII – *Smallpox epidemics at Penrith in the 17th and 18th centuries*

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SMALLPOX has been described as the most infectious human disease known and was greatly feared in England from the time of the final visitation of bubonic plague in 1666 until the end of the 19th century when it ceased to be endemic.[1] Smallpox deaths were relatively rare in England until the 1630s and, after 1666, smallpox replaced plague as the most feared of diseases.[2] Many accounts suggest that a particularly virulent strain began to afflict people of all ages in the middle and later decades of the 17th century[3] and the evidence points to a gradual but significant increase in the virulence and case fatality rate of smallpox from the later 16th through to the end of the 19th century.[4] By the first half of the 18th century almost everyone had suffered at some time from the disease and it was thought to be directly, or indirectly, responsible for one death in every five. After 1750, inoculation or variolation began to be more widely administered among the educated and affluent, but there was a time-lag of about 10–20 years before the same degree of acceptance reached the northern counties of Cumberland, Lancashire and Yorkshire.[5] Although smallpox was not completely conquered, a rising proportion of the population had been given immunity by inoculation so that the potential breeding ground for smallpox was steadily contracting.

Smallpox was endemic in London during most of the 17th and 18th centuries but every few years there was a marked increase in deaths;[6] elsewhere the disease was usually absent for sustained periods, often between five and ten years (much longer in remote communities) with sporadic outbreaks being the result of infection introduced from outside. Consequently, it has been suggested that market towns and villages on main trading routes were particularly susceptible to random infection by travellers.[7] A considerable body of information concerning smallpox epidemics in rural England during the 17th and 18th centuries has been accumulated[8] but, inevitably, much of it is anecdotal or a synthesis of reports and opinions of the time. There are many accounts of major outbreaks throughout Britain.[9] For example "It was a major source of loss of life through the [18th] century and a disease relatively easily identified. In rural parishes and small towns it appeared every four years or so, usually in summer and sent up child mortality sharply".[10]

The community at Penrith

We are currently studying the parish of Penrith, Cumbria, making considerable use of the published parish registers, 1557–1812.[11] We have shown that this community was living under marginal farming conditions during the 17th and 18th centuries and suffered grievously from famines. Mortality was high and fertility was low from 1600 to 1750.[12] Penrith was also devastated by the plague in 1554 and 1597/98; 608 people died in this second visitation. Smallpox deaths were recorded in the Penrith parish registers only in 1656 and 1661 and consequently we have had to resort to

indirect evidence to determine whether smallpox epidemics occurred regularly at that time.

Dynamics of smallpox infections

Epidemics of viral infections (both currently and historically) have been modelled mathematically and by computer simulations, and the periodicity of such epidemics can be predicted from the equation

$$T = 2 \Pi \sqrt{(AD)}$$

where T = the interepidemic period, A = average age of infection and D = the sum of the latent and infectious periods.[13] The value of D for smallpox is 12 days. We have determined the ages of those dying of smallpox at Penrith in the known epidemics of 1656 and 1661 by family reconstitution; their mean age (including two adults) was 4.5 years. Smallpox has been recorded as being almost wholly a disease of children and nearly all native inhabitants of London had been infected by the age of seven. In Kilmarnock, 1728–62, the mean age at death from smallpox was 2.6 years and of a total of 613 smallpox deaths, 563 occurred under the age of 5.[14] Inserting a value of 5 years for A in the equation above suggests that the interepidemic period for smallpox was 2.5 years, i.e. epidemics would be expected every two to three years, a value that we have shown to be correct for London from a study of the Bills of Mortality, 1647–1812. Did Penrith, a semi-isolated, rural community, some 280 miles away, suffer from similar 2–3 year outbreaks of the disease?

Smallpox epidemics at Penrith

We have used a technique called time-series analysis to investigate the burial series of the parish registers. This is a technique that enables one to filter by computer a noisy data series, thereby removing unwanted oscillations and fluctuations, and leaving cycles of specified wavelength. The computer programme allows the design of the filter to suit individual requirements. Since smallpox was a disease that was largely confined to children we initially determined child mortality for each year, 1600–1812, and these are shown plotted in Fig. 1. Preliminary analysis of this time-series suggests that there is a short wavelength oscillation (period of about 5 years) contained within it. Fig. 2 shows the same data after filtering to reveal any oscillations in the waveband 4 to 9 years, and regular cycles of childhood mortality can now be clearly seen. Time-series analysis tells us that these cycles have a period of five years.

Are these cycles associated, in whole or in part, with smallpox epidemics? Did Penrith experience regular outbreaks of smallpox every five years? We have examined the records further as follows. Many historical reports[15] show that smallpox epidemics exploded suddenly but quickly burnt out so that major outbreaks tended to be confined to a few months in the year. Inspection of the child

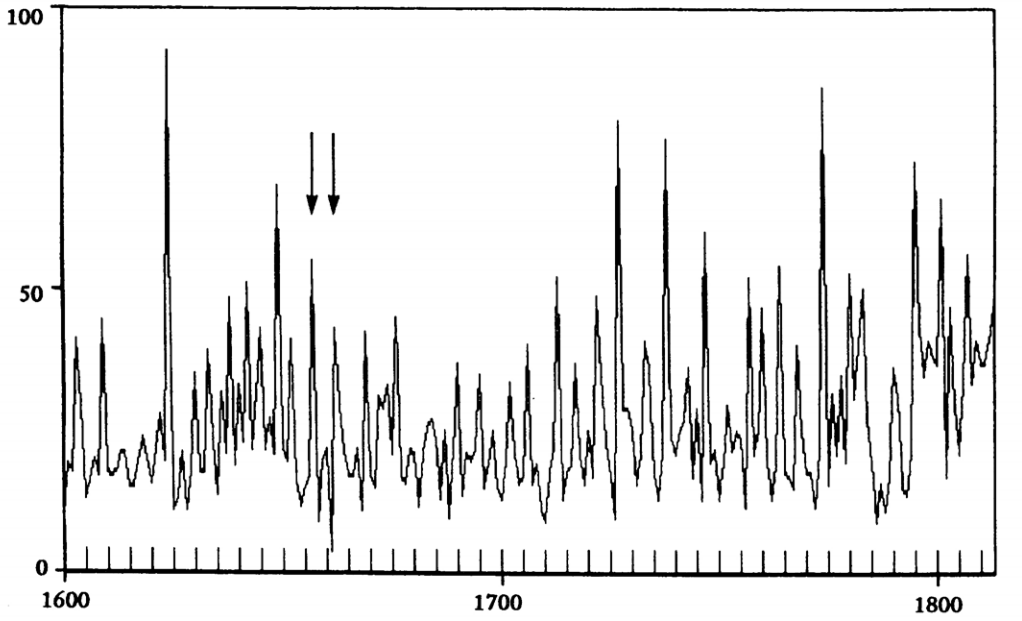

FIG. 1. The annual number of child burials at Penrith 1600–1812. Arrows indicate the years in which an outbreak of smallpox was recorded in the parish registers.

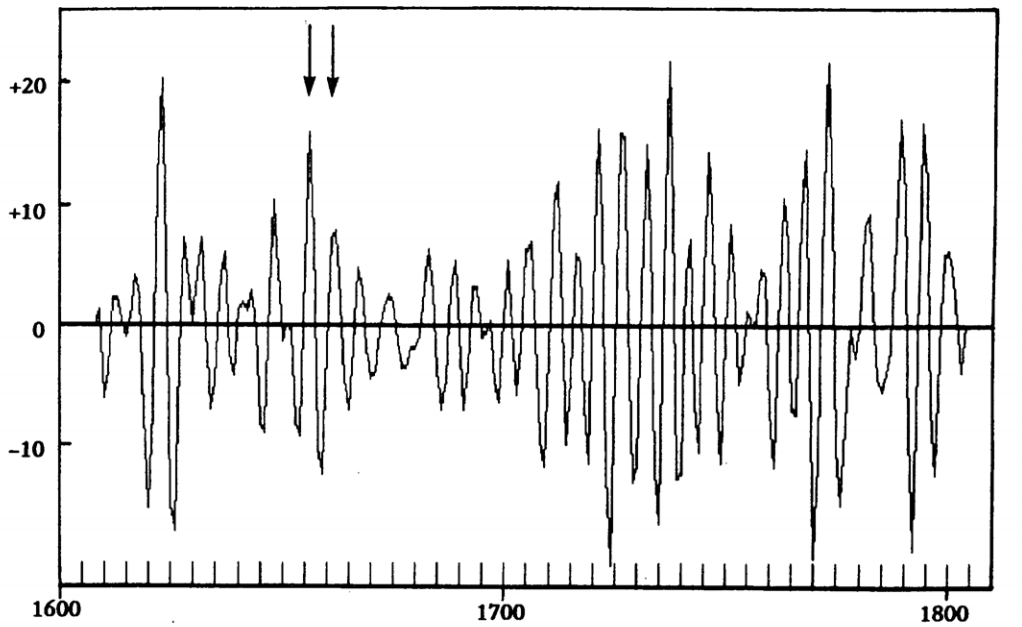

FIG. 2. Child burials series 1600–1812 after filtering; the 5-year oscillations in mortality are clearly seen. Filter "window" = oscillations of wavelengths 4 to 9 years. Arrows indicate the years in which smallpox epidemics are known to have occurred.

burial registers show periodic aggregations of deaths for 10–12 weeks. The series has therefore been analysed by determining the largest total of deaths for three consecutive months in each year. Again, a five-year oscillation is revealed by filtering which synchronizes exactly with that shown in Fig. 2.

Child burials were then determined on a month-by-month basis and the data series studied by time series analysis. Again, filtering revealed a clear oscillation with a period of 63 months (i.e. a peak of child mortality every 5 years 3 months). From the foregoing there is evidence of 5-year epidemics at Penrith of an infectious, lethal disease, with a strong seasonality, and in which the epidemic burnt out within three months with the disease apparently largely confined to the children. The peaks of these 5-year cycles fit with the recorded years of smallpox outbreaks and we suggest that this study provides evidence of smallpox epidemics with an interepidemic period of 5 years. There is no evidence that smallpox persisted during the interepidemic years, i.e. the disease was not endemic.

This 5-year oscillation in child deaths is detectable from the start of the parish register series in 1557. A comparable 5-year cycle in adult deaths emerged only after 1585 (adult deaths do not, however, show any periodicity when calculated on a monthly basis or as the largest total for three consecutive months in each year). There is evidence, therefore, of a basic 5-year cycle in total deaths developing progressively from as far back as the middle of the 16th century, perhaps driven by cyclical, external factors, with the children showing greater sensitivity to them than the adults.

However, the data both for the annual greatest 3-monthly totals for child burials and for monthly child burials show clearly that the seasonal, explosive outbreaks in child (but not adult) mortality did not begin until after 1636, lending credence to the view that a virulent form of smallpox developed during the mid-17th century.[16] We conclude tentatively that the serious, lethal smallpox epidemics at Penrith began about this time (at approximately 5-yearly intervals) and were superimposed on a pre-existing 5-year mortality cycle that was detectable by 1557.

The general, 5-year mortality cycle

What caused the persistent 5-year cycles in child burials at Penrith, that were established by 1557 and are believed to be related to smallpox epidemics in the next century? There is good evidence that infection in many diseases is linked to poor nutrition[17] and it has been suggested that smallpox epidemics have been specifically related to poverty and famine.[18] Annual wheat prices would reflect both the quality of the harvest and the level of hardship, famine and malnutrition, particularly among the labourers and poorly paid. The quality (as well as the quantity) of the diet of pregnant and nursing mothers is known to be of particular importance in determining the birth weight and health of the children.[19] Data for annual wheat prices, 1600–1812, have been taken from Stratton[20] and filtered and, once again, a clear 5-year cycle was demonstrated by time series analysis which synchronized exactly with the child burials series. We have tested further the thesis that wheat prices drive child deaths and have shown that the result is highly significant statistically. We suggest that there is evidence that regular cycles in wheat prices

drive oscillations in child deaths at Penrith which are associated, both directly and indirectly, with malnutrition.

We conclude that the 5-year oscillation in wheat prices generated the 5-year oscillation in child deaths in the 16th century; 100 years later the smallpox epidemics were superimposed on this pre-existing cycle of mortality which caused corresponding fluctuations in susceptibility to the disease, thereby exacerbating the oscillations in child mortality.

Why were the epidemics of smallpox at Penrith at 5-yearly intervals?

Mathematical modelling shows that an epidemic cannot explode unless there is an adequate number and density of susceptible individuals to ensure the spread of the outbreak.[21] Once an epidemic among susceptibles had burnt out, leaving the immune survivors, it took 5–6 years to build up by new births an adequate density of susceptibles of 1 to 6-year olds because of the relatively small size of the population and low birth rate at Penrith. Thus, the 2- to 3-year interepidemic intervals predicted by the equation above were not experienced at Penrith because of the time taken for an adequate density of susceptible children to be re-established.

Mathematical theory of the epidemics of viral diseases also predicts that, if the system is undisturbed, the epidemics will die out. This was clearly not the case, at Penrith, where periodic outbreaks of smallpox persisted for at least 150 years. We suggest that there are two reasons for this apparent discrepancy. Firstly, the population (unlike London) was too small for the disease to become endemic; after one or two epidemics, quite literally, almost all people within the town would have been exposed and the survivors would be immune. Secondly, every five years or so, just when new births had provided a sufficient supply of susceptible individuals, the population suffered from food shortages which led to ill-health and a greater susceptibility to disease; this was an adequate trigger to initiate the next epidemic.

The pattern of a smallpox epidemic at Penrith, 1650–1750

Births at Penrith remained remarkably constant during 1650–1750, with an average of 65 per year. Since the interepidemic interval was 5 years, approximately 325 children would be born during this time to establish a potential pool of susceptibles. We estimate that the total population, 1650–1750, was perhaps 2000–2200, so that, after 5 years potentially 15% of the population would have become susceptible.

Of the recorded epidemics at Penrith, 28 children and 2 adults died in 1656 and 31 children died in 1661. We estimate that between 1635 and 1670 the mean number of children dying within a 3-month period during the epidemics was 26; this figure fell to 17 from 1670–1710 but rose to 28 thereafter. Probably the mean total deaths from smallpox in each epidemic was about 26.

We have determined mortality curves for the population at Penrith by family reconstitution; 38% of children born during 1650–1700 died before reaching the age of 6 years. Thus, of the potential pool of 325 susceptible children born during the 5-year interepidemic period, 124 died of which, on average, 26 died of smallpox

during an epidemic. So that, of the original pool of 325 susceptibles, 201 survived both smallpox infection and the other hazards of childhood. A proportion of the population, particularly those in outlying and isolated farms, may have avoided exposure to the virus throughout their lifetime. If (say) 10% of the 201 1- to 6-year olds were never infected with smallpox during their lifetime, 180 recovered from the disease and became immune. Hence, 206 were infected, of which 26 died and 180 recovered, and the mortality of those children who caught smallpox in this rural community was approximately 12% – a serious threat in childhood but it should be remembered that 22% of children in Penrith died of other causes in the first year of life at that time.

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