A TRANSMISSION MODEL FOR SALMONELLA IN GROWER-FINISHER PIGS

Andrew Hill, Emma Snary, Mark Arnold, Alasdair Cook*
Centre for Epidemiology and Risk Analysis, Veterinary Laboratories Agency, Weybridge, UK
Centre for Epidemiology and Risk Analysis, Veterinary Laboratories Agency, New Haw, Addlestone, Surrey, KT15 3NB, United Kingdom. Tel: +44 (0)1932 357774 Fax +44 (0)1932 357445 e-mail: a.hill@vla.defra.gsi.gov.uk

Abstract This paper presents a model describing the dynamic transmission of Salmonella Typhimurium between pigs on a typical, British pig grower-finisher farm. A modified Reed-Frost discrete-time model was used to estimate the probability of infection for susceptible pigs. Once infected, a pig passes through two stages: Excreting and Carrier/Immune, before becoming susceptible again. The epidemic curve derived from the model shows that the percentage of pigs excreting STM in their faeces declines from approximately 15% initially and levels off at around 7-8% by the age of slaughter. In contrast, the percentage of pigs that are carriers or completely immune rises from 0% to 7-8% over the period of time that pigs remain on the farm.

Introduction Salmonella spp. are the second most common bacterial cause of human intestinal infectious disease in Great Britain (GB). The reported number of cases in 2002 was 15,576 (Health Protection Agency 2004; Scottish Centre for Infection and Environmental Health 2005), of which 1,994 were identified as Salmonella Typhimurium (STM), although it is estimated that only 1 in 3 cases in the community are reported (FSA, 2000). The UK Food Standards Agency (FSA) have set a target of achieving a 20% reduction in the incidence of foodborne illness by 2006 (Food Standards Agency 2002).

One possible source of human Salmonella infection is the consumption of pig meat and pig meat products. In two recent GB abattoir surveys, approximately 23% of slaughter pigs were found to have Salmonella in their caecal contents (Department for Environment Food and Rural Affairs, 2004) and the most commonly isolated pig serovar is STM (Veterinary Laboratories Agency 2004), which is also the second most common isolated serovar in human salmonellosis. Therefore, the FSA target can in part be achieved by reducing the number of Salmonella cases attributable to pig meat consumption. To reduce levels of Salmonella in pigs, the British Pig Executive (BPEx) have introduced a Zoonoses Action Plan (ZAP) programme (British Pig Executive, 2004). This nationwide surveillance scheme uses a meat-juice ELISA test to monitor the Salmonella status of pig farms that send their produce through assured abattoirs. Those farms on which 65% of more of samples are positive must implement a dedicated on-farm Salmonella control package and the aim of the programme is to reduce the burden of human salmonellosis.

The proportion of UK Salmonella cases that are attributable to pork consumption and the effect that an on-farm Salmonella control package would have on these cases are unknown. Therefore, in order to inform the ZAP programme, a farm-to-consumption risk assessment was developed to assess the risk of human salmonellosis from pig-meat products (Hill et al., 2003). The farm-to-consumption pathway was split into six modules, of which the first is a Salmonella transmission model for grower-finisher pig farms.

This paper considers the farm transmission model, which is a further development of a deterministic STM transmission model developed by (Ivanek et al., 2004) that considers an open-plan, all-in-all-out herd. The model described here is stochastic and allows the model to consider the grouping of pigs within the herd.

Materials and Methods

Model development and initial conditions of model The transmission model estimates the prevalence of STM excretion and carriage for a batch of slaughter-age pigs sent to abattoir from an exclusive grower-finisher farm operating a continuous system of production.

In order to facilitate between-farm variability, a ‘most common’ approach to grower-finisher production in Great Britain (GB) has been developed to reduce the complexity of the farm model. We used expert opinion to devise the most common approach to pig farming in GB, which incorporates approximately 40% of GB pig herds. This ‘typical’ farm has the following attributes: inside production, exclusive grower-finisher farm; single house, continuous system of production, and the use of pens in the house to segregate the pigs into smaller groups.
For simplicity, the start point (time $t = 0$) is taken to be the introduction of a new batch of weaners onto the farm. The farm is considered STM-positive if a) the pigs already on the farm are STM-positive or b) the pigs (weaners) entering the farm are STM-positive. These parameters are estimated using data from a national study of pig farms (Davies et al., 2002). STM-positive pigs are assigned one of three STM statuses: Susceptible, Excretor (excretes STM in its faeces) and Carrier/Immune (infected pigs that are not excreting STM, and pigs which have recovered and have acquired immunity). The Carrier/Immune status is important when estimating the number of susceptible pigs on a farm, and also when considering the burden of STM throughout the pig production chain.

The output of the model is the prevalence of STM excretion and carriage/immunity over time for the weaners brought onto the farm at $t = 0$.

Transmission model
Faecal-oral transmission is thought to be the primary route for STM infection on grower-finisher farms (airborne transmission may also occur). This route may transmit infection both within and between pens. Any newly infected pen can also contribute to the spread of STM within the herd. A schematic diagram of transmission between each infection status for two groups of pigs is given in Figure 1.

The transmission of STM on a grower-finisher herd using a continuous system of production was modelled by modifying a stochastic, discrete-time Reed-Frost model as described by Bailey (1975).

The timestep of a discrete Reed-Frost model should be equivalent to the incubation, or latent, period (Bailey, 1975). Incubation periods for STM infection in pigs have been recorded from 24-48 hours (Iowa State University, 2003). For simplicity, the timestep was set as one day.

The probability of transition between Susceptible and Excretor status over one discrete timestep, $P_I(t+1)$, can be given as:

$$P_W(t+1) = (1-(1-w)E_w(t))$$

where $E_w(t)$ is the number of excreting pigs within a pen at time $t$ and $w$ is the probability of an “effective contact” between a susceptible pig and excreting pigs within the pen over the period $(t, t+1)$. An effective contact is defined as the infection of a susceptible pig given direct contact between a susceptible and excreting pig. This equation is adopted for each of the infected pens.

Both the faecal-oral and airborne transmission routes may contribute to the infection of susceptible pigs by those excreting STM in the same pen. However, it is likely that the faecal-oral route dominates transmission within a single pen due to the sheer number of organisms that may be present in faeces compared to those that are airborne. Therefore, for within-pen transmission, only one mode—contact with contaminated faeces—is considered.

Equation 1 can be re-parameterised to estimate the probability of infection between pens. Therefore, if a susceptible pig resides in Pen A, it has a probability of becoming infected with STM from excreting pigs in an adjacent pen (Pen B) as follows:

$$P_B(t+1) = (1-(1-b)E_B(t))$$

where $E_B(t)$ is the number of excretors within Pen B at time $t$, and $b$ is the probability of an effective contact between the susceptible pig in Pen A and excretors within Pen B at time $t$. For simplicity, it is assumed that $b$ is directly proportional to the number of excretors within pen B at time $t$. Similar equations can be constructed for STM transmission between pens on the same side of the house (but not adjacent to each other) and on the other side of the house. In these cases, $b$ is simply replaced by other transmission probabilities, $r$ and $s$ respectively. Due to a lack of data, the latter two parameters were linked to $b$, where expert opinion was used to state that $r$ is equal to $b/3$ and $s$ equal to $b/100$. The mode of $b$ and $r$ was assumed to be contact with faeces, where $s$ was assumed to be because of airborne transmission.

In the model each susceptible pig on the farm is considered in turn, where the effect of any pen containing Excretors on the infection status of the susceptible pig is estimated. Infection status is randomly assigned according to the transition probabilities.

After each susceptible pig has been updated according to the method above, those pigs classified as Excretor or Carrier/Immune are updated. The removal of infected animals from a population in a stochastic model can be represented as a random Poisson process (Bailey, 1975). Thus,
the period a pig excretes STM can be shown to follow the form of a negative exponential model. Therefore, the probability of transition between Excretor and Carrier/Immune status, $P_C(t+1)$, can be given by Equation 3.

$$P_C(t+1)=1-e^{-\gamma t_e}$$

where $\gamma$ is the rate at which pigs recover from excreting STM to being carriers of the organism, with units of days$^{-1}$ and $t_e$ is the number of days the pig has been excreting STM. Therefore, $\gamma$ can be estimated as $(1/\text{length of Excretor status})$. The probability of transition between Carrier/Immune and Susceptible status also can be estimated using equation 3, but using $\varphi$ (defined as the rate at which Carrier/Immune pigs regain their susceptibility, with units of days$^{-1}$) instead of $\gamma$ and $t_C$ (time spent within the Carrier/Immune status) instead of $t_e$.

The number of susceptible, excreting and carrier pigs at the end of each timestep (day) is calculated once the infection status of all pigs has been determined. The model output is the prevalence of STM excretion and prevalence of STM carriage. The epidemic curve over time is then generated.

**Parameter Estimation** A number of parameter estimates used in this model are estimated in Ivanek et al. (2004). The herd size, $N$, and the number of pigs within a pen, $n$, are estimated from expert opinion. The length of the grower-finisher stage, $T$, is estimated from data collected by the UK Meat and Livestock Commission (Meat & Livestock Commission, 2003). All parameters describing the herd and within-herd prevalence of pig farms (both weaner and grower-finisher) have been based upon the same GB observational study (VLA, 2000). Data from a Danish study (Stark et al., 2002), which estimates the ratio of shedding to carrier pigs within a Danish finisher farm, is used to estimate the prevalence of within-herd STM carriage, assuming that this Danish study is also applicable to GB finisher farms.

The probability of infection being transmitted from an excreting pig to a susceptible pig during a period of 24 hours if the pigs are in the same pen or in adjacent pens, $w$ and $b$ respectively, are unknown parameters. Maximum likelihood estimates for $w$ and $b$ were estimated simultaneously from the simulation model and data obtained for relevant farms from the British ZAP *Salmonella* programme. To account for using a serological test in the model rather than a bacteriological one it was assumed that once a pig has become infected with STM it remains seropositive, and hence will be identified as such in the ZAP programme (assuming sensitivity and specificity of 100%). The estimation of $\gamma$ and $\varphi$ has been described previously in Ivanek et al.

**Results** The average epidemic curve of STM infection, for the time period of pigs entering and leaving a grower-finisher farm, described by the model is given in Figure 2. The mean prevalence of STM-excreting pigs within the followed batch decreases from approximately 15%, when the pigs are weaners, to 6-7%, dependent on the age of slaughter (84 to 116 days). It can be seen that as $t$ increases, the mean prevalence of infecteds reaches a steady-state phase. As the weaners grow, the mean prevalence of carrier/immmunes increases over time from 0 to 7-8%. Variability of the model output has
also been estimated: the prevalence of excretion within the batch followed at slaughter age may vary between 0 and 28%, and prevalence of carriage 0 and 23% (5th and 95th percentiles respectively).

**Discussion** The objective of this work was to describe the change in the prevalence of STM infection (excreting and carrier pigs) on a farm over time. The model predicted that the average prevalence of carrier/immunes at slaughter will be higher than that of infecteds, but only marginally. Current thinking suggests that the prevalence of carrier pigs should be higher than the prevalence of excreting pigs at the time of slaughter (Stark *et al.*, 2002). This model confirms this statement. It also raises an important point from a human health perspective. Due to stress during transport, these carrier pigs are likely to begin re-shedding of STM in their faeces; leading ultimately to an extra burden in the number of infected pigs entering the slaughterhouse.

The model is sensitive to the transition probability parameters, i.e. probability of transfer between susceptible and excretor or excretor and carrier status. The data and methods used to estimate these parameters are uncertain, and further research is required to determine the true values of these parameters.

**Conclusions** A stochastic, discrete-time transmission model has been developed to describe the epidemic curve for the dynamics of STM transmission between pigs on a typical GB grower-finisher farm. On average, STM excretion decreases during the initial period after pigs enter the farm, and then a state of equilibrium is reached, with as many pigs becoming infected and excreting STM as those recovering to a carrier/immune state. There is further research required to estimate crucial parameters.

**References**


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