

Destructive tension: mathematics versus experience – the progress and control of the 2001 foot and mouth disease epidemic in Great Britain

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Summary

The 2001 foot and mouth disease epidemic in Great Britain was characterised by control using both traditional and novel methods, some resulting from conclusions of mathematical models. Seven days before the implementation of the novel controversial automatic pre-emptive culling of all susceptible livestock on premises adjacent to infected premises (the 'contiguous cull'), the spread of infection had already been controlled by a combination of the traditional stamping out policy with a national movement ban on livestock. A second controversial novel policy requiring the slaughter of sheep within 3 km of premises on which disease had been confirmed (the 3-km cull) also commenced after the peak of infection spread, was untargeted and took several weeks to complete; serosurveillance of culled sheep detected infection in only one flock, suggesting that cryptic infection of sheep was not propagating the epidemic. Extensive post-epidemic serological surveillance of sheep found only a small number of seropositive animals in a very few flocks, suggesting that foot and mouth disease may self-limit in extensive sheep populations. The epidemic was finally brought to an end following the introduction of enhanced agricultural movement restrictions and biosecurity measures. A welfare culling scheme of unaffected animals was required to support the prolonged national livestock movement ban. The models that supported the contiguous culling policy were severely flawed, being based on data from dissimilar epidemics; used inaccurate background population data, and contained highly improbable biological assumptions about the temporal and quantitative parameters of infection and virus emission in infected herds and flocks.

Keywords

2001 – 3-km sheep cull – Biosecurity – Britain – Contiguous culling – Control procedure – Foot and mouth disease – Great Britain – Mathematical model – Stamping out.

Introduction

A total of 2,026 outbreaks of foot and mouth disease (FMD), caused by the Pan-Asia O strain of FMD virus, was confirmed in Great Britain (comprising England, Scotland and Wales) between 20 February and 30 September 2001.

This marked the end of the country's longest period of freedom from FMD in recent history; the last epidemic on the mainland having occurred in 1967/1968 (9). The various control policies (some traditional, some novel) that were applied in 2001 resulted in the destruction of more than 6,500,000 animals.

The virus

The type O Pan-Asia strain, which was responsible for the 2001 epidemic in Great Britain, was first identified in India during 1990. It spread northwards into Nepal in 1993, westward into Saudi Arabia during 1994 and then throughout the Middle East, essentially becoming endemic and progressively displacing the other type O strains that were circulating. In 1996 it reached Turkey, from where it spread into Greece and Bulgaria. The virus reached mainland China by 1999, as well as Chinese Taipei, and in 2000 it was identified in South Korea, Mongolia, eastern Russia and Japan – the last country having been FMD-free for almost 100 years. In September 2000, it caused the first outbreak of FMD type O in southern Africa, near Durban in the Republic of South Africa. The origin was attributed to the feeding of untreated ships' waste to pigs. Phylogenetic analyses showed an extremely close relationship between the Great Britain and South African virus isolates (42), but South Africa was ruled out as the source of the epidemic in Britain because the virus had been eradicated from South Africa many months previously. It is probable that the Great Britain and South African epidemics had a common, unidentified source.

The index case and the hunt for the primary case

The first suspicion of FMD in the 2001 epidemic was reported to the Ministry of Agriculture, Fisheries and Food (MAFF), which later, in June 2001, became the Department for the Environment, Food and Rural Affairs (DEFRA), on Monday, 19 February, by the Official Veterinarian (OV) at an abattoir in Essex (Fig. 1) in the south-east of England (23). On that morning, the OV had observed vesicular lesions in sows delivered to the abattoir on Friday, 16 February, from two farms in southern England. Samples collected from these pigs were submitted to the World Reference Laboratory for FMD at Pirbright, Surrey, which confirmed infection with FMD type O virus on Tuesday, 20 February. At this time, early lesions of FMD were also found in boars delivered to the abattoir from a farm in northern England on Sunday, 18 February. Immediate tracing visits were made by MAFF veterinarians to the three farms, but no disease was found. All the farms previously visited by the livestock delivery vehicles that had transported the pigs to the abattoir were identified, visited and had all their livestock examined, with similar negative results. The absence of disease on these farms, and in the area around the abattoir, made it increasingly likely that the abattoir had been contaminated by a previous consignment of infected animals, in which disease had not been detected. Urgent veterinary visits

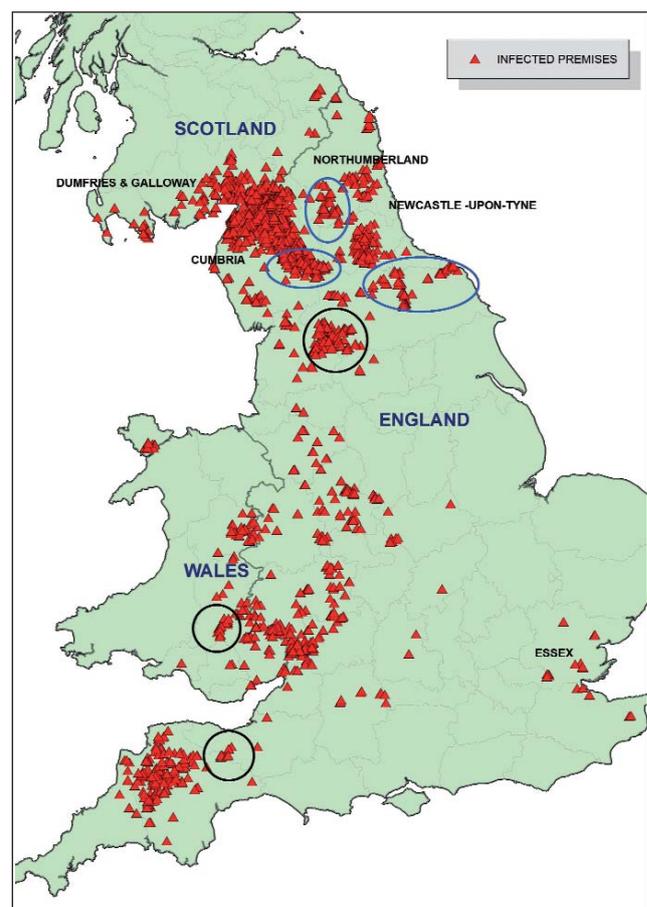


Fig. 1
Location of infected premises confirmed in Great Britain in the 2001 foot and mouth disease epidemic

Circled are those areas where disease was confirmed between July and September 2001 during the epidemic 'tail'. Blue circles indicate areas subject to measures for restricted infected areas implemented after 27 July 2001

then began to the 600 farms that had supplied livestock (mostly pigs) to the abattoir in the previous two weeks, with priority being given to premises licensed to feed processed waste food.

The epidemic's primary case

On Thursday, 22 February, disease was found in pigs on premises feeding waste food at Heddon-on-the-Wall, near Newcastle-upon-Tyne in the north-east of England (Fig. 1), 400 km from the confirmed outbreak at the abattoir in Essex. When contacted the previous day, the premises' operator had declined an immediate visit, responding that there was nothing wrong with his pigs. Prior to slaughter two days later, on 24 February, almost 90% of the 540 pigs on the premises, comprising cast (formerly breeding animals being fattened) sows and boars, and fatteners,

were found to be clinically affected with FMD. The lesions ranged from one to 12 days of age, with almost half of the pigs showing lesions of more than nine days. Almost all of the remaining clinically normal pigs tested positive for antibodies against FMD, based on blood samples taken at the time of examination (1). It was estimated that clinical disease had been present on this farm since at least 12 February, and that infection could have been introduced to the pigs as early as 26 January, by the feeding of unprocessed waste food that was found on the premises. The finding of cutlery and bones in the troughs and pens with the pigs clearly indicated that the waste material had not been subjected to a maceration procedure (1, 23). Subsequently, in April 2001, MAFF investigators discovered commercial quantities of illegally imported, air-dried, bone-in, pork legs from Asia, at the premises of a wholesaler supplying local restaurants in the Newcastle-upon-Tyne area, from which this waste-food feeder collected waste (66). However, tests performed on pork legs submitted to the Institute for Animal Health, Pirbright, failed to demonstrate that any were contaminated with FMD virus. The operator's various records showed that he normally dispatched weekly consignments of pigs to the Essex abattoir but had sent none between 9 January and 7 February, resuming trade by sending pigs on 8 and 15 February. It was estimated that almost half of the pigs in the herd were excreting virus by 15 February and so large quantities of airborne FMD virus would have been emitted from the premises over several weeks (24, 56). No disease was found on any of the 200 premises that had either supplied pigs or had some form of contact with the Heddon-on-the-Wall farm since the beginning of January. Moreover, no disease that pre-dated that on the pig farm was found on any premises in the surrounding 3-km and 10-km protection and surveillance zones, or on any other premises. The earliest date of infection found for any animals during the epidemic was 12 February, in pigs on this farm, confirming this waste-feeding pig farm as the primary outbreak in the epidemic (66).

Early dissemination through sheep marketing

Sufficient virus could have been released from the infected pigs at the Heddon-on-the-Wall premises to form a viral plume from 12 February onwards, and analysis of meteorological data during early February showed that conditions were favourable for the windborne spread of virus to farms up to 10 km away, particularly during 12 and 13 February (24). Airborne dispersal of FMD virus from the pig farm is considered to have been the most likely method of infection of sheep and cattle on a farm 5 km away (24). Exhaustive investigations into the source of infection for this farm found no evidence of disease on

any farm with which there had been contact from 1 January 2001 or on any farms within a 3-km radius (66). It seems likely, therefore, that the sheep and cattle on this farm were exposed to infection shortly before 16 sheep were sold for slaughter at Hexham livestock auction market in Northumberland on 13 February. Seven of the 16 sheep were purchased by a livestock dealer who took them to his premises in northern England before slaughtering them shortly afterwards; disease was subsequently confirmed in sheep on his farm and in sheep in the lairage fields of the abattoir at which they had been slaughtered. The remaining nine sheep were bought by another livestock dealer, who mixed them with 175 sheep. These 184 sheep were penned closely together for the next 48 h, first at Hexham market and then at nearby Longtown livestock market in Cumbria (Fig. 1), before entering the national sheep marketing system on 15 February (46). The conditions of close contact between animals found in market pens and livestock transport vehicles are particularly favourable for FMD virus transmission, both directly from infected to susceptible animals and indirectly from contaminated surfaces to animals (16); the potential for FMD virus to survive outside the host being well documented (11). Epidemiological investigations at the two markets concluded that the movement of the 184 sheep was responsible for the introduction of infection, before the initial confirmation of disease on 20 February, to as many as 79 premises in Great Britain, 20 of which were operated by large-scale dealers, in ten of the 12 separate geographic epidemiological clusters of infected premises (IPs) that were identified during the epidemic, and to Ireland and France (23, 46). Virus was further disseminated from these premises by the movement of animals, particularly of sheep, both locally and over longer distances, during the five-day period before the first outbreak was confirmed.

Progress of the epidemic

These infections sowed the seeds for the early intense part of the epidemic, during which approximately 1,600 outbreaks were confirmed in the ten weeks up to the end of April (23). Thereafter, these first-affected areas remained relatively free of disease, with only occasional isolated IPs being confirmed over the following weeks (23). The national IP report date curve (Fig. 2), constructed using the date on which suspicion of disease was reported to MAFF/DEFRA and subsequently confirmed, rose to a peak on 27 to 29 March (23). Almost half (640) of the 1,600 IPs confirmed in this early phase were in the county of Cumbria in the north-west of England, one of the most densely populated areas of livestock production in Great Britain. It was concluded from epidemiological investigations that over 100 farms in the county, particularly in the north near Longtown

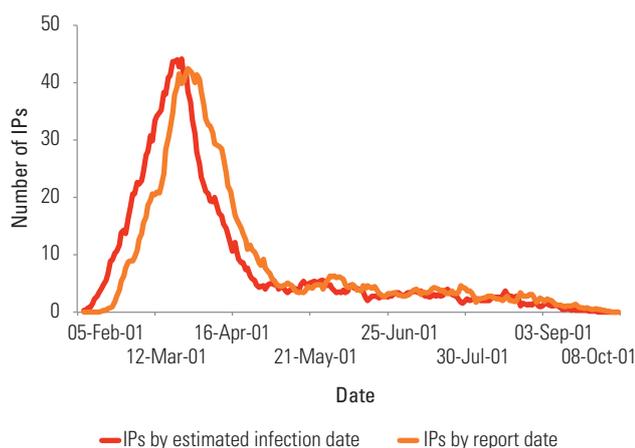


Fig. 2
Epidemic curves for infected premises (IPs) confirmed in Great Britain in 2001, based on the date on which the disease was reported and the date of estimated infection (seven-day rolling means)

market, could have been infected before the first outbreak had been confirmed in the area on 1 March (67). Thus, the national peak (around 28 March 2011) was largely due to the effect of the north Cumbrian cluster of outbreaks, with local epidemic peaks occurring up to a week earlier in other geographical areas, such as 21 March in Dumfries and Galloway (177 IPs) (64). The early phase was followed by the epidemic 'tail', a prolonged phase characterised by the confirmation of 400 IPs over a 20-week period between May and September in six previously largely unaffected, widely separated, geographic areas of the country (Figs. 1 & 2). Within each geographical area, separate clusters of IPs developed, but the source of infection for the first outbreak in each cluster generally defied identification.

Animal movement (1) was probably the mechanism by which most of the major geographical clusters of outbreaks were initiated before restrictions came into force (66). Disease spread within each cluster was believed to have been perpetuated by fomites (23) because the outbreaks occurred after the livestock movement ban. During the tail of the epidemic, disease often spread within areas of farm fragmentation (indicating farms composed of several separate patches of land), at a time of year when most farm animals had been turned out to grass and essential seasonal activities, such as silaging, hay making, sheep shearing, deworming etc., were at a peak, resulting in an increased frequency of movement by people and vehicles within and between agricultural communities. Several potential sources of infection of IPs were often identified but definite links between IPs were difficult to prove. In fact, a definitive source of infection was only identified for 101 IPs (5%) during the epidemic (22), although long-distance spread by fomites and inapparent infection of

sheep were implicated (23). The last outbreak in the 2001 epidemic was confirmed on clinical grounds in sheep on 30 September in Cumbria, but laboratory tests for this and the three preceding outbreaks were negative.

Control procedures adopted in Great Britain in 2001

The stamping out policy and national livestock movement ban

Following disease confirmation on 20 February, MAFF implemented its notifiable disease stamping out policy. Briefly, this policy requires:

- the rapid slaughter and disposal, by incineration or burial, of all affected animals and all susceptible animals on IPs and on other premises considered by veterinarians to have been exposed to infection: so-called 'dangerous contacts' (DCs)
- the establishment around each IP of a 3-km protection zone and a 10-km surveillance zone, defined by European Union (EU) and United Kingdom (UK) legislative guidelines, in which animal movements are prohibited and agricultural activities strictly limited
- increased farm biosecurity measures
- enhanced veterinary surveillance
- the completion of veterinary epidemiological investigations to identify potential sources and spread of infection and to detect 'at risk' premises (64, 67).

When it became apparent that FMD was not confined to Essex, a national ban on animal movement was announced by the Chief Veterinary Officer (CVO) on 22 February and implemented on 23 February (66). The national livestock movement ban therefore complemented the stamping out policy that was targeting IPs and DCs. However, a limitation of stamping out is that it is reactive: control operations on premises are triggered only when the disease is suspected and reported, by which time onward spread may already have taken place. On 23 February, disease had been found in Essex and in Heddon-on-the-Wall, but no one knew how much or how widely infection had spread beyond these two locations. Subsequent events proved both to have been substantial. Based on IP contact tracing data, combined with the putative infection dates calculated for each IP, derived by subtracting a 14-day maximum incubation period (21) from the estimated date when the earliest signs of vesicular lesions had appeared on each IP (22, 68), it was later determined that animals on as many as 200 holdings could have been exposed to infection and were incubating disease on 23 February.

Initial challenge to the emergency response capability of the State Veterinary Service

In reality, when the national livestock movement ban effectively halted disease spread by the movement of animals, Britain was already faced with what amounted to multiple initial foci of FMD, scattered widely across the country, from which virus had already begun to spread up to seven days before the first outbreak was confirmed. Thus, no matter how efficiently the contingency plans were implemented following the first confirmation of disease, a disaster of unprecedented scale was inevitably about to unfold. Within a short time, 12 geographically separated Local Disease Control Centres (LDCCs) and the National Disease Control Centre were established, staffed and resourced. During the first three weeks of the epidemic, the State Veterinary Service (SVS) was faced with 8,300 urgent tasks related to the disease control operation (Table I). Veterinary staff were required to respond to 1,100 reported cases of suspected disease, 257 of which became confirmed IPs, resulting in the investigating veterinarian being quarantined and removed from field operations for a five-day (later three-day) period. In addition, there were approximately 4,700 urgent veterinary tracing visits to be made to premises linked by contact to the index and primary outbreaks, livestock markets, livestock dealers and other IPs and 2,500 daily surveillance visits to premises contiguous to IPs. With only 240 permanent veterinary staff, most of whom had just returned home from a six-month period controlling and eradicating a classical swine fever outbreak in eastern England (4), few of whom had any experience of FMD control, the SVS was facing a task of unprecedented size with limited staffing resources.

The 3-km cull

In the first two weeks of the epidemic, it became apparent to investigating SVS veterinarians that much of the initial

Table I
Urgent veterinary tasks undertaken in the first three weeks of the 2001 foot and mouth disease epidemic in Great Britain

Type of investigation	Number of tasks	
Investigation of reported outbreaks	Week 1	166
	Week 2	427
	Week 3	541
Investigation of infected premises	Week 1	39
	Week 2	72
	Week 3	146
Tracings from index and primary cases		800
Market tracings		900
Dealer tracings		3,000
Daily visits to contiguous premises		2,500

dissemination of disease that had occurred, prior to the imposition of the national livestock movement ban, had been due to the movement of inapparently infected sheep, particularly from Longtown market. This led to fears that infection had been introduced into many more sheep flocks than could be traced within a short period of time. Foot and mouth disease in sheep often results in mild or inapparent clinical signs (16, 19), and frequently is detectable only by a thorough clinical examination or blood sampling and serological investigation. There were concerns that infection was 'creeping' undetected through populations of sheep in areas with close ties to Longtown market, creating a localised reservoir of 'hidden' infection, with the potential to infect other susceptible animals (13). Additionally, evidence had accumulated suggesting that there had been unrecorded movement of sheep through the sheep-marketing and dealer network in northern Cumbria and neighbouring Dumfries and Galloway. The Ministry of Agriculture, Fisheries and Food announced on 15 March the intention to destroy small ruminants (essentially sheep, although goats were also included) and pigs within 3 km of IPs in three localised areas in these counties. The initial aim was to pre-emptively cull sheep nearest to IPs and around the edges of the associated 3-km protection zones to create sheep-free zones. Pigs were included in the cull because of their ability to produce huge amounts of airborne virus (2). By the time the cull commenced, the three areas had enlarged to such an extent that they had coalesced, requiring the creation of a sheep-free zone extending throughout north Cumbria and Dumfries and Galloway. The 3-km cull was managed by local auctioneers and the army, and began in Dumfries and Galloway on 22 March and in north Cumbria on 28 March. Live sheep were collected from farms and moved by licensed transporters for slaughter at one of two specially designated abattoirs or one of two mass slaughter-and-disposal sites, where they were subjected to ante-mortem inspection. The carcasses from the abattoirs were buried at the disposal sites. In Dumfries and Galloway, the cull was compulsory, whilst in Cumbria it was based on the voluntary surrender of animals. By the time consideration was given to compulsory slaughter in Cumbria, the local disease situation had improved markedly and the cull was allowed to lapse. In total, over one million sheep (plus approximately one million lambs) and small numbers of goats and pigs were slaughtered as part of the 3-km cull.

The contiguous cull

On 23 March, acting on the advice of the Government's Chief Scientific Officer (36), MAFF issued instructions for the automatic compulsory slaughter, as DCs, of all FMD-susceptible stock on all premises contiguous to (i.e. with any land directly bordering onto) an IP that had been confirmed on or after 16 March. This replaced the existing

policy, which required a veterinary risk assessment of the likelihood of exposure to infection before premises could be classified as a DC. This new policy, which proved to be controversial, was justified by mathematical modellers, who predicted that, on average, susceptible species on one-in-four contiguous premises would become infected, unless removed, and that this would drive the epidemic inexorably on (20). The compulsory contiguous cull began on 29 March in all areas – except the county of Cumbria where it was never implemented – with a requirement to automatically slaughter these animals within 48 h of confirmation of disease on the associated IP. At the same time, a target of 24 h from the time of disease confirmation was set for the slaughter of animals on IPs. The policy became known as the ‘24 h/48 h rule’. Some limited exemptions from the policy were permitted later in the epidemic, subject to veterinary discretion; for example, cattle and rare breeds of livestock that a veterinary risk assessment indicated had not been exposed to infection (67). Over 1,200,000 animals on 3,369 premises were slaughtered as part of the contiguous cull (4).

The automatic contiguous cull was never implemented in Cumbria due to a lack of resources, as the Cumbria LDCC struggled to cope with the large number of outbreaks being experienced, and to serious resistance to the policy from Cumbrian farmers and veterinarians. Susceptible livestock on premises defined as contiguous to an IP continued to be the subject of traditional veterinary risk assessment and were culled as DCs if exposure to infection was suspected. Post-epidemic analysis of that approach has shown that such veterinary risk assessment can and did identify those contiguous premises that were at risk of infection and preserved those that were not (29).

Confirmation on clinical signs and slaughter on suspicion

As the epidemic escalated, veterinarians working for the SVS were able to confirm disease when obvious clinical signs of FMD were detected, laboratory confirmation only being required in cases of doubt when animals with equivocal lesions were found. Minimising the time from report to confirmation and rapid slaughter of affected animals has long been recognised as vitally important in reducing virus excretion and controlling an outbreak (9, 30, 31), and this was subsequently confirmed by analysis of the field data (28, 64). Instructions to designate animals as infected on clinical signs alone, and to slaughter all livestock on so-defined IPs within 24 h, without waiting for laboratory confirmation for doubtful cases, were issued on 26 March. The category ‘slaughter on suspicion’ (SOS) was introduced at this time to allow animals with equivocal lesions of FMD to be slaughtered, along with all susceptible stock on the premises, without triggering automatic contiguous and 3-km culls until affirmative

laboratory results were available. When laboratory tests proved positive for FMD, SOS premises were confirmed as IPs, and compulsory culling of stock on contiguous premises and on veterinarian-identified DCs was carried out. Foot and mouth disease was confirmed in five instances from animals sampled on 205 SOS premises (12) and over 125,000 animals were culled during SOS operations (4).

Restricted infected areas (‘Blue Boxes’)

When the ‘tail’ of the epidemic continued, analysis of detailed outbreak investigations by field veterinarians suggested that spread was being maintained by mechanical means and in particular by the movement of contaminated personnel and vehicles. The introduction, on 27 July, of legislation to enhance biosecurity measures in cartographically delineated ‘restricted infected areas’ (RIAs) or ‘Blue Boxes’ (so-called because they were delineated in blue in DEFRA publications) resulted in the more effective control of disease and eventually the eradication of the virus (55). The special measures applied included:

- the proper cleansing and disinfection of all vehicles entering or leaving farms
- the licensing of feed lorry and milk tanker routes – the latter to be accompanied by DEFRA staff
- the cleansing and disinfection of agricultural vehicles entering or leaving the RIA
- continuous biosecurity patrols by the police within the area
- the licensing of all agricultural activities such as slurry movement, forage harvesting and sheep shearing, etc.
- a structured programme of serosurveillance of all sheep flocks to identify evidence of exposure to the virus (4).

In all three areas where an RIA was applied, the disease was eradicated within three weeks.

Welfare culls

A major problem created by the prolonged restrictions on livestock movement was the increased number of animals on farms that would normally have entered the food or livestock breeding chains, a situation exacerbated by the cessation of the export trade in meat and live animals. To alleviate potential welfare problems, the Livestock Welfare (Disposal) Scheme was agreed on 22 March but, when implemented, faced many problems, not least of which was the lack of rendering or disposal capacity for the slaughtered animals. Eventually, 2.5 million animals were slaughtered in this and subsequent schemes (4).

Post-epidemic surveillance

To demonstrate the country's freedom from FMD virus after the epidemic, it was necessary to clinically inspect all susceptible stock and to serologically sample flocks in protection and surveillance zones to detect evidence of infection to a specified probability (70). A total of more than 2,500,000 sheep on approximately 27,000 premises were clinically examined and their blood tested. As a result, 640 samples from 46 flocks were found to be antibody-positive and, of these, a single sheep in each of two flocks was found to be positive for the virus by probang sampling, resulting in the farms being declared IPs. The positive sheep on the other 44 farms were culled and the remaining FMD-susceptible stock subjected to regular, intensive veterinary surveillance – with negative results.

Exclusion of vaccination

The possibility of vaccination was continually debated during the epidemic. One particular strategy proposed by the SVS was to vaccinate cattle in Cumbria and Devon during the spring of 2001 before they went out to pasture. Emergency vaccine was prepared for this purpose but the policy was not implemented, due to opposition from the National Farmers' Union, which objected on the grounds of possible increased economic loss from extended embargoes on the export of livestock and animal products. Vaccination was used in 2001 in only one country, the Netherlands, where dampening down vaccination (63) was employed.

Stages in the epidemic's control

The outbreak report date curves (Fig. 2) commonly used to show the progress of an epidemic can be misleading because they are based on the date that disease has been observed and reported, a procedure subject to many variables (22). The date against which control efforts must ultimately be judged is the date when the spread of infection has been controlled (Fig. 2). Gibbens and Wilesmith (22) constructed a national infection date curve for the 2001 epidemic by subtracting an average incubation period for the Pan-Asia strain virus of five days (38) from the date estimated, during field investigations, for the appearance of the first lesion of FMD on each IP. It was found that the curve peaked on 21 March, by which date it can be said that the increasing spread of infection characterising the intense early phase of the epidemic had been brought under control. However, in some places, the spread of disease continued at a low level and across previously unaffected areas – the 'tail' of the epidemic (Fig. 1). This continued spread was finally halted after the introduction of RIA measures in July and August, in the

last three areas experiencing disease (Fig. 1). Following extensive clinical and serological surveillance to demonstrate freedom from infection, the World Organisation for Animal Health (OIE) recognised the UK as having regained its status as FMD-free without vaccination on 22 January 2002 (70).

The role of mathematical models in 2001

Mathematical models, which attempt to represent events in quantitative terms, have been applied in human and veterinary medicine for over 200 years (63), and several have focused on FMD. The only models validated for FMD before the 2001 epidemic were Rimpuff, developed by the Risø National Laboratory, Denmark (49), and the Danish Emergency Response Model of the Atmosphere (DERMA) (58, 60). The dispersion model Rimpuff can be linked with the local-scale atmospheric flow model LINCOM, which simulates airflow over hills and terrain with different land use characteristics. These models simulate the airborne spread of FMD over short or long distances, respectively, and had been validated using historical data from outbreaks of FMD in France and the UK (Isle of Wight) in 1981, and from Denmark and the former German Democratic Republic in 1982 (59, 60).

During the early stages of the 2001 epidemic, some IPs contained pigs, which are known to excrete large quantities of airborne virus, and so there was concern about potential airborne spread within the local area and to the nearby continent. The risk of airborne spread was analysed, both in 'real time' and when more detailed virus emission data became available, using the validated Danish atmospheric models mentioned above (48) and two models, the 10-km Gaussian plume and the Numerical Atmospheric dispersion Modelling Environment (NAME), developed at the UK Meteorological Office (24). Analysis of the results showed that there was only a limited risk of the virus spreading for long distances from the primary outbreak at Heddon-on-the-Wall. However, the short-range models suggested that there was a considerable risk of airborne transmission to cattle and perhaps sheep located within 5 km to 10 km. Cattle and/or sheep on a farm 5 km away were most probably infected by this route before sheep were sold into the national marketing system (1, 24).

The InterSpread model was used by MAFF/DEFRA on a daily basis during 2001 to monitor the epidemic size, duration and spatial spread (50). The model includes accepted veterinary assumptions, such as animals being infectious from just before the appearance of clinical signs until slaughter; excretion rates being variable depending on the stage of disease; the species affected; the occurrence

of an on-farm epidemic, and various farm factors. It also allows transmission by specific contact routes and considers the effects of having control measures in place, e.g. DC assessments and contact tracings data, allowing greater parameter flexibility. There was a cautious interpretation of its output, recognising the dynamic and often unpredictable nature of FMD infection, although the results closely matched field observations, thus promoting confidence in its output. For example, the conclusion by field staff that disease spread was being maintained by mechanical means, and in particular by the movement of contaminated personnel and vehicles, was supported by the output of the InterSpread model (50), and the need for the heightened biosecurity measures was eventually adopted in the 'Blue Boxes'.

The models that proposed the introduction of the automatic compulsory contiguous cull policy in 2001 suffered from the deficiency of using parameters derived from the 1967/1968 UK epidemic, which mainly involved cattle but also long-range spread from pig farms, and the 1997 Chinese Taipei epidemic, which only involved pigs (20, 30). The 2001 epidemic in the UK, on the other hand, was driven by sheep initially and then propagated by cattle (23, 64, 67, 69). Moreover, these and more refined models developed during the epidemic (e.g. 20, 34) were profoundly flawed in that they used deficient historic population census data. For example, in some areas of the country, over 15% of all premises were omitted and, of those recorded as having no stock, almost 20% had some, whereas 10% that were documented as having stock actually had none (27). Furthermore, they relied on MAFF/DEFRA contact tracing data, which only identified a definitive source of infection for 5% of IPs (22). Perhaps most importantly, the models contained highly implausible biological assumptions: for example, that all animals on any particular premises, irrespective of location, husbandry, species, age, intercurrent disease, stress factors, or degree or route of exposure, would (i) be infected simultaneously; (ii) complete a fixed incubation period, although it was known that there is natural variability in incubation periods (53); and (iii) begin excreting virus maximally from one to four days after the virus entered the farm, depending on the model, and continue to do so until culled, despite antibody being produced from around four days after the onset of the disease (2), which has been shown to lead to rapidly decreasing viraemia (32).

It was further assumed that virus would then spread evenly and radially from the premises' boundary, irrespective of the animals' locations. The risk of spread from an IP to contiguous premises was first predicted to be 26% (20), later reduced to 20%, then to 17% (35). These model assumptions inevitably biased their output towards the conclusion that radial or contiguous culling would be effective in containing disease spread as simulated by these models.

Discussion

The scale and extent of the 2001 FMD epidemic can be attributed to a series of independent events that took place before the first case of disease had been reported. The chance combination of these events had devastating consequences. First, and most importantly, after Britain's Customs' defences had been breached by the entry of FMD virus, there was a delay of several weeks before its presence became apparent to the veterinary authorities. The primary outbreak involved pigs, which are potent excretors of airborne virus, and on several occasions the prevailing climatic conditions were favourable for the formation and movement of viral plumes towards nearby cattle and sheep farms. Sheep infected by this route had entered the national sheep dealing and marketing system around a time when the seasonal movement of sheep was at a peak, resulting in the widespread dissemination of virus throughout the country. Furthermore, the existing cold, damp climatic conditions were particularly favourable for virus survival outside the animal, supporting further distribution of the virus by mechanical means. Finally, the SVS lacked the emergency response capacity to deal effectively with the size of the epidemic and very rapidly became over-stretched.

It is probable that the virus gained entry to Britain by the smuggling of contaminated pork products from Asia and that waste meat from this contraband was collected by a waste-food processor, who fed it to his pigs without prior heat treatment (66). The cases of FMD that subsequently occurred in the pigs were not reported by the waste-food processor – the presence of disease was only detected through the 'back-tracing' activities of the SVS. Retrospective analyses indicate that a plume of virus produced by the pigs and transported on the wind was the probable source of infection for a mixed cattle and sheep farm located 5 km downwind (24). Before the presence of disease was recognised on this farm, a group of sheep were removed and sold at a local market, entering the national livestock marketing system at a time that coincided with a seasonal peak in sheep sales (46). The sheep-dealing and sheep-marketing system in Great Britain is large and complex, capable of transporting thousands of animals over hundreds of kilometres each day. In 2001, sheep were not individually identified and some movements were poorly recorded, making rapid tracing difficult. The environmental conditions and animal management practices at the time were also very favourable for spread by mechanical means. For example, virus would probably have survived for many days in the prevailing cold, damp climatic conditions, while transmission by fomites and contaminated people would have been facilitated by the increase in recent years of stock numbers, farm size and fragmentation, as well as by the greater reliance on shared or contract labour and equipment. Thus, conditions for

infection to be spread widely by the movement of animals, especially by sheep, and by mechanical means, were ideal during late February and early March 2001, laying the seeds for the extensive epidemic that followed.

Since the last FMD epidemic in 1967/1968, the SVS had been progressively reduced in number, due to cost-cutting in the public sector, while the absence of large-scale epidemics had resulted in a loss of expert knowledge and experience (4). Consequently, when it was severely challenged in 2001, the SVS was found to be lacking in both response capability and widespread expertise. The 2001 epidemic clearly illustrates the danger of neglecting or reducing national Veterinary Services during 'peacetime' and the serious economic consequences that can result for the state, the agricultural and tourist industries and other sectors.

The size and temporal patterns of the 2001 and 1967/1968 epidemics are similar (4). The epidemic curves differ only slightly, in that the peak of the 1967/1968 epidemic was higher and occurred slightly sooner than in 2001. Both reflect the practical problems of controlling epidemics characterised by initial multiple seeding followed by local spread, although the initial seeding in each case had been by different routes. The 1967 to 1968 epidemic had an explosive start, as the result of airborne spread of virus from pigs at the source farm to cattle up to 60 km downwind (25), resulting in 300 outbreaks within a three-week period (8). In 2001, by contrast, apart from the primary outbreak at the Heddon pig farm, airborne spread was not a significant feature and the initial spread of disease primarily involved the movement of inapparently affected sheep over much greater distances.

The date for the peak of national spread of infection in 2001 was estimated to be 21 March (22, 26), and as early as 16 March in the separate geographic cluster of Dumfries and Galloway (65). Therefore, the spread of infection during the intense early phase of the epidemic was controlled nationally 31 days after the first confirmation of disease on 20 February, and more quickly in the regional clusters. For example, in north Cumbria it was 20 days and, in Dumfries and Galloway, 15 days from the first confirmation of disease on 1 March until the spread of infection peaked. At this time, the only control procedures in place were the traditional stamping out policy and the national livestock movement ban.

The 3-km sheep cull began five days after the spread of infection had peaked in Cumbria and six days after it had peaked in Dumfries and Galloway. The cull was untargeted, took six weeks to complete, and serosurveillance of 115 flocks sampled during the cull found only one flock of sheep with any seropositive animals (nine positives from 56 sheep) (10). Cattle on this farm, which were subjected to regular veterinary surveillance, never showed any clinical

signs of disease. Thus, whilst there may have been some justification for a cull of sheep in limited geographic areas where unrecorded or illegal movements were suspected, there is little evidence to support the need for the extended sheep cull that evolved in 2001. In fact, the opposite may well be the case. While some experimentally infected sheep can excrete large quantities of virus during both the clinical and pre-clinical phases of the disease (32), it would appear that, under field conditions, close contact between animals, perhaps exacerbated by stress factors, is necessary for infection to persist and spread. Such conditions exist during transportation and marketing, thus allowing a small number of infected sheep to disseminate the virus widely throughout Great Britain several days before the disease was first recognised. However, when the movement of animals was stopped, the role of sheep in the propagation of the 2001 epidemic was much reduced. Although severe clinical disease was occasionally encountered in sheep in 2001, usually associated with the close contact and stress of parturition (52), it was more usual for clinically mild or inapparent infections to be found (5, 15, 23). It has been hypothesised that infection in a flock of sheep can decline and 'die out' (3, 39). Evidence in support of this from the field occurred at the end of the 1967 to 1968 epidemic in the UK (8), from Greece (45) and North Africa (43, 44), and from experimental work reported by Kitching and Hughes (39). Extensive ovine serological surveillance completed during and after the epidemic in 2001 found only a small number of seropositive sheep in a very few flocks, suggesting that FMD may well self-limit in extensive sheep populations, such as those found in Great Britain. However, the evidence remains indirect and is based on the apparent lack of transmission rather than on direct quantification of the amounts of virus being excreted.

Compulsory confirmation on clinical signs and the SOS policy were implemented on 29 March; that is, after the epidemic had peaked, and inevitably led to an increase in the number of IPs designated as infected but not confirmed by laboratory tests. In fact, of the samples collected from 90% of IPs, 23% yielded negative results (37); the majority associated with suspected disease in sheep. This, in itself, is unsurprising, given the well-documented difficulties associated with diagnosing FMD in sheep (2, 16, 19), but had serious consequences when associated with automatic contiguous culling around such IPs. In future FMD emergencies, the refinement and field deployment of rapid testing kits (37) and recognising the difficulty of clinically diagnosing FMD in sheep should preclude the adoption of compulsory clinical 'confirmation' and the SOS policy.

The national livestock movement ban was a draconian measure and its implementation so early in an outbreak was without precedent in the history of FMD control in Great Britain. It is without doubt that this single measure played a pivotal role in reducing the scale of the epidemic because the movement of infected animals is by far the

most common mechanism of FMD spread (16). By contrast, it was over three weeks before a national livestock ban was put in place in 1967/1968, when the previous large epidemic of FMD affected Great Britain (9). A national livestock movement ban, however, does have very serious adverse effects, particularly on animal welfare and farm incomes, because animals that would normally have been sold have to be retained, housed and fed on the farm for lengthy periods. In 2001, a government-funded, livestock-welfare cull programme was eventually implemented but encountered many problems, particularly of carcass disposal. To support any future national livestock movement ban, a properly structured and funded animal-welfare culling programme is required, whilst the length of time that the ban is in place should be kept to a minimum, for example until initial tracings have been completed (9) or following risk analysis (54). Even after the stamping out policy and the national livestock movement ban came into operation in 2001, the presence of disease on the vast majority of premises was neither known nor suspected. Farming practices continued as normal, with a variable application of biosecurity measures, thereby providing many opportunities for the continued spread of infection by mechanical means – for example, by people (stock-handlers) and fomites, including vehicles. Some countries are fortunate during emergencies, in being able to call on the police and/or army to enforce local movement restrictions and the fire brigade to assist with disinfection. In 2001, it was four weeks before the army was deployed to move carcasses (4), despite their inclusion in MAFF's national and local contingency plans.

The general impatience that met the wait for the full extent of infections to become apparent, accompanied by an ever-increasing number of outbreaks and piles of carcasses awaiting disposal, was perceived as a lack of success of the traditional control measures and provided the opportunity for self-styled 'experts', including some veterinarians, biologists and mathematicians, to publicise unproven novel options.

This was not a new phenomenon. In 1952, following an epidemic of FMD in Canada, the Canadian CVO stated, 'I find it truly amazing, the number of foot and mouth disease experts (self-proclaimed) who appeared almost overnight' (7). It was against this background, of an ever-increasing incidence of disease and an epidemic apparently running out of control, that novel policies, involving the automatic pre-emptive slaughter of susceptible livestock on premises contiguous to IPs, were promoted as being the only solution (20, 35, 36) and given credibility by media coverage (6). Theoretical, non-validated, disease models, prepared by mathematicians with little knowledge of farm husbandry practices and containing improbable veterinary and virological assumptions, were widely publicised and used to drive policy for the first time in a major disease

epidemic, despite the widespread concerns expressed by veterinarians experienced in FMD control as to their validity and applicability (18, 33, 47). The models' veterinary assumptions did not fit with either field or experimental reality and represented a different (wholly theoretical) virus, perhaps best dubbed the 'Armageddon virus', given its ability to infect whole herds at once and be excreted several days in advance of clinical manifestation, maximally and indefinitely, unless the animals were killed. The further assumption that this 'Armageddon virus' would then spread evenly and radially from the premises' boundary, irrespective of the animals' locations, produced a self-fulfilling prophecy inevitably weighted towards radial/contiguous culling being necessary to halt the spread of infection. Spatio-temporal analyses of the epidemic in Cumbria (62) concluded that the spread of infection beyond 1.5 km occurred in almost 50% of cases, indicating that limiting disease control measures to contiguous premises (i.e. within 1.5 km, as epitomised by the contiguous cull) was not sufficient to stop the epidemic, and would lead to huge numbers of farms being culled as a result. Similar conclusions were reached by Thrusfield *et al.* (65) in Dumfries and Galloway and Wilesmith *et al.* (69) in Devon and Cumbria.

The automatic contiguous cull began on 29 March, eight days after the early intense spread of infection had peaked nationally and 13 days after the peak in Dumfries and Galloway (65). Thus, the novel 48-h contiguous cull policy – driven by mathematical models – was implemented when the epidemic was already in decline. Furthermore, the contiguous cull was not implemented in north Cumbria, yet the epidemic curve for Cumbria mirrors the curve for the rest of Great Britain in 2001 (Figs 2 & 3) and also the 1967/1968 epidemic curve (4, 23). The Cumbrian and 1967/1968 UK curves show that disease can be effectively controlled using only the proven, traditional, stamping out policy, supported by a national livestock movement ban. The identical nature of the curve for the rest of Great Britain in 2001 brings into doubt the very necessity and indeed usefulness of the contiguous culling policy and the accuracy of the statement: '... there is a mountain of evidence to show that the cull policy we were following and pursuing... was the policy bringing it under control' (35).

Post-epidemic analysis has provided further support for the effectiveness of traditional control measures and the lack of impact of the contiguous culling policy. Honhold *et al.* (28) showed that the epidemic would be controlled when the time from the first lesion in the livestock on a farm to completion of slaughter was consistently reduced to below 3.5 days. The same analysis did not demonstrate any significant contribution to control of the epidemic from culling animals on contiguous premises, whereas culling of veterinary-assessed, non-contiguous DCs did have a statistically and biologically significant effect. The automatic culling of contiguous premises promoted by some

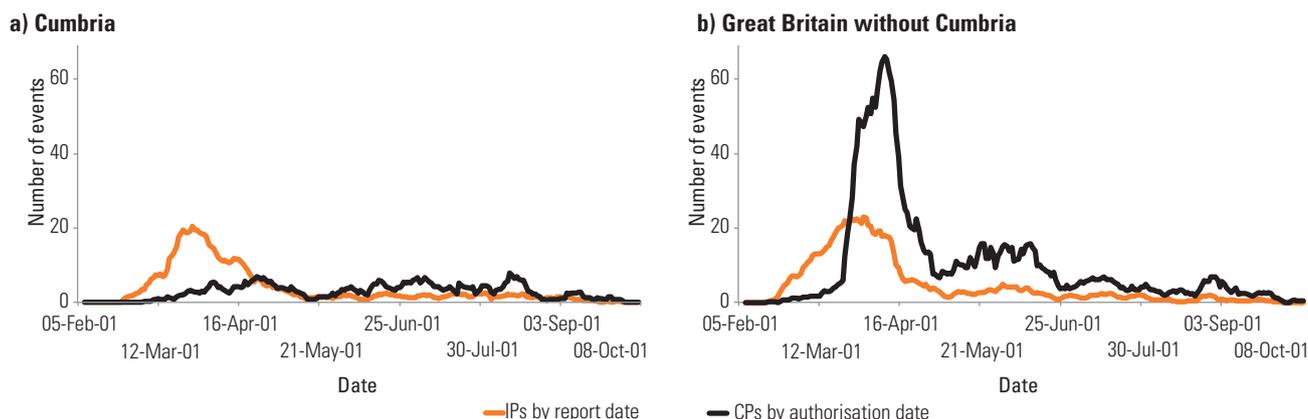


Fig. 3
Seven-day rolling means of infected premises (IPs), by date of report, and premises subjected to contiguous culling (CPs), by date of authorisation, for Cumbria, and the rest of Great Britain without Cumbria

mathematical models assumed that risk was evenly spread and/or could not be assessed quickly enough to control disease effectively. Further analysis (29) showed that veterinary risk assessment of contiguous premises was able to differentiate in real time between different levels of risk and remove animals from those premises that would become IPs, while preserving stock on premises at a lower risk that would subsequently remain disease free. This, and other field analyses (29, 65), also indicated that, even for contiguous premises, the most likely route of infection was by carriage on fomites entering through the farm gate, rather than across the contiguous farm boundary, and was therefore susceptible to control by good enforcement of biosecurity. The positive impact of the RIA system on the eventual control of the epidemic 'tail' showed just how vital it is to restrict the amount of contact between farms and to enforce proper cleansing and disinfection procedures where contact cannot be avoided for business reasons. The RIA system is a clear example of the benefit of combining knowledge of the virus and of farming activities with veterinary common sense and multi-disciplinary cooperation.

The mathematical models were, at best, crude estimations that could not differentiate risk between farms and, at worst, inaccurate representations of the epidemiology of FMD. Ultimately, the models neither correctly predicted the course and duration of the epidemic nor the effectiveness of the traditional control measures put in place nor the novel ones proposed (61). Thus, they failed the acid tests of refutedness, testedness and usefulness (41). The rush to embrace non-validated mathematical models in policy-making, presented without balancing their apparent numerical certainty against the degree of improbable biological assumptions they contained, resulted in traditional methods proven by generations of veterinarians (8, 9) being neglected (40, 65). As Kitching *et al.* put it: 'The UK experience provides a salutary warning

of how models can be abused in the interest of scientific opportunism' (41).

The consequences of the contiguous cull policy were severe. Not only were over a million animals culled on more than 3,000 farms, but further problems were generated, including:

- the diversion of scarce resources from the high-priority tasks of IP and DC tracing and culling
- a huge increase in the number of carcasses awaiting disposal
- an exponential increase in the movements of vehicles and personnel engaged in the cull in the protection zones, perhaps facilitating local spread
- reduced cooperation from farmers (sometimes leading to a conscious or unconscious delay in reporting suspicion for fear of the consequences on neighbours)
- a hugely demoralising effect on the British population in general and among farmers in particular
- a major loss of epidemiological data (17).

Mathematical models can be useful tools to study disease in inter-epidemic periods, in contingency planning and for training purposes during simulation exercises, but they remain theoretical systems and must be accorded the caution that theories deserve (14). Retrospective analysis using 'real' data can aid our understanding of epidemics by modelling hypothetical scenarios and intervention strategies – the outcomes, when combined with veterinary expertise, can be a valuable guide for decision-makers (61). The use of non-validated models as predictive tools to guide policy during an epidemic of FMD remains highly questionable, especially given the imprecision of the available data and the complex nature of the biology of the FMD virus (26, 41, 61). In addition, there is the risk of

ignoring the wider potential fallacy of *petitio principii* ('begging the question') of assuming that a model can be considered to be 'mathematically successful', yet fails to explain the biological truth. The extent to which a mathematically successful theory can fully explain reality – the belief that it can being termed, 'the Crime of Galileo' (51) – has been tendentiously redacted elsewhere in the wider scientific community (57).

Many lessons were learned from the experiences of the UK 2001 FMD epidemic that were tested all too soon when FMD again struck the UK, in 2007. Not least among these was the policy of employing the traditional, well-established methods of FMD control and eradication and not using novel procedures, based on non-validated mathematical models. This strategy proved to be correct and the virus was relatively quickly eradicated. ■

Une tension destructrice : les mathématiques contre l'expérience – la propagation de l'épidémie de fièvre aphteuse en 2001 en Grande-Bretagne et son contrôle

L.M. Mansley, A.I. Donaldson, M.V. Thrusfield & N. Honhold

Résumé

L'épidémie de fièvre aphteuse qui s'est abattue en 2001 sur la Grande-Bretagne a fait l'objet d'une stratégie de contrôle basée sur l'utilisation simultanée de méthodes traditionnelles et de méthodes innovantes, dont certaines découlaient des résultats générés par des modèles mathématiques. Sept jours avant l'instauration de la méthode controversée consistant à abattre systématiquement, à titre préventif, tous les animaux d'élevage des espèces sensibles dans les exploitations situées à proximité des exploitations infectées (politique des « abattages contigus »), la propagation de l'infection avait déjà été maîtrisée en associant une politique classique d'abattage sanitaire à des mesures d'interdiction des mouvements d'animaux d'élevage au plan national. Une deuxième mesure innovante et controversée a également été instaurée après le pic de l'épidémie : il s'agissait de l'abattage des ovins situés à un rayon de 3 km des exploitations infectées (politique de « l'abattage à 3 km »). Cette mesure n'était pas ciblée et il a fallu plusieurs semaines avant d'en achever la mise en œuvre. Lors du suivi sérologique des ovins abattus dans ce cadre, un seul troupeau a été trouvé infecté, ce qui semble indiquer que la propagation de l'épidémie n'avait pas pour origine une infection cryptique chez le mouton. La vaste campagne de surveillance du cheptel ovin réalisée après l'épidémie n'a décelé qu'un très petit nombre d'animaux séropositifs répartis sur très peu d'élevages, ce qui permet d'avancer l'hypothèse d'une limitation spontanée de la capacité de la fièvre aphteuse à se propager dans les populations ovines. Les restrictions plus sévères imposées aux mouvements entre exploitations et les mesures de biosécurité ont finalement permis de mettre un terme à l'épizootie. L'abattage d'animaux sains, dans le respect du bien-être animal, a été nécessaire afin de soutenir l'interdiction prolongée des mouvements d'animaux d'élevage au niveau national. Les modèles qui ont servi à élaborer la politique d'abattage contigu présentaient des faiblesses importantes : d'une part, les données de base utilisées émanaient d'épidémies très différentes, d'autre part, les données sur les populations de référence étaient inexactes ; enfin, les hypothèses biologiques concernant les paramètres temporels et quantitatifs de

l'infection et de l'émission virale dans les troupeaux et les cheptels infectés étaient fortement improbables.

Mots-clés

2001 – Abattage contigu – Abattage sanitaire – Abattage sur un rayon de 3 km – Biosécurité – Fièvre aphteuse – Grande-Bretagne – Modèle mathématique – Procédures de lutte contre la maladie.



Tensión destructiva: las matemáticas contra la experiencia. Progresión y control de la epidemia de fiebre aftosa de 2001 en Gran Bretaña

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Resumen

La lucha contra la epidemia de fiebre aftosa que en 2001 asoló Gran Bretaña se caracterizó por una combinación de métodos tradicionales y novedosos, fruto en algunos casos de los resultados de modelos matemáticos. Siete días antes de que se implantara la inédita y polémica medida de sacrificar preventiva y automáticamente a todos los animales susceptibles de explotaciones adyacentes a los centros infectados (el llamado 'sacrificio contiguo'), ya se había logrado contener la propagación de la enfermedad combinando la tradicional política de 'sacrificio sanitario total' con la prohibición de los movimientos de ganado a escala nacional. Una segunda medida novedosa y polémica, que exigía el sacrificio de todas las ovejas en 3 km a la redonda de las explotaciones donde se hubiera confirmado la presencia de la enfermedad (el 'sacrificio en un radio de 3-km'), también se puso en marcha una vez pasado el pico de propagación, se aplicó indiscriminadamente y se prolongó varias semanas hasta su conclusión. El análisis serológico de las ovejas sacrificadas reveló la presencia de la infección en un solo rebaño, de donde se deduce que la infección críptica de las ovejas no propagaba la epidemia. Las amplias medidas de vigilancia serológica de las ovejas instituidas después de la epidemia sólo permitieron detectar un pequeño número de ejemplares seropositivos en muy contados rebaños, lo que indica que quizá la fiebre aftosa se autocontenga en las grandes poblaciones ovinas. Finalmente se logró acabar con la epidemia tras introducir más estrictas restricciones a los movimientos pecuarios y medidas de seguridad biológica. Para secundar el cumplimiento de la prolongada prohibición de movimientos de ganado en todo el país hubo que aplicar un plan para el sacrificio compasivo de animales no afectados. Los modelos que alentaron las medidas de sacrificio contiguo adolecían de graves defectos, pues reposaban en datos de epidemias que poco tenían que ver con aquella, en datos demográficos de referencia inexactos y en premisas biológicas harto improbables en cuanto a los parámetros temporales y cuantitativos de la infección y la emisión de virus en los rebaños infectados.

Palabras clave

2001 – Fiebre aftosa – Gran Bretaña – Modelos matemáticos – Procedimientos de control – Sacrificio contiguo – Sacrificio de ovejas en un radio de 3 km – Sacrificio sanitario total – Seguridad biológica.



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