Current Understanding of The Epidemiology of Tuberculosis

R S Morris, D U Pfeiffer, R Jackson and P R Wilson
Department of Veterinary Clinical Sciences,
Massey University, Palmerston North, New Zealand

ABSTRACT

Mycobacterium bovis is a pathogen with an exceptionally wide host range, but until recent years concern was largely limited to infection in cattle and man In recent years there has been acceptance of the need for control in other domestic animals, notably deer There has also been recognition that self-maintaining infection is present in wildlife hosts in some countries - particularly the European badger in the United Kingdom and Ireland, the Australian brush-tailed possum in New Zealand, and various species of ungulates in limited areas of a number of countries This paper summarises the stage which has been reached in our understanding, drawing heavily on our research program dealing with the epidemiology of the disease in New Zealand

Although transmission of *M bovis* can occur by a number of different routes, control programs have reduced most of them to a very minor role, leaving the airborne route responsible for most remaining transmission Contamination of feed and pasture appears to be of no importance in transmission of the disease, because survival times of infective doses of organisms in the environment are relatively short under realistic conditions and because animals are not commonly exposed to a dose high enough to be infective by the alimentary route While many species of animals can become infected with *M bovis*, only a few act as maintenance hosts and the rest are spillover hosts in which infection is not self-maintaining With the exception of cattle and deer, other species have become maintenance hosts only within part of their ecological range For both badgers and possums, maintenance of infection within a local population is due to pseudo-vertical transmission from mother to young, and horizontal transmission linked to breeding activity The disease is patchy in occurrence because of environmental influences on the time delay between infection and development of detectable disease Transmission from possums to domestic animals appears to occur mainly during atypical behavioural interactions between the species, when possums are in the terminal stages of the disease

It would appear from our studies that substantially improved control effectiveness could well be possible through application of tightly integrated livestock management and possum control procedures at farm level, plus modified regional control operations Greater gains could be made if new control measures could be developed, initially vaccines but possibly also long term population control systems for possums

INTRODUCTION

Mycobacterium bovis has a very wide host range (Grange and Collins, 1987) with a complex epidemiological pattern Infection can be exchanged among human beings, domestic animals

and wild animals. Over recent years the range of species recognized as important in the epidemiology of the disease worldwide has increased significantly, and there are indications that these represent part of a continuing process of adaptation of pathogenic mycobacteria to new ecological opportunities This paper summarises current understanding of the epidemiology of the disease, and considers the possibility that deer may play an unexpectedly important role in this evolutionary process.

ECOLOGY OF THE ORGANISM

M bovis is an obligate pathogen, but it is capable of survival for significant lengths of time in favoured locations In general, the organisms survive better in soil or sub-soil than on herbage or the soil surface (Kelly and Collins 1978), principally because of the desiccating influence of sunlight Although some studies have shown survival of organisms for months under special circumstances, the weight of the evidence suggests that survival in sites likely to cause infection is commonly very short (at most days to weeks), and that organisms are infective to hosts for a shorter time than the period for which they can be isolated by cultural methods (Morris *et al* 1993a) Even survival in faeces and urine, for example from badgers, is 3 days to 2 weeks in summer and about a month in winter (Little *et al* 1982). One reason why long survival times have been found in some studies is that artificial contamination produces much longer survival times than natural infection.

For wild hosts such as possums and badgers, persistence in infected animals after death may provide a source of infection for scavengers and possibly later for domestic stock which graze the site of decomposition. The length of time that *M. bovis* can be recovered from carcases of tuberculous possums depends on the speed of putrefaction and decomposition, and hence on the ambient temperature and degree of environmental protection given to the carcase. Livingstone (1979) concluded that recovery was possible if tuberculous lesions were still recognisable in the carcass, but not after decomposition had proceeded beyond that point. Pfeiffer and Morris (1991) were able to recover *M. bovis* from the interior of largely dry carcases at up to at least a month after death when the moist interior was swabbed However in this same study, tuberculous carcases left in accessible locations were typically scavenged completely within 2 to 3 days at most, thus eliminating the protection otherwise given to the organisms Recovery from tuberculous badger carcasses varied from 2 weeks when the carcase was lying on pasture to 6 weeks for a buried carcass (Little *et al* 1982) while badger tissues in a badger sett were negative after 1 month (Anon 1979)

Although it has on occasions been suggested either that strains of organisms may vary in virulence for particular hosts or that hosts may vary in their susceptibility to infection, there is no evidence to suggest that either possibility is a factor in the epidemiology of the disease. Neither is there any data to suggest alterations in susceptibility due to prior or intercurrent exposure to mycobacteria of different species or to other less closely related organisms

It is well recognized that tuberculosis varies in prevalence between regions, and between farms and livestock enterprises within the same geographical region. Some of the differences are due to specific management practices, and others are probably due to ecological considerations, many of which have not yet been well-defined Pfeiffer *et al* (1991) studied risk factors associated with breakdown of cattle herds with tuberculosis in the southern

Waikato, and used statistical methods to identify from a much larger initial list, a sub-group of factors which appeared to be associated with herd breakdown for tuberculosis. At the time the study was conducted, tuberculous possums were just entering the area, and the study was conducted to resolve whether herd breakdowns could be linked to possums or other factors The study identified a number of influential factors, but under the specific circumstances a set of cattle management factors which were linked to likely purchase of cattle from TB-endemic areas were the most important risk factors which were associated with entry of infection to herds

Evidence from the study of possum infection suggests that there are also environmental and ecological factors which influence the distribution and density of tuberculous possums within a given region. Availability of den sites appears to be the single most influential factor in determining possum density, and our data suggests that the degree of weather protection offered by sites is an important influence on the local prevalence of clinical tuberculosis Feed supplies (as indicated by changes in body weight of adult male possums), particularly over winter, are also important

TRANSMISSION OF INFECTION AND EPIDEMIOLOGICAL PATTERNS IN MAJOR SPECIES

Cattle

Prior to the implementation of effective TB control programs in cattle, there were multiple different routes of transmission of tuberculosis, producing a range of forms of the disease. Infection by inhalation of organisms has always been the single most important route, but was supplemented in earlier times by oral transmission and spread by other minor routes (Francis 1947) These alternative routes produced possibly up to 10 to 20% of new cases Current tuberculin testing procedures applied in cattle have prevented almost all transmission by these other routes, and (in the absence of a wildlife vector) almost all transmission between cattle is by inhalation The main reason for this is that the infective dose by inhalation is at most a few organisms and may be as little as one, whereas the infective dose by ingestion is millions of organisms, and the same is probably true for other routes

During exhalation large numbers of water droplets are carried with the air flow, and these can carry *M. bovis*. Once outside the respiratory tract those of suitable size form droplet nuclei (residues of small droplets which dry down to a size capable of staying airborne for extended periods and moving away from the source which exhaled them) Droplet nuclei (supplemented by dust particles under some circumstances) are the principal vehicles which are capable of meeting the three requirements for airborne transmission between animals - they are capable of carrying bacteria of the size of *M bovis*, they can persist long enough in the air to be inhaled, and they are small enough to meet the requirements worked out by Wells *et al* (1948) and Lurie *et al* (1950) to penetrate into the lung and initiate infection.

Evidence from both human and animal tuberculosis is that infection is not a continuous risk arising from close contact, but rather an occasional event when conditions are right for droplet nuclei to be exchanged As Langmuir (1961) says of the human disease, "only certain tuberculous individuals act as effective disseminators and these do so probably intermittently

and only under certain circumstances " Moreover these are not necessarily just advanced cases, but may commence quite early in the disease. In natural infections, Neill *et al* (1992) found that excretion commenced typically at 87 days and in some cases occurred in tuberculin test negative but recently infected cattle.

Farmed Deer

The epidemiology of *M bovis* infection has not been as fully investigated in deer as in cattle, and some aspects of the disease are as yet poorly understood The disease in deer has recently been reviewed in detail by Clifton-Hadley and Wilesmith (1991).

Typically lesions appear to be most common in the retropharyngeal lymph nodes, lungs and lymph nodes of the thoracic cavity, and mesenteric nodes (Livingstone 1980, cited by Beatson 1985; Brooks 1984, Wilcockson 1986). However large superficial (often visible) abscesses also occur and may (Robinson *et al* 1989) or may not (Fleetwood *et al* 1988) discharge to the exterior in particular cases. Mesenteric nodes draining to the lumen of the intestine have also been reported in deer (Bertram 1986) The distribution of lesions suggests that both inhalation and ingestion are important routes of infection in this species. Lesions found in deer with natural cases of *M. bovis* infection range from caseous and granulomatous to quite liquid lesions, probably related to the much greater role of neutrophils in the inflammatory process in deer than in other species.

There is little direct evidence on the epidemiology of the disease in deer, and extrapolation from other species may not be entirely valid It has been suggested that farmed deer may be more susceptible to *Mycobacterium bovis* infection than cattle. Under suitable circumstances extensive lesions can develop rapidly, producing increased probability of spread within a herd (Clifton-Hadley and Wilesmith 1991). As in cattle, the pathogenesis of the disease is mainly dependent on the size of the infecting dose and the susceptibility of the host Susceptibility has been stated as depending on factors such as genetic constitution, previous exposure to *Mycobacterium spp* , nutrition, social status in the herd, handling stress and endocrine factors (de Lisle *et al* 1985), but the solid evidence available on epidemiological factors influencing susceptibility and transmission in deer is sparse, to say the least

Although the scarcity of sound studies on the epidemiology of the disease in deer makes it difficult to be confident of the situation, deer appear to be more infectious for other species than cattle, and possibly fall at the high end of the range as sources of infection for other species They appear unusually likely to cause human infection compared with cattle and possums (Fanning and Edwards 1991) There is also both clearcut and circumstantial epidemiological evidence from various incidents in New Zealand of their ability to initiate new foci of infection in possums, whereas cattle seem to have done so rarely, considering the relative numbers of tuberculous animals of each species with which possums would have had the opportunity for contact The first reported infections of badgers (which occurred in Switzerland) were also attributed to transmission from roe deer (Bouvier *et al* 1957, Wilesmith 1983). There is a need for the role of deer as a reservoir host for *M bovis* to be investigated using the various epidemiological methods which have been employed in other species but not so far in deer.

Other domestic animals

Infection in other domestic animals is largely a spillover from infection in major hosts, so tends to occur at a level proportional to that in major hosts in the area Sheep, pigs and horses are all susceptible, but infection of these species is rare in New Zealand and they do not influence the field situation Although occasional dogs and rather more cats can become infected, their only real importance is as a potential source of infection for the owners

Epidemiology in wildlife

Tuberculosis has been known as a serious clinical disease in wild mammals in captivity for more than a century Thoen and Himes (1981) state that it is widely distributed in wild mammal populations in the United States, where outbreaks caused by infection with *Mycobacterium bovis* have been reported mainly from zoos, game parks and primate colonies Schliesser (1985) notes that in European countries sporadic incidents of bovine tuberculosis in wild mammals were mainly reported before eradication of cattle tuberculosis was achieved Evidence from various countries in the world shows that given conducive epidemiological circumstances, significant levels of tuberculosis infection can be found in feral and free-living wild species such as buffalo, goats, pigs, deer, badgers and brush-tailed possums (Lepper and Corner 1983). The risk which these reservoirs of infection constitute for infection in domestic animals and man is quite variable depending on the specific epidemiological situation - primarily the wild species involved and specific features of the environment and management system used for the domestic stock It is noteworthy that each of the major wild reservoir hosts (badgers, possums, deer) are of importance in one or more countries but not in other apparently similar ones.

Badgers

The first report of *M bovis* infection in the European badger (*Meles meles*) was in Switzerland in 1956 (Bouvier *et al* 1957) However while there has not been any evidence of continuing transmission of *M bovis* between badgers and domestic livestock in the European continent, infection is endemic in badger populations in both the United Kingdom and Ireland, and transmission to cattle is a significant factor in the epidemiology of bovine tuberculosis in both countries. But because of management and other factors which amplify the amount of transmission within the cattle population, Ireland has a much higher national incidence rate and different epidemiological pattern (Downey 1990)

Transmission among badgers appears to be mainly by the respiratory route, and serological evidence points towards a high component of pseudo-vertical transmission from mother to cub (Wilesmith 1991b). This presumably takes place during the rearing period in the underground sett through the respiratory route, rather than *in utero* Some transmission occurs as a result of fighting between males, which would include infection of bite wounds as well as aerogenous transmission between the combatants. Cheeseman *et al* (1989) recorded that the distribution of lesions was consistent with a respiratory infection in 23 out of 28 badgers examined, and that the other 5 could have been infected from bites. Gallagher *et al* (1976) found similarly that 22 of 36 naturally infected wild badgers had lesions in the lungs or

thoracic cavity nodes, but that where haematogenous spread had occurred there was a predilection for the kidney

Badgers are unusual in that kidney infection with excretion in urine is much more common than in other species (37% of tuberculous badgers excreted in urine), and it has been proposed that infection of cattle occurs predominantly from urine deposited on pasture by foraging badgers, especially those in which the disease has reached an advanced stage. Cattle do not avoid pasture contaminated with badger urine to the extent that they avoid areas around badger faeces. However maximum survival time of organisms from urine on pasture is quite short (3 days in summer and 28 in winter, Wilesmith 1991a) The occurrence of pasture contamination does not rule out respiratory transmission as at least a substantial contributor to the total amount of transmission from badgers to cattle, and possibly the most important Some of the field evidence fits best to respiratory spread (Wilesmith *et al* 1982; 1986a) While normal badgers avoid close contact with cattle, terminally ill tuberculous badgers can exhibit abnormal behaviour which may facilitate transmission (Cheeseman and Mallinson 1981, Collins, JD, pers comm., 1991) There are numerous individual reported instances where large numbers of cattle have become infected over a very short period of time, and such cases are more consistent with respiratory transmission from a heavily infected badger than with pasture contamination by urine, the second mechanism being a better explanation for the much more common finding of low incidence rates, with or (more commonly) without persistence of infection in a herd Tuberculous badgers have been shown to be able to act as a source of infection to calves by contact, using both naturally infected and experimentally infected badgers (Little *et al* 1982)

Brush-tailed possum

In the nineteenth century the Australian common brushtailed possum (*Trichosurus vulpecula* Kerr), was introduced to New Zealand and liberated at numerous locations over several decades (Pracy 1962). The susceptibility of possums to *Mycobacterium bovis* infection was first experimentally demonstrated by Bolliger and Bolliger (1948) In 1967 the first possum with tuberculous lesions to be identified in New Zealand was found by a trapper on a farm with a persistent tuberculosis problem. In this and later cases it was reported that in all tissues examined, large numbers of *Mycobacterium bovis* organisms were present and the animals were discharging organisms through open sinuses or the respiratory tract (Ekdahl *et al* 1970)

Since then various workers (such as Cook, 1975, Cook undated; Julian 1981; Coleman 1988; Hickling *et al* 1991) have demonstrated that infection of this species is present in various areas of New Zealand, and is growing in geographical distribution Studies have shown point prevalence of cases with visible lesions in affected areas to average about 5%, with seasonal variation typically from 2% to 10%. Lesions are most common in the respiratory tract (about 55 to 70% of animals), although lesions in superficial lymph nodes have been reported in over 50% of tuberculous possums in various studies. It is quite common for these lesions to discharge intermittently or continuously to the skin through sinuses.

The disease is progressive and invasive with large tuberculous nodules which have central necrotic areas containing relatively few polymorphs but a large number of organisms There is no fibrous capsule, and liquefaction of the central necrotic area produces greenish semi-liquid exudate which discharges to the exterior The lesions are consistent with a poor host

response to the disease process. Lung lesions are commonly very extensive, involving multiple lesions, from miliary to large abscesses, and provide ample opportunity for airborne excretion in most infected animals. In contrast, although Corner and Presidente (1981) found urine shedding in experimentally infected animals, our work shows it to be unimportant under field conditions. Faecal shedding also appears from our work to be unimportant (Jackson, unpublished data) .

However transmission from mothers to their dependent joeys between birth and independence (termed pseudo-vertical) is a very important method of transmission The close association of mother and joey, with only 18 days *in utero* but approximately 5 months of pouch rearing followed by a period of back-riding, appear to expose joeys born to tuberculous mothers to a very high risk of infection (O'Hara *et al* 1976, Pfeiffer and Morris 1991) For those of our cases where the TB status of both mother and joey is known, 100% of joeys born to tuberculous mothers subsequently became clinically tuberculous

A longitudinal field study of the epidemiology of tuberculosis in possums and cattle which is still in progress (Pfeiffer and Morris 1991; Pfeiffer 1993) is clarifying the transmission of infection among possums and to both cattle and deer. The current hypothesis from this work is that local transmission is pseudo-vertical between the generations, and that horizontal spread within local possum communities is predominantly associated with courting and mating activities between the sexes, and competition among males. It is not yet certain whether one or other of these two main mechanisms is substantially more important than the other Outward movement of infection arises principally from the dispersal of juvenile males and relocation of some adult males The time from infection to development of clinical disease is believed to be very variable, and appears from our data to be strongly influenced by the severity of environmental, climatic and other stresses to which a particular infected possum is exposed. The combination of these factors produces the marked clustering of infection seen in cross-sectional and longitudinal studies We have shown that animals totally free of lesions may harbour *M bovis*, and we suggest that these are the animals from which clinical cases arise when and where environmental stress is most severe Evidence from detailed behavioural research (Paterson 1993, Sauter and Paterson, unpublished data) suggests that both cattle and deer (but not sheep) are highly likely to become infected principally through investigating terminally ill possums - which commonly behave abnormally and thus attract the attention of cattle or deer, each species reacting differently to the presence of the possum..

It seems likely that very occasional domestic stock and probably almost all of the scavenger species (wild pigs, ferrets, stoats, feral cats) become infected by investigating and/or consuming possum carcases It does not appear that surface contamination of pasture or of den sites and other areas frequented by possums is responsible for a significant amount of transmission either among possums or between possums and other species

Wild buffalo and bison

These are infected in Australia and North America, and represent control problems in affected countries

Feral deer

Infection with *Mycobacterium bovis* has been reported from a number of free-ranging deer species, as pointed out in the review by Clifton-Hadley and Wilesmith (1991). These authors and others report that there have been some incidents where infected feral deer were suspected of introducing infection into captive deer populations. Mackintosh and Beatson (1985) state that in New Zealand a high proportion of wild deer captured or shot was found to be infected with *Mycobacterium bovis*. The capture and domestication of feral deer in New Zealand has on the face of it played a major part in the evolution of tuberculosis infection in this country, although as discussed above factual data on the subject is sparse

Other wild and feral animals

Feral pigs have been found to be infected with *Mycobacterium bovis* at significant levels in a number of countries Recently a survey was conducted in Central Otago New Zealand, where 251 feral pigs were post-mortemed and 31% were found to have tuberculous lesions (Wakelin and Churchman 1991) The authors suggested that the disease possibly had spread between pigs by airborne transmission. Initial work in Australia found quite a high level of infection in feral pigs in the Northern Territory, but Corner *et al* (1981) subsequently showed that they were almost certainly dead-end hosts, which rarely transmitted the disease on to other species.

Feral goats were found with tuberculosis prevalences of up to 31% within individual groups in areas with endemic tuberculosis on the West Coast of the South Island (Sanson 1988). The epidemiological significance of bovine tuberculosis in goats is generally considered as minimal In most cases it is related to the presence of a reservoir of infection in another species, such as the possum.

Little *et al* (1982) examined a range of wild mammals in an area of Dorset where tuberculosis was endemic in badgers, and found a low prevalence of infection with *M bovis* but no pathology in rats and foxes. Wilesmith *et al* (1986b) undertook a very detailed study of wildlife in an area where badgers and cattle were infected, and found no evidence of infection in any of the 15 species of small mammals examined, including rabbits. Rabbits kept under laboratory or domestic conditions are highly susceptible to infection with *M bovis*. Yet only a single case of field disease has ever been recorded in the world (Anon 1980), despite efforts to find evidence of infection in various places. Tuberculosis has been found in one and possibly two hares out of a small number examined in an area with a high prevalence of infection in possums, although the mechanism of transmission is unclear (Jackson, unpublished data).

Infection in feral carnivorous species has to be expected in areas with endemic tuberculosis in important reservoir hosts such as the possum. Allen (1991) reviewed the evidence available on the occurrence of bovine tuberculosis in feral carnivores in New Zealand Although cats are relatively resistant to infection with *M bovis*, the disease is present at a low level in the feral cat population, and the limited evidence available suggests that infection is acquired mainly by predation and scavenging of other affected species, although some transmission among cats could occur, especially associated with fighting among males and mating activity. Mustelids are quite susceptible to *M bovis*, and the disease has been

diagnosed in ferrets, weasels and stoats. Infection would appear to result from scavenging of carcases of tuberculous animals in most situations, although there are some limited areas in New Zealand where carnivores may play a more central role

A SYNTHESIS OF THE CURRENT EPIDEMIOLOGICAL SITUATION

Maintenance and Spillover Hosts

In the absence of a wildlife reservoir of infection with *M bovis*, tuberculosis in cattle is now a readily controllable disease. Test and removal of infected animals at intervals of less than a year can eliminate the infection from herds provided that an epidemiologically sound control policy is followed which leaves no loopholes for persistence of infection. Such a policy eliminates virtually all transmission mechanisms other than airborne infection, and that can be controlled effectively as well, provided that infected animals are not left in or allowed to enter herds. Where infection persists under such circumstances, it is entirely due to management procedures allowing infected animals to remain in herds and to move between herds, thus starting new foci of infection. There is no evidence that long-term persistence of infection in cattle herds or in areas is due to any unexplained cause, if there is no wildlife reservoir host. The fundamental epidemiology of the disease remains as it was 30 years ago, and if anything has been simplified by the elimination of almost all transmission mechanisms other than airborne infection.

The situation in farmed deer is somewhat more difficult because of the apparent high transmissibility of disease within this species, and the fact that the effectiveness of testing procedures is not as definitively determined as in cattle In addition, the epidemiology of the disease in deer has not been as well defined as in cattle, especially with regard to the contribution of different transmission mechanisms. However, as in cattle, the answer to more effective control does not rely on finding the elusive ideal test with maximum sensitivity and specificity, but rather on using adequate tests as epidemiological tools to eliminate infection at herd level The evidence suggests that this is generally achievable in deer with only moderately greater difficulty than in cattle

However there are hints in the evidence presented above that both wild and farmed deer may be exceptionally effective in transferring infection to other species, and thus would deserve special attention in control programs. At present the epidemiological evidence to confirm or refute any hypotheses about the contribution of deer to the disease are very meagre indeed, and this deficiency needs to be rectified

The major complication of recent years has been the recognition of reservoirs of infection in various wildlife and feral species around the world. Once a wild species can maintain infection in an area in the absence of cross-transmission from other species of domestic or wild animals, then total elimination of disease from the population becomes an elusive goal. This status of maintenance host appears to have been reached by the badger, the brush-tailed possum and various species of ungulates in some countries, although it is notable that none of the maintenance hosts have achieved that status in all countries where they occur in significant numbers If anything, it is the exception rather than the rule for a species to

become a true maintenance host in a country, even though it has achieved that status elsewhere.

In addition, there is a long list of spillover hosts which become infected when the challenge level is relatively high, but on current evidence do not seem to maintain infection within the species in the absence of continuing acquisition of infection from maintenance hosts. Man belongs in this category Yet another group of species is susceptible to experimental infection (rabbit,sheep) but does not reach significant prevalence under field conditions

Under New Zealand conditions there are some susceptible feral species which on a national scale appear to be merely spillover hosts (pig, ferret, cat, possibly stoat), but for which as yet limited evidence suggests that one or more of these species may have become either a secondary or even the primary maintenance host in certain specific local environments While on one hand it is important not to discount such evidence, it is equally important not to mistake spillover hosts for maintenance hosts, and particularly not to diversify control efforts away from the possum without confidence that control efforts would provide substantial benefits to overall TB control, and would not have adverse side-effects, such as changing the predator/prey balance Judgments on an appropriate course of action will only be possible when anecdotal evidence is balanced by evidence from structured epidemiological investigations designed to discriminate between the maintenance and spillover categories of infection

Transmission Pathways

The evidence concerning wildlife tuberculosis points to marked similarities in the transmission mechanisms within maintenance hosts, and from these to other species In both badgers and possums, the evidence to date suggests strongly that pseudo-vertical transmission from mother to young is a key factor in maintenance of infection within local populations, with local dissemination resulting from competitive interaction among adult males and from courting and mating activity between the sexes. Even in swamp buffalo it would seem that there are comparable features to the epidemiological pattern (Freeland and Boulton, 1993). Distant spread within wild animal populations is due largely to dispersal of animals seeking new home ranges, although in practice this is intertwined with spread of infection due to commercial trading of infected domestic stock The vast majority of spread within wildlife is by the airborne route, and elimination of this route of transmission would probably render the species no longer a maintenance host As in human tuberculosis, transmission by environmental contamination does not contribute significantly to the spread of infection. This fact deserves considerable emphasis because it simplifies the problem greatly.

Transmission from wildlife to domestic animals and among domestic animals appears now to be predominantly also by the airborne route, and occurs principally when there are (usually behaviourally atypical) interactions between an excreting (frequently terminal) wildlife host and domestic animals. The badger is exceptional in excreting organisms extensively in urine and hence contaminating pasture, but the evidence is so far equivocal that transmission from badgers to cattle is more by this method than by airborne spread

Spillover hosts seem to become infected by routes other than the respiratory one more commonly than do maintenance hosts - for example the infection of predators and scavengers

which consume infected animals. By definition these hosts have only limited capacity to transmit infection to other members of their species. This may reflect different location of lesions arising from different entry portals, different susceptibility to development of clinical disease, different excretion routes or quantities of organisms excreted, or different social behaviour patterns.

CONTROL OF TUBERCULOSIS

The basic control measures required for bovine tuberculosis in domestic stock are well-defined and the information is readily accessible (Blood and Radostits 1989) In essence, regular testing of all eligible animals with a test equal to or superior in sensitivity and specificity to the intradermal tuberculin test will, if meticulously carried out in combination with appropriate hygiene measures and restrictions to prevent introduction of infected animals, control bovine tuberculosis very effectively. The disease has been eradicated from countries and large regions using this approach, even under circumstances where some aspects of the control measures are mildly compromised by inescapable limitations

Where control difficulties have arisen, there has typically been too much concern with test characteristics and with uncontrollable sources of failure to eradicate at herd level, and inadequate concern with identifying and preventing methods of transmission. There has also been undue concern with "singleton reactors" - the herd which has one positive animal at a test Given that no test for tuberculosis is 100% specific, singleton reactors must be found routinely in the course of testing. Most single positives will be false positives, but a small proportion will be the first in a series of infected reactors. Various strategies are available for dealing with this problem (which is universal in disease eradication programs), and the strategy chosen should represent a careful balance between cost and effectiveness - it is fundamentally an economic problem rather than a disease control problem, and should not be allowed to confuse the situation.

The design of a regional control program therefore requires certain basic principles, regardless of whether or not a wildlife reservoir exists. There must be multiple interlocking control procedures which block transmission by each of the pathways known to be operating in the population. In this way, failure of one control measure will not undermine the whole control strategy. The first step is to motivate farmers to cooperate, and convince them that progress is achievable. Unless this can be done, there is little prospect of success with tuberculosis control Increasingly, use is being made of farmer leadership in programs to ensure that the farming community contributes fully to the design of control measures and their enforcement. Where possible, the control approach chosen should be based on incentives for achievement of program goals rather than on coercion to participate

If there is a wildlife reservoir of infection as in New Zealand, then the control measures described above will still produce a low prevalence of infection across the livestock population, but there will be patchy herd breakdowns producing a higher herd prevalence of infection within the population than otherwise, combined with a lower than expected within-herd incidence since most transmission will be direct from wildlife to domestic stock, not within the domestic population.

At present the only control measure available for wildlife hosts is removal of infected animals In New Zealand the situation is easier than in the United Kingdom or Ireland with the badger, since the possum is considered a pest species on multiple grounds and control by large-scale aerial and ground poison baiting is an accepted practice. This reduces the scale of transmission to cattle for some years, but only under favoured circumstances is there any real prospect of local eradication with current methods. The reality in New Zealand has been one of geographical expansion of the disease, and a holding operation in endemic areas rather than positive progress with control

If future progress is to be made, it will depend on broadening the range of available control measures and integrating them into combined programs which jointly reduce transmission There are strong epidemiological similarities between tuberculosis and wildlife rabies, where oral vaccination of the wildlife reservoir is proving a major advance in control of the disease In the case of tuberculosis, vaccines are unlikely to solve the problem but could well offer a major improvement to the effectiveness of current control strategies if integrated fully with other methods. Interestingly, the epidemiological evidence would suggest that a vaccine for possums deserves higher research priority than a cattle vaccine, with a deer vaccine of second priority This is consistent with experience with fox rabies

Improvements should also be possible in currently used population reduction methods, and are the subject of current research For animals such as the possum, where it is recognized as a pest species for reasons beyond its transmission of tuberculosis, a mix of population control measures may well offer advantages over area poisoning alone. Mechanisms which deserve consideration are fertility control in adults of one or both sexes, measures to reduce the dispersal of infected juvenile animals and in the short term the use of continuous-access poison sources such as bait stations

However all of these potential new control measures require major research investment and are unlikely to produce a useable result in under ten years. In the meantime, evidence is accumulating from our own work and others that there is significant scope for reducing transmission between wildlife and domestic stock by farm-based control programs These are likely to be built around a combination of effective control of the disease in domestic stock, use of stock management procedures which minimize transmission-prone behavioural interactions between stock and wildlife, and in some cases carefully timed local population control measures. Timing of these various measures may turn out to be as important as the nature of the measures taken. However no control policies based on measures other than simple population reduction have yet been attempted, so there is no experience so far to report We are currently working to design such control systems, for subsequent field evaluation.

These various techniques will in future be incorporated into epidemiologically-based decision support systems (Morris *et al* 1993b), which will combine herd testing and livestock movement data, local geographical data and information on wildlife host distribution and infection to permit evaluations to be conducted both of past effectiveness (by epidemiological analysis) and of future options (by computer modelling). This in turn will allow veterinarians to make the kind of detailed integrated evaluations of control options at farm and regional level which offer the best hope of making short to medium term progress in control of the disease, pending the development of new control technology

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