PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Forecasting the Airborne Spread of Foot-and-Mouth Disease and Newcastle Disease [and Discussion]

J. Gloster, L. P. Smith, W. H. G. Rees, J. D. Gillett, A. I. Donaldson, J. G. Loxam, R. F. Sellers and F. B. Smith

Phil. Trans. R. Soc. Lond. B 1983 **302**, 535-541
doi: 10.1098/rstb.1983.0073

Phil Trans. R. Soc. Lond. B **302**, 535–541 (1983)
Printed in Great Britain

Forecasting the airborne spread of foot-and-mouth disease and Newcastle disease

By J. Gloster

Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, U.K.

The methods used in the United Kingdom to predict the airborne spread of foot-and-mouth disease and Newcastle disease are described in this paper. A brief description of both diseases and of the importance of their control is given first. Developments leading to the present methods of prediction are also described.

The importance of controlling foot-and-mouth disease and Newcastle disease in the United Kingdom

Outbreaks of foot-and-mouth disease (FMD) and Newcastle disease (ND) can impose a severe financial strain on the livestock industry in the United Kingdom. Losses may occur under three main headings: through severe reduction in export of livestock to other countries, by lowering productivity within the country and finally through the cost of control of outbreaks. The Ministry of Agriculture, Fisheries and Food (M.A.F.F.) is responsible for the controls that minimize the chance of the diseases entering the country, and in the event of an outbreak for taking steps to detect, control and eradicate the disease. To perform these tasks most effectively M.A.F.F. must be aware of all possible routes by which the diseases spread and, for any particular outbreak, must recognize the relative importance of these routes.

Foot-and-mouth disease

The characteristics of FMD have been summarized by Donaldson in the previous paper in this symposium.

FMD is not endemic in the United Kingdom; disease incidence has varied through the years from 2210 cases in 1967 to nil during the whole period 1969–80 (figure 1). When outbreaks occur the Government maintains a slaughter and compensation policy; affected livestock and those in contact to a degree likely to lead to their becoming infected are valued and slaughtered and the owner compensated. During a major epidemic in 1967/8 over 400000 animals were destroyed and £27M paid in compensation. Estimates of the total cost of this epidemic to the industry have reached up to £150M (*Report of the Committee of Inquiry on Foot and Mouth Disease* 1968); included in this figure are estimates for such factors as loss of earnings incurred in the period after slaughter and before restocking. An epidemic of similar size but at current prices would probably cost £100M in compensation alone.

FMD can be transmitted by airborne virus, as well as by movements of animals, animal products, vehicles and people (Henderson 1969; Smith & Hugh-Jones 1969; Wright 1969; Hugh-Jones & Wright 1970; Sellers & Forman 1973).

Newcastle disease

ND (or fowl pest) is a highly contagious viral disease that chiefly attacks chickens and turkeys. Disease severity varies with the virulence of the virus; severe forms result in 100% mortality whereas mild forms may produce mild or even subclinical infection.

The incidence of disease over the last 32 years is given in figure 1. The last major epidemic, when 7533 cases were reported, occurred during the period 1970/71. Since that time, with the exception of one outbreak in 1978, the United Kingdom has remained disease-free.

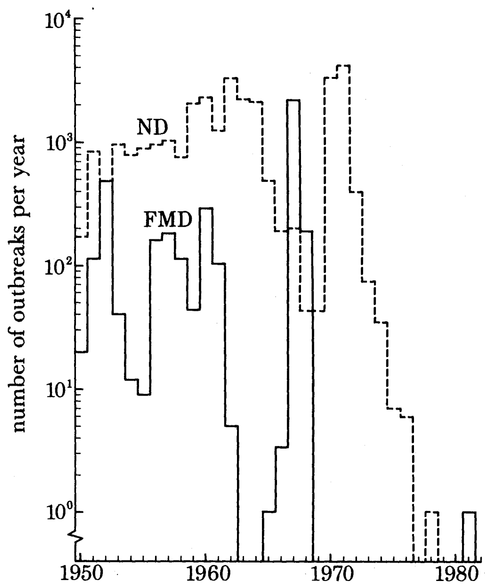

FIGURE 1. The number of confirmed outbreaks of FMD (——) and ND (---) over the period 1950–82.

Accurate estimates for the cost of epidemics are hard to ascertain. However, it is probable that the 1970/71 epidemic cost the poultry industry in excess of £20M (Allan & Stuart 1974).

It has been proposed that the major mechanism of transmission of ND within a flock is by airborne virus (see, for example, Sinha *et al.* 1954; Hugh-Jones *et al.* 1973). It has also been suggested that disease spread from one flock to another may be caused by airborne virus (Drummond & Hunnam 1961; Smith 1964; Gilmore 1971; Gloster 1983*a*). ND has also been shown to be transmitted by the movement of infected poultry, contaminated feed stuffs, carriage of infected materials (e.g. crates and feed sacks) and by movement of people carrying virus on their hands and clothes (Jungherr & Terrell 1964; Dobson & Simmins 1951; Bolin 1948; Jungherr & Markham 1962).

AIRBORNE TRANSMISSION OF ND AND FMD (1960–81)

After a series of apparently inexplicable outbreaks of ND near Bedford, England, during 1960 the Meteorological Office were asked if the weather could have influenced the pattern of disease spread. M.A.F.F. veterinarians believed that virus had been released into the atmosphere from the affected birds. For each of the outbreaks the potential for downwind dispersal of airborne particles was estimated for the period before confirmation of disease, and Smith (1964) concluded that much of the disease spread might have been attributable to airborne virus.

The explosive spread of FMD during the very early stages of the 1967/8 epidemic in the United Kingdom was unparalleled in British experience of the disease. By the end of the third week 349 cases had been confirmed, the majority of which were situated in Shropshire, Flint, Denbigh and Cheshire. Later studies of the meteorological conditions and the geographical distribution of outbreaks suggested that the wind could have played an important part in the initial spread of infection. At the time of the first outbreak and for the following 19 days the prevailing wind was from the southwest and 75 of the first 100 outbreaks were to the north and northeast of initial outbreak (*Report of the Committee of Inquiry on Foot and Mouth Disease* 1968; Smith & Hugh-Jones 1969; Hugh-Jones & Wright 1970).

Such was the strength of the evidence on windborne spread of the disease that the Committee of Inquiry on Foot and Mouth Disease recommended in its Report the establishment of an epidemiological team to investigate future outbreaks and if possible help in their control by predicting spread. This team was later established with personnel from the Animal Virus Research Institute (A.V.R.I.), the Ministry of Agriculture's Veterinary Laboratory Services and Field Service, and the Meteorological Office. The meteorologist's function was to predict airborne disease spread in the light of prevailing atmospheric conditions. A simple system was designed to aid prediction in which the wind directions, over a defined period, would be analysed and a risk sector defined. The limitation of this scheme was demonstrated in a simulated disease outbreak in which virus was assumed to have been emitted into the atmosphere over a 10-day period. During that time the wind direction swung throught 360°; consequently, it was very difficult to assess the likely area within which secondary infection might occur (Blackall & Gloster 1981).

Laboratory investigations into the airborne properties of FMD virus were intensified from 1968 onwards. By 1981, much had been learnt about the quantity of virus released into the atmosphere from affected animals, virus survival once airborne, and the ability of the virus to cause infection (Sellers & Parker 1969; Donaldson *et al.* 1970; McVicar 1977; Sellers 1971; Sellers *et al.* 1971; Barlow 1972; Donaldson 1972).

To summarize, during the period 1960–81 airborne transmission of FMD and ND had been postulated, with meteorological and laboratory findings, particularly in the case of FMD, supporting this suggestion. A simple attempt had also been made to predict airborne transmission of FMD.

Prediction of airborne spread of FMD and ND, 1982/3

An adequate forecast of the spread of airborne disease can only be made when it is possible to estimate the following: (*a*) the quantity of virus released into the atmosphere, (*b*) how well this virus survives once airborne, and how it disperses, and (*c*) the method and dosage required to cause infection.

It is possible to attempt such a prediction for FMD, because much is known about each of these three areas. It is more difficult to predict airborne spread of ND because fewer quantitative data are known (for a detailed discussion see Gloster (1983*b*)).

The methods currently used to predict airborne transmission of FMD and ND in the United Kingdom are now discussed.

Long-distance spread of FMD over the sea

Long-distance disease spread over the sea is most likely when the following four conditions are satisfied simultaneously: (*a*) high output of virus, (*b*) low dispersion of virus, (*c*) high survival of virus and (*d*) large numbers of susceptible livestock exposed to virus for many hours. In practice these conditions are achieved in the following circumstances. High outputs of virus are usually associated with disease in pigs; at the time of generalized lesions pigs excrete 30 to 2000 times more virus than do cattle or sheep (Sellers *et al.* 1973). Secondly, low dispersion of virus occurs with low levels of atmospheric turbulence associated with stable surface air, and light winds (Gloster *et al.* 1982). Thirdly, high survival of virus occurs when the relative humidity of the air is greater than about 60% (Barlow 1972; Donaldson 1972). Fourthly, a large number of cattle should inhale air containing virus for many hours; cattle have been shown to be the most susceptible of the livestock to airborne infection (Chamberlain 1970; Sellers 1971; McVicar 1977).

In the specific case of predicting the likelihood of disease transmission from the European Continent to the U.K. the steps involved are as follows:

(1) reports of confirmed outbreaks of FMD are received by M.A.F.F. via the Office International des Épizooties;

(2) M.A.F.F. pass the known disease information to the Meteorological Office and A.V.R.I.;

(3) the A.V.R.I. estimate the likely period for virus emission;

(4) the surface meteorological charts are then examined to determine whether emitted virus would have been carried towards the U.K., and an estimate for atmospheric dispersion is made;

(5) the direction for disease spread is then estimated and passed to M.A.F.F.;

(6) the Ministry veterinarians in areas thought to be at risk are alerted.

This procedure was operated during March 1981 when, after notification of disease in Brittany, France an early warning of potential spread of disease to the United Kingdom was issued by the Meteorological Office and A.V.R.I. to M.A.F.F. (Donaldson *et al.* 1982). As a result, when disease occurred within the predicted zone, veterinary staff who were on alert were able to take immediate and effective action. These events contrast with those in Denmark during 1982, when no early warning of disease spread was given, disease diagnosis took several days, and as a result disease spread to 20 other farms.

Short-distance spread of FMD over the land

Blackall & Gloster (1981) and Gloster *et al.* (1981) described a numerical model that has been constructed to provide an objective estimate of the area most at risk from a known source. This model forms the basis for advice on airborne disease spread and replaces the simple method described in an earlier section. An estimate of daily virus output, provided by the epidemiological team, together with meteorological data and details of the topography surrounding the outbreak, serves as input to the model. The Gaussian dispersion equation is then solved for the whole of the emission period and a daily inhaled dosage for cattle estimated. The calculations are performed at each of 360 grid points within a 10 km radius from the source. The results of the calculations are made available to M.A.F.F. within a few hours of the input being available. The model was run operationally during the 1981 outbreak of FMD on the Isle of Wight (Donaldson *et al.* 1982). Disease was suspected on the afternoon of 21 March and by later that day a preliminary estimate of the area at risk from virus emitted from the

Isle of Wight was available to M.A.F.F. When the epidemiological team had fully assessed the potential virus release the area at risk was updated. The results suggested that there was very little likelihood of virus being carried either to other farms on the island or to the mainland. No further disease spread was in fact recorded.

Short-distance spread of ND over the land

It was pointed out earlier that prediction of spread of ND was more difficult than that of FMD as fewer quantitative data are available on, for example, the amount of this virus emitted by infected livestock, or on infective dosages. Consequently the model used to predict airborne spread of FMD is not suitable for use with ND. However, it is possible to estimate the direction of spread of disease. An inspection of affected birds can yield information about the period of virus release and the history of the disease on the farm. By combining this information with wind observations representative of those experienced at the farm a sector at risk can be defined. When the wind has blown from a constant direction throughout the period the sector is narrow and the farms at risk can be easily identified. When the sector is large it is necessary, but difficult, to identify which farms are preferentially at risk. The difficultly arises because little is known about the relation between infection and the number of birds at a given location, the age of the birds, the health of the birds, etc. (Gloster 1983*b*); for example a large unit exposed to virus for a short period may be more at risk than a smaller one exposed to virus for many hours.

Future developments

FMD

A forecast of the risk of spread of disease from the near European Continent to the United Kingdom and within the country can already be made by using the techniques described in the previous section. Any future research will concentrate upon refining these methods and providing better input data.

A sector of disease spread over a long sea passage is identified at present by examining the surface meteorological observations. However, wind directions over the virus emission period, a matter of days, are often variable, and consequently the sector at risk may be large. When this occurs it is necessary to identify the area most at risk. If the track of parcels of air originating at the virus source can be estimated accurately then these areas can be found. Clearly a practical system needs to be devised that includes precise trajectory analysis in the prediction procedure.

A limitation of the present model for prediction of disease transmission over the land is that calculations are restricted to 10 km radius from the virus source. If large quantities of virus are released into the atmosphere the disease may spread substantially further. Thus a model that deals with greater distances needs to be developed; it will also need to incorporate a method of determining virus trajectories away from the source with greater accuracy than at present.

ND

Prediction of airborne spread of ND is more difficult to estimate than that of FMD; the reasons for this have been discussed earlier. Before an accurate prediction of disease spread, with the use of models similar to that of FMD, can be made the following questions need to be answered.

(*a*) How much virus, as a function of virus strain, stage of disease, and age of the poultry, is released into the atmosphere?

(*b*) Once airborne, what governs virus viability?

(*c*) What is the minimum quantity of virus to cause infection?

(*d*) What effect does the number of birds exposed to virus have upon the likelihood of subsequent infection?

References

Allan, W. H. & Stuart, J. C. 1974 In *Proceedings and abstracts, 15th World Poultry Congress and exposition, New Orleans, 11–16 August, 1974*, pp. 408–411.
Barlow, D. F. 1972 *J. gen. Virol.* **15**, 17–24.
Bolin, F. M. 1948 In *Proc. 48th Meet. Soc. Am. Bacteriologists*, p. 43.
Blackall, R. M. & Gloster, J. 1981 *Weather, Lond.* **36**, 162–167.
Chamberlain, A. C. 1970 *Nature, Lond.* **225**, 99–100.
Dobson, N. & Simmins, G. B. 1951 In *Rep. 9th World's Poult. Cong., Paris*, vol. 3, pp. 18–21.
Donaldson, A. I. 1972 *J. Gen. Virol.* **15**, 25–33.
Donaldson, A. I., Gloster, J., Harvey, L. D. J. & Deans, D. H. 1982 *Vet. Rec.* **110**, 53–57.
Donaldson, A. I., Herniman, K. A. J., Parker, J. & Sellers, R. F. 1970 *J. Hyg., Camb.* **68**, 557–564.
Drummond, D. J. & Hunnam, R. 1961 *State vet. J.* **16**(46), 42–52.
Gilmore, J. D. 1971 *State Vet. J.* **26**(77), 135–136.
Gloster, J. 1983*a* *J. agric. Met.* **28**, 177–189.
Gloster, J. 1983*b* *Br. vet. J.* (In the press.)
Gloster, J., Blackall, R. M., Sellers, R. F. & Donaldson, A. I. 1981 *Vet. Rec.* **108**, 370–374.
Gloster, J., Sellers, R. F. & Donaldson, A. I. 1982 *Vet. Rec.* **110**, 47–52.
Henderson, R. J. 1969 *J. Hyg., Camb.* **67**, 21.
Hugh-Jones, M. E., Allan, W. H., Dark, F. A. & Harper, G. J. 1973 *J. Hyg., Camb.* **71**, 325–339.
Hugh-Jones, M. E. & Wright, P. B. 1970 *J. Hyg., Camb.* **68**, 253–271.
Jungherr, C. L. & Markham, F. S. 1962 *Poultry Sci.* **41**, 522–528.
Jungherr, C. L. & Terrell, N. 1962 In *Proc. 50th Annual Meet. U.S. Livestock Sanit.*, pp. 158–171.
McVicar, F. 1977 *Boln Cent. Panam, Fiebre Aftosa* **26**, 9–14.
Report of the Committee of Inquiry on Foot-and-Mouth Disease 1968 Part One. London: H.M.S.O.
Sellers, R. F. 1971 *Vet. Bull.* **41**, 431–439.
Sellers, R. F. & Forman, A. J. 1973 *J. Hyg., Camb.* **71**, 15–34.
Sellers, R. F., Herniman, K. A. J. & Donaldson, A. I. 1971 *Br. vet. J.* **127**, 358–365.
Sellers, R. F. & Parker, J. 1969 *J. Hyg., Camb.* **67**, 671–677.
Sinha, S. K., Hanson, R. P. & Bradley, C. A. 1954 *Am. J. vet. Res.* **15**, 287–292.
Smith, C. V. 1964 *Met. Mag.* **93**, 257–263.
Smith, L. P. & Hugh-Jones, M. E. 1969 *Nature, Lond.* **223**, 712.
Wright, P. B. 1969 *Weather, Lond.* **24**, 204–213.

Discussion

L. P. Smith (*formerly Meteorological Office, Bracknell, Berkshire, U.K.*). The outbreak of a disease seems to depend on the coincidence in time and place of two or more 'stresses', principally a pathological 'stress' and environmental (meteorological) 'stress'. Before a disease outbreak can develop into an epidemic, it appears necessary for there to be a succession of such coincidences, and it appears likely that the interval between these events is a function of the incubation period of the disease. This hypothesis would explain why epidemics are relatively infrequent, because the probability of such as sequence of coincidental events is small.

W. H. G. Rees (*M.A.F.F., Tolworth, Surbiton, U.K.*). Another important factor in assessing the potential for airborne transmission of FMD virus is the population density of the target animals, in this case mainly cattle, in the area under threat. It is highly unlikely therefore that even if climatic conditions had been favourable for spread from the Isle of Wight outbreak in 1981 a situation similar to that in the west Midlands in 1967 would have developed.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

J. D. Gillett (*London School of Hygiene and Tropical Medicine, U.K.*). I was interested in Mr Gloster's remarks about aerial passage of FMD virus and humidity: some 20 years or more ago it was suggested that whereas the aerial passage of polio virus depends on a high relative humidity, the aerial passage or spread of influenza virus depends on or is more likely at a low humidity; hence poliomyelitis tends, in temperate zones, to be a disease of summer and influenza a disease of winter. Has any recent work been done that supports or throws light on this question?

A. I. Donaldson (*Animal Virus Research Institute, Pirbright, U.K.*). Although laboratory studies (J. H. Hemmes, K. C. Winkler & S. M. Kool (1960) *Nature, Lond.* **188**, 430–431) have shown that lipid-containing viruses such as influenza virus survive best in aerosols at low relative humidity whereas naked viruses such as poliovirus survive best at high relative humidity, it is likely that other factors account for the seasonal incidence of these diseases. There are examples of other viruses that can spread by the respiratory route causing disease at times of the year when relative humidity conditions are likely to be unfavourable for their airborne survival, e.g. the spread of human colds due to rhinoviruses, indoors in winter. It therefore appears that adverse relative humidity exerts only a minor influence in these circumstances. With longer periods of exposure to the atmosphere, e.g. in the long-distance spread of foot-and-mouth disease, the effect of relative humidity is likely to be more important.

J. G. Loxam (*State Veterinary Service, M.A.F.F., Tolworth, Surbiton, U.K.*). The State Veterinary Service greatly appreciates the cooperation and service of the Meteorological Office in forecasting possible incursions and spread of foot-and-mouth disease. It is most useful in control planning, and epidemiologically in determining the possible origin of infection.

We must, however, put into perspective the role of the airborne route of spread of foot-and-mouth disease. Movements of animals, animal products, livestock vehicles, people, etc., are still the most important, and fortunately these modes of spread are controllable; atmospheric conditions are not.

R. F. Sellers (*Animal Virus Research Institute, Pirbright, U.K.*). Various mechanisms have been described by which the numbers of insects are concentrated at the end of their flight. Are there any mechanisms by which virus particles or spores are concentrated?

F. B. Smith. Concentration of virus particles or spores cannot take place if they act as purely passive particles following the motions of the air: turbulence on its own can only dilute material, never concentrate it.

However, if the particles have a significant terminal velocity (1 m s^{-1} or greater) and do not stick to the ground but are constantly being resuspended back into the atmosphere, then a concentration continually increasing with time near the ground can result. Similarly, rain or snow can capture particles, bring them down to the ground from aloft and, if resuspension occurs, then again increased concentrations can result, even if the particle's terminal velocity is small.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES