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Biosecurity Measures to Control Salmonella and Other Infectious Agents in Pig Farms: A Review

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Abstract: Salmonellosis is the 2nd most common cause of human bacterial food poisoning and can be acquired from meat or eggs, either via direct consumption or cross-contamination in the kitchen. The European Commission has set the criteria to control *Salmonella* infections within the poultry sector and it is proposed that the swine sector should follow. Pork is considered, after eggs, the major source of infection in humans in the EU, with *Salmonella typhimurium*, including monophasic strains, being frequently implicated. Good control measures at the farm level are likely to correspond with lower prevalence of *Salmonella* infection and, subsequently, a reduction of cross-contamination of carcasses processed at the slaughterhouse and a reduction in human salmonellosis. This review focuses on biosecurity measures in pig farms that can help to control important pig diseases at the same time as reducing the within-herd prevalence of *Salmonella*. This information is likely to provide an economic incentive for farmers to apply improved general standards of farm biosecurity and hygiene management that would have a positive impact in food safety.

Keywords: Pigs, farm, Salmonella, Biosecurity, Food (safety)

Introduction

Worldwide, salmonellosis is the 2nd most common cause of foodborne infectious gastrointestinal disease in humans [(Pires and others 2011) as cited by (Arguello and others 2013a)], with the associated important cost to society. The success in the reduction of the *Salmonella* prevalence in the poultry sector, particularly *Salmonella Enteriditis* in laying and breeding hens, has resulted in a correlated reduction in the human cases associated with the consumption of eggs (EFSA 2011; O'Brien 2012; Harker and others 2014). The EU was originally expected to introduce regulations concerning the monitoring and control of *Salmonella* in pigs after an initial focus on the control of *Salmonella* in poultry and its subsequent reduction, although proposals have been dropped following a negative cost–benefit analysis (DGSANCO 2010). In the EU, *Salmonella* is most often detected in meat and products thereof (EFSA 2013), and human outbreaks are often linked with the consumption of pork. In the last 10 y, pork has been identified as the 2nd most important source of human salmonellosis in many EU countries (Hauser and others 2010). In Great Britain, *Salmonella typhimurium* and *Salmonella derby* have predominated in British pigs but monophasic strains of *S. typhimurium* have emerged since 2007, becoming the 2nd most common serovar in British pigs in 2010 and accounting for 25% of the incidents in that year (Mueller-Doblies and others 2013). *Salmonella* serovars are defined by means of an antigenic formula based on the presence of somatic and flagellar antigens, according to the White-Kauffmann-Le Minor scheme (Grimont and Weill 2007). In most *S. enterica* subsp. *enterica* serovars, the antigenic formula is composed of 2 flagellar phases. The monophasic variants lack the 2nd flagellar phase due to the absence of the flj B gen and they emerged worldwide several years ago (Switt and others 2009). More recently, the pig slaughter survey carried out in the United Kingdom in 2013 has found that monophasic strains of *S. typhimurium* were the most common serotype isolated from pig carcasses (AHVLA 2014). Across the EU, *S. typhimurium* was by far the most frequently reported serovar over the period 2004 to 2011, with monophasic strains becoming more prevalent through the years, as becoming the 3rd most frequent serovar in 2011 (EFSA 2013).

Infection or contamination with *Salmonella* may occur at different points through the production chain, either at the primary farm production level or during slaughter and further processing (Arguello and others 2013a). Nonetheless, farm level controls are very important as it has been demonstrated that there is a strong association between on-farm prevalence and meat contamination (Sorensen and others 2004; Baptista and others 2010b). However, the views of other authors seem to differ on this point, and based upon mathematical models, a Danish study established that only acting at primary production level would have limited impact upon the level of contamination, meaning that large reductions in the number of seropositive pigs delivered to slaughter would result in only small reductions in the probability of *Salmonella*-positive carcasses, thereby casting doubt that focusing solely on primary production would be an economically efficient option (Alban and Stark 2005). In any case, it could be said that any control measures applied at the farm should correspond with less-contaminated meat by reducing the burden on subsequent steps of the

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production chain as demonstrated in Sweden, Norway, and Finland. In addition to this, control of *Salmonella* at the herd level can prevent further spread within the sector, to other food animal sectors and potential zoonotic infections due to contact with infected pigs and manure (Lo Fo Wong and others 2002; Hendriksen and others 2004). It is acknowledged that pigs commonly carry *Salmonella* bacteria, which are typically not associated with clinical infectious disease, remaining subclinical but with pigs still acting as "carriers" (Boyen and others 2008; Wales and others 2011; Palomo Guijarro and others 2012). After infection with *S. typhimurium*, pigs may develop a carrier state, shedding the bacteria in feces for up to 28 wk without showing clinical signs (Wood and others 1989). These carrier pigs play an important role as the initial source of contamination of the environment, other animals, and carcasses in the slaughterhouse. The large intestine and mesenteric lymph nodes, as well as tissues relating to the buccal cavity, represent the tissues most consistently colonized by *Salmonella* in infected animals and these organs often harbor *Salmonella* in carrier animals (Nollet and others 2005) providing a source from which it may be spread in the abattoir, contaminating carcasses and other food products, (Morgan and others 1987) particularly if used to make sausages. Because of the lack of clinical infectious disease, farmers and pig owners do not usually see the need to intervene to reduce its prevalence at farm level as a priority. Equally, the lack of any financial incentives or penalties in most EU member states may have led to the perception that *Salmonella* infection in pigs is of lesser importance than other swine diseases or *Salmonella* in poultry. Nonetheless, some EU countries, like Denmark, have shown that a reduction in the *Salmonella* prevalence in pig herds corresponded with a decline in the number of human cases of salmonellosis (Nielsen and others 2001). Therefore, a compulsory *Salmonella* control program was introduced in Denmark, in which the national herds are classified according to their *Salmonella* serological status, and pigs from highly infected farms are subject to a price penalty, being slaughtered separately and under increased hygienic precautions (Alban and others 2002). This acts as a general incentive among pig farmers who wish to avoid the financial consequences of these penalties.

At this point, discussion of the serology compared with bacteriology dilemma is relevant, regarding the most suitable method to use for monitoring the *Salmonella* status of pigs. From a practical and financial point of view, it has been said that bacteriology is expensive, requires more complicated sampling and the laboratory tests on individual animals have a relatively low sensitivity while serology is cheaper and easier to perform (Alban and others 2012). Pooling samples for bacteriological tests can both increase the sensitivity and reduce the cost, as well as providing the opportunity to identify specific high-priority zoonotic serovars or strains. Serology indicates prior exposure to *Salmonella*, which the animals may or may not be still shedding at the time of sampling (Lo Fo Wong and others 2003) and which can misclassify herds as the bacteria may not be present by the time that pigs that were infected earlier in life reach slaughter age. Bacteriology indicates actual shedding and potential for cross-contamination during transport and slaughter, which is more important from a public health point of view and may not always be correlated with positive serology, depending on the stage of infection as there is a time lag between serology and bacteriology (Kranker and others 2003) or animals may exhibit a low serological response (Lo Fo Wong and others 2003). This could lead to misclassification of some herds when only serology is used. However, studies have found an association between herds with high seroprevalence and the proportion of pigs with *Salmonella*, which was used as the foundation for the surveillance and monitoring scheme in Denmark (Alban and others 2012)

Other countries, like Norway, Finland, and Sweden have a more strict approach to *Salmonella* control in food animals and they operate a pre- and postharvest surveillance program together with an eradication strategy; and, as in Denmark, vaccination against *Salmonella* is not used on the grounds that it may interfere with surveillance (Alban and others 2012). In the United States, no preharvest measures are commonly applied and only postharvest actions, like decontamination of the carcasses at the abattoir, takes place (FSIS 1996; Funk and Gebreyes 2004).

The EU is considering what measures should be applied in order to reduce the *Salmonella* prevalence in pigs across the member states, but it is likely that successful control will include preharvest actions on the pig farms. The prevalence of *Salmonella* among the member states greatly varies in the commercial breeding herd holdings between 0% and 56% with a community-wide mean prevalence of 33.3%. The United Kingdom is among the countries with the highest prevalence, around 44% (EFSA 2009), and the slaughter pig survey carried out in 2007 showed that the United Kingdom had a 21% prevalence of *Salmonella,* with almost 14% prevalence of *S. typhimurium* (EFSA 2008). It should be noted that prevalence depends on detection sensitivity, and includes sample size, representativeness, and characteristics of sample handling and testing, which creates a wide variability and adds difficulty when trying to compare prevalence in this review.

It has been discussed that biosecurity plays a very important role in avoiding the introduction of *Salmonella* and other pathogens into the farm and also to limit its spread within the farm once it has entered (Barcelo and Marco 1998; Amass 2005a). However, there is no universal protocol of biosecurity that all farms can put into place to minimize the risk of disease introduction. Each farm is unique in terms of location, facilities, management, host susceptibility, and other influential factors. Therefore, biosecurity should be a continuous process which assesses the risks, implements protocols according to need and costs, evaluates the effectiveness, and modifies the procedures as critical areas of risk change (Amass 2005a).

Biosecurity

Broadly, the concept of biosecurity relates to the implementation of hygienic and sanitary measures that can prevent the introduction of diseases into a farm and/or contain their spread once they are already present. Following the classification used by some authors (Moore 1992; Barcelo and Marco 1998; Morillo Alujas 2005), and in order to better understand the different biosecurity practices and their impact, they can be grouped into 3 different categories: Biosecurity measures related to the farm location, related to the replacement of animals, and, finally, those related to husbandry.

Biosecurity related to location

It is clear that the geographical situation of a pig farm is likely to have an influence over the biosecurity practices to be implemented. In general terms, the higher the density of pig farms in the area, the greater the risk of introducing disease and the stricter the biosecurity measures that have to be applied to avoid the spread of infections between herds. The most important way to transmit porcine pathogens into a herd is to introduce infected pigs (Amass and Clark 1999). It is speculated that the type, number, and density of pig units in a 2-km radius are crucial (Pritchard and others 2005). In the case of the United Kingdom, the pig production is primarily based in Yorkshire and Humber, Eastern England, Northern Ireland, NE Scotland, and SW England (81% in England, 10% in NI, 9% Scotland, and 1% in Wales). Norfolk, Suffolk, and North and East Yorkshire counties account for well over half of England's pigs (Houston 2013). For commercial reasons, pig production in Britain is concentrated in these few regions, where endemic diseases are inevitably prevalent (Pritchard and others 2005). Geography plays a role in where the farms are located, hence outdoor farms and breeding farms are more likely to be found in eastern England, where free-draining sandy soil is prevalent, while many finisher farms are in Yorkshire. Some geographical distribution patterns are also the result of localized expansion of integrated pig breeding and production companies.

When establishing a new pig farm, the location can be chosen, subject to planning permission, restrictions, environmental regulations, and so on, but this is a unmodifiable parameter once the farm has been built (Amass 2005a; Casal and others 2007). The location of the farm is a key point in limiting the introduction or reintroduction of certain diseases which may be prevalent in the area. It has been hypothesized that only an isolated farm will have a good chance of prevention of disease entry, specially airborne pathogens (Julio Pinto and Santiago Urcelay 2003) and a minimum of 3 km (more for high-value/high-health nucleus herds) had been suggested, as that distance is usually not exceeded by the possible vectors of diseases like flies and mice (Morillo Alujas 2005; Kirwan 2008). Some authors have speculated that a distance of less than 2 km between farms increases the chance of a positive *Salmonella* result (Hotes and others 2010) and because this distance could be exceeded by some vectors, such as wildlife, it is advisable that pig farms have a good pest control regimen in place to avoid the introduction of infection by this route. The size of the nearest farm is also important in relation to the weight of the challenge (FAO 2010). However, there are examples in which the distances between farms are small and yet they have been able to keep herds free of specific diseases, as is the case of Denmark reported by the Natl. Committee for Pig Breeding and Production (Moore 1992). It has been said that in densely populated areas, biosecurity, compliance with procedures, and adequate management practices are very important to prevent the introduction and spread of diseases (Barcelo and Marco 1998; Amass and Clark 1999; Ribbens and others 2008). The location is particularly important for primary breeding pig companies, due to their key role in the production chain, as they can act as a source of disease and spread pathogens widely. A poor location can be responsible for infections like enzootic pneumonia, Aujeszkies disease, and porcine reproductive, and respiratory syndrome and therefore increase the possibility of selling animals with undesirable diseases (Barcelo and Marco 1998). It has been suggested that a minimum distance of 500 m between pig farms may reduce the risk of acquiring common airborne infections, but in high pig density areas, it has proven to be very difficult or impractical to maintain disease freedom from endemic diseases such as porcine reproductive and respiratory syndrome, enzootic pneumonia, swine influenza, and postweaning multisystemic wasting syndrome (Pritchard and others 2005). Curiously, a study on the perceptions of biosecurity measures by Spanish farmers revealed that distance from other farms was not considered to be an important biosecurity measure. However, this probably is not because farmers were not aware of its importance, but because it was seen an unmodifiable factor and, therefore, was generally not properly evaluated when they were interviewed (Casal and others 2007). It should also be mentioned that apart from the location of the farm, the links that it may have with other farms are also of considerable importance. Studies in the network analysis of pig transport in the United Kingdom found that interconnectivity between farms is higher than originally envisaged. This interconnectivity is not only direct (animals moving from 1 farm to another), but also indirect via transporters, abattoirs, and collection of fallen stock. The authors hypothesized that encouraging the farms to reduce the number of connections could be a good way of reducing *Salmonella*, as it would reduce the effect of high prevalence on other farms within the network. This could also partially explain the comparatively low prevalence observed in some of the U.K. regions, like Scotland (Smith and others 2013).

The geographical and climatic characteristics of the area where the farm is located are also relevant. Factors like the prevailing winds, the air temperature, and air humidity of the area should not be underestimated. Generally speaking, low temperatures and higher levels of humidity favor the persistence of pathogens; and organisms' survival is usually shorter during hot periods. In the case of *Salmonella*, it is precisely the contrary, and a recent study in the United States has found that there was a strong correlation between infection and high temperatures, as warmer temperatures enable rapid replication (Akil and others 2014). Therefore, it is of importance that the design of the farm buildings takes into consideration all these factors and tries to counteract them. For example, it has been said that if the location is in an area where the winds are very important, the farm should be located down a valley and at the opposite side, while it should be located at the top of a hill if it is in an area of very hot weather (Moore 1992). It is accepted that farms located in flat land without any trees or other types of protection can be considered at greatest risk (Barcelo and Marco 1998). In the United States, planting trees around poultry farms has been suggested as an added potential biosecurity measure. Although no scientific papers could be found that have studied this, it is believed that certain trees act by restricting airborne particulates and may aid in blocking airborne poultry pathogens from entering as well as exiting a farm (Malone and Abbott-Donelly 2000). The same could therefore be extrapolated to pig farms and it has been already considered (FAO 2010). Trees, hedges, or bushes could also act as a physical barrier to prevent access from people and some terrestrial wildlife but they also can act as an attraction or other wildlife, such as birds and rodents. The movement of surface water should also be considered when deciding the location of a farm, especially within valleys, as the moving effluents can act as carriers of specific pathogens (Abu-Ashour and others 1994) that can find in this way an entry to infect the herd.

In terms of *Salmonella* infection, the location of the farm can play a role in the way that the infection can be introduced in the herd. For example, in coastal areas, seagulls can act as important vectors, while in wooded zones birds, badgers, and rodents can introduce and maintain the infection, acting as reservoirs. However, it has been observed in poultry that primary introduction of infection from wildlife, as opposed to amplification of excreting infection by wildlife, is relatively uncommon (Wales and others 2007). Farms that are on the fringes of an urban nucleus can be exposed, directly or indirectly, to human waste which can also lead to infection of the pig herd (Strauch 1991).

Type of farm. Mixed farms, those with different animal species, are by their very nature more risky in terms of introduction and perpetuation of *Salmonella* and other common infections. *Salmonella* serotypes are normally divided into 2 groups on the basis of host range; host-adapted and ubiquitous (nonhost-adapted).

Host-adapted strains may cause serious illness in the host species (for example, *Salmonella* Dublin in cattle, *Salmonella gallinarum* in chickens, and *Salmonella choleraesuis* in pigs). However, *Salmonella* is a common commensal of many animals and this is important since nonhost-adapted strains can be maintained as a reservoir of infection in clinically asymptomatic carriers and certain species of wildlife, potentially leading to the perpetuation of infection in the farm. Only a small number of serotypes typically cause severe systemic disease in man or animals and those serotypes are often associated with one or few host species, especially pigs and poultry (Uzzau and others 2000). The presence of cattle, sheep, or poultry could be considered a risk if housed at less than 100 m (Alexander and Harris 1992). Different animal species in the same farm has been correlated with increased *Salmonella* prevalence, but there are also other studies that have not been able to find a clear association between *Salmonella* infection and other domestic animals in the farm apart from pigs, which are a more "potent" source of infection because of the high within-herd prevalence (Funk and Gebreyes 2004). Interestingly, a study in Spain showed that mixed farms seemed to be less concerned about biosecurity, suggesting that the more specialized a farm, the higher the awareness of the risks associated with introduction of diseases (Casal and others 2007).

The size of the farm is another controversial risk factor. One might think that the larger the herd, the greater the risk of introduction of contamination (Moore 1992) and risk could be associated with practices of mixing pigs, which may happen most frequently in larger herds. It has been considered that the larger the herd, the higher the risk of transmission given the higher number of "infectious" and "susceptible" animals, offering an increased chance of more effective contacts per unit of time (Correia-Gomes and others 2012). The Natl. Animal Health Monitoring Service (NAHMS) reported that 53% of U.S. herds were infected with at least 1 serovar of *Salmonella*, with prevalence being highest in herds marketing greater than 10,000 pigs annually [(Haley and others 2012) as cited by (Stevens and Gray 2013)]. However, only a proportion of studies have found that an increased herd size imposes an increased risk of *Salmonella* infection (Dahl 1997; Carstensen and Christensen 1998; Lo Fo Wong and others 2004; Poljak and others 2008; García-Feliz and others 2009; Correia-Gomes and others 2013). In contrast, there are observations that suggest that large farms can be very well managed, using practices such as batch farrowing and all-in/all-out (AIAO) housing and may, therefore, be more successful in controlling *Salmonella* and other infections. It has been reported by some researchers that *Salmonella* can be more prevalent in small- and medium-size herds than in large ones, mainly owing to the fact that large companies may have the necessary resources to implement effective biosecurity measures and good hygiene practices (van der Wolf and others 2001a). A recent study in Belgium has found that, generally, biosecurity measures are better implemented in some larger herds (Laanen and others 2013), which could explain the lower prevalence of *Salmonella* in larger farms. In any case, it may be misleading to analyze this solely based upon the size of the farm, as other associated factors, such as number of buildings, pen density, pig contact between adjacent pens, stress levels at the farm, stock replacement, feeding policies, and so on, could have a considerable influence, and they are very variable among farms of a similar size (Lo Fo Wong and others 2004; García-Feliz and others 2009). The size of the farm can also be associated with different management aspects that may increase the risk. For example, larger farms may need to purchase weaners/replacement animals and require more transport but they may also breed their own replacements and therefore operate as a close herd (Boklund and others 2004).

The type of production within the farm is also important. Similarly to what has already been said for the size of the farm, authors seem to disagree on this matter. Pigs of different ages in the same site, animal movements, and complex flows make breeder-finisher farms likely to be infected with persistent *Salmonella* infections. It is accepted that weaning is a stressful and critical period that increases the susceptibility of piglets to infections. Therefore, a possible way to break the *Salmonella* cycle is to rear the weaners away from the main source site to minimize the organism early in the production cycle (Wales and others 2011). It has been suggested that for farms with large herds (approximately 1000 sows) consideration should be given to the possibility of using separate sites for weaning and fattening (Barcelo and Marco 1998). Several authors have studied this approach and found that there is a beneficial effect in terms of *Salmonella* control (Nietfeld and others 1995; Dahl and others 1997; Fedorka-Cray and others 1997; Nietfeld and others 1998). In contrast, it has been reported in Canada and the United States that farrow-to-finish farms have a lower risk of becoming infected by *Salmonella* than finishing farms (Davies and others 1997b; Rajic and others 2007). Similarly, some authors have found in Spain that high prevalence of *Salmonella* was associated with herds from farms with only finishing pigs (Vico and others 2011), and this is likely to be associated with the risk of introducing carriers (replacement animals) from other sources, especially if pigs are originating from multiple supplier herds (Lo Fo Wong and others 2004).

Although the biosecurity controls for *Salmonella* in outdoor production systems are more difficult than indoor ones, mainly to the impossibility of carrying out cleaning and disinfection procedures, a Danish study identified that there were no general differences in the proportion of Salmonella seropositive animals based upon the production system (organic, outdoor, and indoor pig farms). They found that the occurrence of seropositive pigs in the herds was mostly associated with the risk of introducing Salmonella in the herds by purchasing and transporting growing pigs (Zheng and others 2007).

Access. It is acknowledged that other enterprises that may need to have access to the farm or to which the farm will need to interact with, such as slaughterhouses, slurry disposal, feed suppliers, animal by-products collectors/renderers, and roads used by pig transporters represent a risk, and therefore the farm should be relatively distant from those risks (Pritchard and others 2005). Pig farms will need to take animals to slaughter and if the abattoir is located less than 1 km away, it may represent a significantly increased risk, while if located more than 5 km away the risk is reduced (Barcelo and Marco 1998). Equally, the same authors discussed that animal by-product disposal plants are dangerous if less than 2 km away. Main roads and public pathways should be reasonably far away, although the farm will need to provide access to trucks, ideally at the perimeter of the enclosed site only, and will need to consider biosafe procedures for the provision of electricity, water, and staff (Morillo Alujas 2005). Roads with a high density of traffic transporting pigs at less than 50 m are thought to represent an important contamination risk for airborne respiratory pathogens, while distances over 400 to 800 m greatly minimize it (Barcelo and Marco 1998).

Biosecurity related to replacement animals

Without a doubt, the biggest risk of introducing *Salmonella* and many other pathogens into a herd is via infected pigs. Therefore, the movement of pigs is widely recognized as one of the biggest risks of *Salmonella* introduction (Stark and others 2002). Closed farms are by definition less risky and generally less exposed to exotic pathogens, but, in contrast, they can have a less rapid genetic improvement of the stock. Similarly, in finishing farms, multiple origins of animals and lack of sectioning, isolation, or quarantine are risk factors (Lo Fo Wong and others 2004) that can lead to introduction of infection and subsequent persistent contamination of the environment with recycling infections appearing in most of the batches of pigs being finished.

It has been suggested that the health status of nucleus and multiplier herds should be superior to all those beneath them and the pig flow should be always unidirectional (Kirwan 2008). However, in the United Kingdom, as well as other countries, one very important problem is presence of *Salmonella* infection in nucleus herds and multipliers (Wales and others 2009). Pig producers down the pyramid have to face the likelihood of importing *Salmonella* and other infections into their farm when buying animals in. It is important to note that, although the introduction of live pigs represents the main risk of importing infections into a farm, semen and embryos can also be the sources of some pathogens, as it is the case with postweaning multisystemic wasting syndrome and classical swine fever (Pritchard and others 2005).

Source of animals. As a rule of thumb, replacement pigs should be sourced from premises which have an equal or superior health status to the recipient farm to prevent the introduction of infections that are absent in the receiving farm, and trying to match the health status of donor and recipient farms to avoid the introduction of *Salmonella* has been already implemented in Denmark as an strategy to mitigate that risk (Dahl 2014). However, consideration needs to be given to "disease free" and therefore immunologically naive incoming animals, as they may require vaccination or a period of acclimatization before they enter the new herd (Morillo Alujas 2005; Pritchard and others 2005). Some authors have suggested that replacement gilts should be brought into the herd early and exposed to fecal material from the herd well before their service, while being kept separate from other pigs so any new *Salmonella* strains that they may be carrying will subside (Davies and Cook 2008). It has been identified that farms with higher health status appear to have lower *Salmonella* prevalence in their herds (Funk and Gebreyes 2004). A good and well-accepted biosecurity principle is keeping to a minimum the number of animal sources coming into the farm. Having a closed herd is desirable (Amass 2005a), but, if not a possibility, sourcing pigs from a single supplier which can satisfy the required genetics, and freedom from important animals and production-limiting diseases reduces the risk (Moore 1992; Nowak and others 2007). Closed herds are likely to have most pigs exposed to farm-resident *Salmonella* strains and then develop a certain level of herd immunity and so stop carrying or excreting the specific strains involved. The balance is upset if new pigs come in with new strains of *Salmonella* or have no immunity to the resident strains and so become infected after arrival. This may also occur in closed or very large farms when pigs are moved from 1 area of the farm with a given immunological status to another with a different status (Davies and Cook 2008). Contrary to this, some authors have reported no beneficial effect of maintaining an integrated or closed herd, although they found that sourcing replacement pigs from more than 3 suppliers was a risk factor (Lo Fo Wong and others 2004). Similarly, a French study reported that for fattening farms, a supply of weaners by 2 or more sow units throughout a period of 12 mo was a risk factor (Correge and others 2009). Such variability is to be expected in view of the diverse nature of pig management practices, prevalence of infection, and circulating *Salmonella* strains.

Isolation/quarantine/monitoring. Many producers find it impossible or impractical to operate a closed herd system and they have to bring replacement pigs directly into the main herd. A recommended approach to minimize the high risk imposed with these imports is to isolate or quarantine the pigs for a given period of time, in which they are closely monitored as to observe any sign of infectious disease in the incubation phase and checked for the presence of chronic diseases (Barcelo and Marco 1998). A well-run quarantine procedure not only increases the chance of a successful claim for replacements, if disease occurs soon after arrival, but also allows for vaccination and laboratory testing for *Salmonella*, sarcoptic mange, serology for porcine reproductive and respiratory syndrome, and so on (Pritchard and others 2005). Based upon the virulence of the pathogen and status of the main herd, different approaches can be taken if quarantined animals demonstrate the infectious agent of concern; from culling to avoid the introduction of the disease into the main herd, to treatment or returning the animals to the source where they came from. In the case of *Salmonella*, the approach will be very much based upon the serotype isolated and the *Salmonella* status of the recipient farm.

The use of quarantine facilities for replacement breeding pigs is favored by most authors who recommend, whenever possible, an offsite isolation facility or, if not possible, a minimum the distance of 100 to 150 m from the main farm buildings (Moore 1992). For the quarantine to be effective, it should be run as a completely separate unit from the rest of the farm. Farm staff attending quarantined animals should visit them at the end of the working day, with separate protective clothing and minimizing contact with the animals. Waste management systems should be independent from the main farm and any equipment used in the quarantine area should not be used, under any circumstances in the rest of the farm. Strict AIAO policies should be applied for all batches of quarantine animals, and effective cleaning and disinfection should be carried out between batches (Lo Fo Wong and others 2004).

The period of isolation should vary according to the pathogen(s) of concern and be based on their maximum shedding period (Amass 2005a). Recommendations given by authors are based on speculations or extrapolation from cattle studies (Evans and Davies 1996), while some authors favor a minimum period of 21 d for recognition of diseases that may have been incubating at the time of arrival of the pigs (Morillo Alujas 2005), a majority seem to agree that a period of 6 wk is recommended (Moore 1992; Pritchard and others 2005). In the case of replacing fattening pigs introduced to a multiple age site, it is not possible to use quarantine arrangements, and an extra move may be detrimental. There should, however, be good separation between buildings holding pigs from different sources and of different ages, with minimal use of shared equipment, such as manure scrapers, between different risk categories (Pritchard and others 2005).

Despite being a widely accepted and recommended practice, adherence to the quarantine policy varies greatly. A study in Chile reported that 56% of the producers will use quarantine for the new pigs on arrival and suggested that this was similar to the situation reported in the United States by the Natl. Animal Health Monitoring Systems, which reported that between 33.6% and 60.9% of the producers separate or quarantine new breeding animals on arrival (Pinto and Urcelay 2003). This percentage is also in line with what it has been reported in other European countries during similar biosecurity surveys, such as in Spain (Simon-Grifé and others 2013).

Biosecurity related to husbandry

Although the location and the replacement of the animals are 2 of the most important aspects to be considered from a biosecurity point of view, farm management has also a great impact in avoiding the entrance and spread of pathogens. Husbandry and management practices can have a great influence in the control and eradication of certain diseases, such as pneumonia (Straw 1992; Maes and others 2008), and it is important to sensitize the farmers to the presence of *Salmonella* and the need of good hygiene practices and management to avoid the introduction and spread of *Salmonella* on the farm (Stede and others 2008).

Movement and mixing of animals: AIAO. This is a controversial practice because, despite being widely considered as one of the most important to reduce the presence of swine diseases, there are not many studies that have specifically identified a reduction in *Salmonella* following the adoption of AIAO systems (Funk and Gebreyes 2004). It is believed that, although it may not prevent the introduction of disease into the herd, especially if replacement pigs originate from multiple sources of infection unknown status, AIAO can prevent the cross-contamination between production cycles by allowing thorough cleaning and disinfection and, consequently, reducing the potential for *Salmonella* exposure and infection in the subsequent batch (Amass 2005b). Its adherence is recommended, together with the concept of 2-site production, but it can be difficult to implement because the space usage may not be optimal and it becomes expensive (Moore 1992). In Canada, it was found that *Salmonella* prevalence in grower-finisher systems can be reduced by a combination of AIAO and liquid feeding (Farzan and others 2006). An experiment in Denmark suggested that AIAO management in the nurseries and grower units, together with the movement of the weaners or growers to either new facilities or to properly cleaned and disinfected finishing units, resulted in the elimination of infection (Dahl and others 1997). A European study (Germany, the Netherlands, Greece, Denmark, and Sweden) looked at the adoption of an AIAO system together with the provision of areas for changing protective clothing and found that, compared to farms that they do not use these practices, they were 3 times less likely to be seropositive (Lo Fo Wong and others 2004). Curiously, another study in the Netherlands found that herds with an AIAO system that did not disinfect the pigs' accommodation after cleaning were associated with lower *Salmonella* seroprevalence than those that did disinfect always or occasionally (van der Wolf and others 2001b). The same authors reported a plausible explanation for this intriguing finding by suggesting that producers that regularly disinfect may clean less adequately with the idea that any remaining bacteria will be destroyed by the disinfectant. Other studies in France suggested that *Salmonella* infection could be managed by strict application of AIAO procedures including cleaning and disinfection (Beloeil and others 2004; Fablet and others 2005), while a German study identified that not having an AIAO system was a risk factor for *Salmonella* (Gotter and others 2012). In Belgium, the development of a sanitary risk index for *Salmonella* in pig husbandry found that applying a strict AIAO procedure was associated with a lower prevalence (Hautekiet and others 2008). In contrast to all this, another Danish study suggested that the batch production in an AIAO system appeared to be associated with *Salmonella* infection, although the analysis was based on very few herds (Stege and others 2001). Research in Canada and the United States (Davies and others 1997b; Proescholdt and others 1999; Rajic and others 2007; Davies and Cook 2008) concluded that there was no difference on *Salmonella* presence between farms with continuous flow when compared with those that used AIAO practices.

Despite all these reported differences regarding the role of AIAO systems in the control of *Salmonella* in pigs farms, restricting the movement of pigs around the farm and the management of groups of animals have been shown to contribute to successful *Salmonella* control. The stress generated by moving, mixing, and remixing of pigs, together with the potential to mix infected animals with immunologically naïve ones and exposing to new sources of environmental contamination during moving or rehousing has been hypothesized to increase the risk for extending and perpetuating endemic infections (Belluco and others 2015).

Finally, total or selective depopulation is used in some countries, such as Sweden, as a control measure, while other countries, like Denmark (Dahl 1999; Møgelmose and others 1999), have also reported some success with this method. However, this intervention, albeit difficult and expensive to implement, is not always successful. It has been said that contamination can persist in the environment and restocking animals can become infected or introduce new infections (Ball and others 2011). Interestingly, Sweden reported that it was impossible to eliminate *Salmonella* on 1 particular unit without permanently decreasing the pig population by 50% (Wahlstrom and others 1997), which agrees with findings of spontaneous clearance of *Salmonella* on some smaller farms (Wales and others 2013).

Pest control. The role of carrier vectors in the transmission of *Salmonella* and other organisms is widely accepted and well-discussed (Amass and Clark 1999). Rodents, birds, insects, feral animals, dogs, and cats can all potentially mechanically transmit pathogens (Amass 2005b). Among them, rodents are of particular importance. While the popular belief is that pests act as a source of introduction of the disease in the herd, it is more likely that they act as a reservoir of farm-resident strains, recycling the infection from 1 crop to the next. Studies carried out in Spain and Denmark suggested that pig farms act as amplifiers of the *Salmonella* infection among wild birds (Hald and Andersen 2001; Andrés and others 2013b). Similar studies in Sweden have also reported the same conclusion for other pig-associated pathogens present in rodents, such as *Lawsonia intracellularia* and *Yersinia enterocolitica*, where these microorganisms were more likely to be transmitted to the rodents from the pigs or the environment on the infected farms (Backhans and others 2013). The influence of vectors is particularly important in outdoor units, where control is more challenging. In outdoor farms, an increasing intensity of rodents and birds constituted a risk factor for *Salmonella* seropositivity (Meyer and others 2005). Rodents, and mice in particular, can contribute to the spread of *Salmonella*, as they can amplify the number of pathogens in the environment and transfer them to food animals via contamination of feed troughs and hoppers (Davies and Cook 2008). The control of rodents on a farm is of paramount economic and health importance, not only because of the damage that they can create to the farm buildings (structure, insulation, and electrical wiring) and the amount of feed that they consume or spoil, but also because of their role in transmitting pig diseases as well as bacterial, viral, and parasitic zoonoses (Backhans and Fellstrom 2012). Some authors have also described another indirect route of infection within and between farms, it is via feed or ingredients that have been contaminated by infected rodents and other animals (Daniels and others 2003; Davies and Wales 2013).

Pest control is based on good hygiene, by removing feed spills and rubbish, with good maintenance of the grounds as to limit the attraction of rodents to the farm and proofing of buildings. It has been discussed that although professional companies can be used when implementing or establishing pest control programs using chemicals, baits traps, and other tools (Amass 2005a), well-trained farm workers are able to respond more quickly and thoroughly to signs of rodents. Several investigations have reported that mice and rats on farms may be infected with *Salmonella*, usually with the same serovars as the domestic species investigated (Funk and Gebreyes 2004). A couple of research studies in Portugal found that the control of rodents was considered a protective factor for the presence of *Salmonella* serotypes other than *S. typhimurium* in pig farms (Correia-Gomes and others 2012, 2013), and this was also highlighted in other studies from Denmark (Skov and others 2008), the Netherlands (Meerburg and Kijlstra 2007), Spain (Vico and others 2011), and Brazil (Kich and others 2005). On the other hand, a study in Canada found no significant association between the presence of rodents and *Salmonella* infection status (Farzan and others 2006). This could be explained by the fact that the farms in the study were all providing the pigs with liquid feed, usually newer farms with apparently better rodent control and cleaning policies, being less attractive to rodents.

Hygiene: cleaning and disinfection. It appears to be common sense that a good hygiene policy for the farm management is of major importance if the herd is to be kept disease-free. It has been reported that a lack of farm hygiene increases the prevalence of *Salmonella* (Berends and others 1996; Berends and others 1997; Stark and others 2002; Beloeil and others 2004; Cook and others 2006; Davies and Cook 2008). However, several U.K. experts were of the opinion that there is a lack of conclusive evidence that improved biosecurity (which include cleaning and disinfection, sourcing of animals, and pest control) reduces *Salmonella* prevalence, and that pig farm buildings are often not designed to facilitate good biosecurity and hygiene (Brunton and others 2013). Their concerns may well arise from the well-known fact that *Salmonella* can persist in the environment from several months to years (Sandvang and others 2000; Baloda and others 2001), and that the farm environment can act as a reservoir of the microorganism because of inadequate disinfection and pest control procedures, thus playing an important role on its reintroduction to the pig population. This was, in fact, observed in a longitudinal study carried out in the United States, despite of the farms adhering to a system of AIAO. However, there was no mention to the cleaning and disinfection procedures, so the failure to totally eliminate *Salmonella* cannot be entirely evaluated (Thakur 2013). Nonetheless, a more recent study in the United States showed that, although an increased frequency and efficiency of cleaning did reduce the prevalence of *S. typhimurium* shedding at the time of slaughter, those efforts alone were not capable of eliminating the infection from the population, and the authors suggested that to control the infection in pigs, cleaning should be combined with other interventions, such as vaccination and/or isolation of high-level shedders (Gautam and others 2014). In the experience of the authors, cleaning and disinfection procedures in the United Kingdom pig farming are mainly centered on the farrowing and weaning accommodation, while growers and finishers buildings are either not regularly cleaned or not done to the same high standards. Turn-around times are usually very tight and lack of accommodation leaves little time for thorough cleaning and disinfection procedures, including drying, to be carried out. The preferred class of disinfectants appears to be peroxide-based products, which are relatively easily inactivated by organic matter (Gradel and others 2004). Detergents, cleaning foams, or gels are not widely used and overdiluted disinfectant is often applied before the surfaces are dried, all of which may result in the failure and/or reduced efficiency of the cleaning and disinfection practices.

Similarly to the U.K. experts, authors in the United States and Spain also agree and share the concerns that there is little indication that current cleaning and disinfection protocols are effective for *Salmonella* contamination control, and they question the economic feasibility of these interventions (Funk and Gebreyes 2004; Argüello and others 2011). The elimination of *Salmonella* in the farm environment is difficult and residual contamination might be responsible for new infections (Pires and others 2013). The lack of strong solid evidence which correlates good cleaning and disinfection procedures with lower pathogen prevalence makes it very difficult to convince producers to solidly adhere to these procedures. Studies in Canada and Belgium were not able to demonstrate a significant difference in the *Salmonella* shedding between farms that did not clean and disinfect with those that did (Nollet and others 2004; Rajic and others 2007). This has led some authors to refer to farm hygiene procedures as "best practices," as opposed to evidence-based interventions (Wilhelm and others 2012).

It is widely acknowledged that residual environmental contamination can be a source of *Salmonella* infection (Funk and Gebreyes 2004). As previously mentioned, there are many references in the literature to inadequate cleaning and disinfection as a risk while effective disinfection is considered an essential part of any successful *Salmonella* control (Fablet and others 2005; Bode and others 2007). Researchers in Ireland found that cleaning and disinfection was an effective measure of reducing *Enterobacteriacae* on pen floors (Mannion and others 2007), but they also mentioned that other equipment, such as feeders and drinkers within the pen, were found with high levels of contamination after the cleaning and disinfection had been completed. This highlights the fact that careful and systematic hygiene procedures, including the tools and equipment, are of paramount importance when trying to achieve effective disease control. If not properly applied, the efforts can be in vain and, from a cost–benefit analysis, could result in wasted time and money. The goals of any sanitation program are to reduce the level of pathogens below an infectious dose at the time of exposure of the pigs and to avoid the build-up of microorganisms over time. In the case of *S. typhimurium*, the infectious dose for pigs has been reported to be more than 10^3 salmonellae (Hurd and others 2001; Loynachan and Harris 2005). Thorough cleaning is very important as some swine pathogens, including *Streptococcus suis*, rotavirus, and *Salmonella*, can be isolated from dust in the buildings (Amass 2005b). The effect of washing alone may relate to stimulation of growth of competing organisms that might lead to a reduction of *Salmonella*, compared with subtotal disinfection in which such organisms are suppressed by the disinfectant leaving *Salmonella* to proliferate. And other authors have also found that the likelihood of *Salmonella* positivity increased with higher hygiene scores as represented by measures such as pressure washing with cold water and disinfection (Poljak and others 2008). A study in France found that smooth surfaces are less likely to have a high level of residual contamination than rough ones (Madec and others 1999). This is important, as concrete is a material that is widely used in pig accommodation and its rough surface could harbor higher numbers of bacteria.

Although current cleaning and disinfection help to remove excess loads of *Salmonella* in the environment, it is not sufficient for complete removal. If not done carefully, power washing may contribute toward the spread and dispersion of contamination in the farm, as some authors have been able to demonstrate (Funk and others 2001b; Wales and others 2009). This has been explained by the environmental robustness of the organism, the protective effect of moisture and residual organic matter, the poor efficacy of many commonly used disinfectants, and mistakes with the dilution rate applied and the application itself (McLaren and others 2011; De Busser and others 2013). The presence of rodent vectors may also invalidate any disinfection procedures, as *Salmonella*-positive droppings are left in cleaned feeders and drinkers when mice, in particular, search for sources of food, as it has been observed in poultry farms (Rose and others 2000). Infected rodents can transmit pathogens from the farm environment to food animals, as this was mentioned with studies on *Salmonella* epidemiology in poultry (Davies and Wray 1995) and in pigs (Andres and others 2013a). Hence, a complete sanitation during 1 production cycle is often unrealistic. Only the continuous repetition, after every movement of any pig group, of a good cleaning and disinfection procedure linked with AIAO housing can lead to sustainable success (Bode and others 2007). Other authors have found that, while rearing the pigs, cleaning when shedding is high had a minimal effect on *Salmonella* prevalence, probably because of the rate at which the infection was able to spread, but they hypothesized that a more frequent cleaning regimen could counteract this (Berriman and others 2013).

Similar to the perception of cleaning and disinfection procedures, boot dips are commonly seen as a good biosecurity control. However, their effectiveness depends on how boot dips are maintained. Boot dips can give a sense of false security, and people may relax other controls. But, more importantly, when boot dips accumulate fecal matter, or get diluted by rainwater, or when an incorrect concentration of disinfectant is used or when they are not frequently replenished, became inactive, and they can even become a source of contamination (Davies and Cook 2008; Rabie and others 2015). On the other hand, although the use of boot dips can be associated with a lower *Salmonella* prevalence, it has been speculated that this may be because there is a greater concern with hygiene and biosecurity by those producers that use them, rather than the direct disinfection controlling *Salmonella* (Twomey and others 2010), as it shows poor susceptibility to commonly used disinfectants (Thomson and others 2007). Ideally a boot wash should be used 1st, so any excess organic material is removed before dipping (Pritchard and others 2005). This avoids inactivating the disinfectant in the boot dip due to excess organic material. There is not much literature on the subject but it has been reported that boot dips, as they are usually used in many pig farms, are not efficacious for disinfecting boots and spending time and money without using them correctly is a waste of resources (Amass and others 2000). The importance of boots to potentially spread the infection through the farm should not be underestimated. A study in 90 Alberta farms reported that boots and main drains have a greater incidence of *Salmonella* than empty pens (Rajic and others 2005), while similar conclusions were observed by a German study in which not having clean boots available was found as a risk factor for *Salmonella* infections (Gotter and others 2012), and a Belgium one where using boot dips was associated with lower prevalence of infection (Hautekiet and others 2008).

Access of vehicles and personal. It has been speculated that humans can act as mechanical and biological vectors that can transfer pathogens from 1 farm to another if biosecurity-related practices are not followed (Amass 2005b). The presence of an area where protective clothing and footwear can be changed before entering pig accommodation is generally thought of as good practice, associated with a reduction of *Salmonella* prevalence. Although this was observed in some studies (Lo Fo Wong and others 2004), it was not seen in others (van der Wolf and others 2001b). Similarly, it has been found that handwashing and having access to toilets and washing facilities have a protective effect against *Salmonella* (Funk and others 2001a; Lo Fo Wong and others 2004). This could be explained by the fact that staff who are conscientious with personal hygiene are more likely to follow good biosecurity measures in general. Coincidentally, the same authors reported that farms which had more staff on site were seen to have an increased risk of high fecal shedding of *Salmonella* (Funk and others 2001a); and in Brazil, the entrance of visitors to the farm was also associated with higher prevalence (Kich and others 2005). This could suggest that increased human traffic on the farms increases the risk of infection in the pigs. It is because of this that a controversial factor is introduced, known as pig-free time. Most farms have rules for visitors to have no contact with pigs or pig postmortem material for at least 24 to 48 h before entry to the farm, but there is little evidence that support this requirement for specific animal avoidance periods (Amass 2005a). Some pathogens, such as foot and mouth disease virus and *Mycoplasma hyopneumoniae* can survive on humans for periods of 11 and 30 h, respectively (Moore 1992). Hence, the suggested minimum of 24 to 48 pig-free time. However, it has been discussed by some authors that recent work and field observations suggest that the likelihood of people actually transmitting pathogens from their nose, throat, and pharynx is minimal, and imposing a blanket downtime causes great inconvenience and is expensive to maintain (Pritchard and others 2005). Showering before entry to breeding farms has been recommended due to the perceived risk of infectious disease transmission and the high investment made in specified pathogens-free primary breeding stock farms (Barcelo and Marco 1998), even though it is not clear that a shower can eliminate microorganisms, it ensures that outside clothes are completely removed and dedicated protective clothing is used on the farm (Moore 1992) as well as discouraging unnecessary visitors (Amass and Clark 1999).

It has been discussed that vehicles can act also act as mechanical vectors which can transfer pathogens from 1 farm to another if biosecurity-related practices are not followed (Amass 2005b). Pig transport vehicles and drivers are in constant contact with other farms and slaughterhouses and, consequently, they represent a considerable risk; therefore, they should not be allowed into the clean areas of the farm.

It has been reported that *Salmonella* contamination is very quickly transferred to roads, standing water, vehicles, and other mobile equipment (Wales and others 2009), thus making the disinfection of vehicles essential to any rigorous biosecurity regimen (Twomey and others 2010). Disinfection can be done via a sanitary wheel wash and spray, or by a dedicated disinfection station, but these are expensive to run and not commonly used even outside large pig farms. Alternatively, banning the entry of vehicles into the farm is a very good way of avoiding any possible infection being introduced by this route. A perimeter fence and locked gates prevent the *ad hoc* entry of vehicles to the premises. It has been suggested that parking for visitors and livestock vehicles should be at least 300 m away from buildings containing livestock (Amass 2005a). In Eastern Europe, where there is a much greater risk of acute infectious diseases, such as African swine fever, biosecurity related to the entry to the farm and housing is much more strict (EFSA 2014), demonstrating that good procedures can be economically utilized if a sufficient strong incentive is present.

Waste management. Manure can be an important source of many infections (swine dysentery, classical swine fever, foot and mouth disease), as well as *Escherichia coli*, porcine reproductive and respiratory syndrome virus, *S. suis*, *Salmonella* spp., and so on. And the risk is particularly high if the manure comes from other pig farms and it has been advised that manure from other swine facilities should not be spread, sprayed or injected within 3.2 km of pig farms (Amass 2005b). When working with liquid slurry, it has been recommended to have running channels from the pig buildings into a pit outside, with the level of the slurry in the pit kept well below that of the channels to avoid a flow-back (Barcelo and Marco 1998). The equipment used for spreading slurry should be, whenever possible, dedicated to the premises, as it becomes a significant threat to the biosecurity of the farm if that equipment has been used on other farms of lower health status (Moore 1992; Pritchard and others 2005; Kirwan 2008). An alternative to reduce the spreading of *Salmonella* when spreading slurry would be to sanitize it before disposal. A study in Poland has found that fermenting it and, to a lesser degree, aerating it, can be promising and a safe way to use slurry for agricultural purposes (Paluszak and others 2012). Urea and, to a lesser extent, ammonia, has been reported to be a good candidate to use to disinfect *Salmonella*- and/or *Y. enterocolitica*-contaminated pig slurry, thereby decreasing the storage time required while increasing its fertilizer value (Bolton and others 2013).

There is considerable diversity in farm designs and flooring, which have an influence on how the waste from the pigs' accommodation can be removed and stored. From a disease control point of view, it would be advisable to use a system that avoids the build-up of feces on the farm and limits the time that the animals are exposed to it, thus reducing the fecal–oral route for recycling infection. Equally, avoiding different groups of animals being exposed to each other's waste is of great importance to minimize the risk of spread of certain diseases. In principle, well designed and maintained slatted floors are most suitable to avoid the accumulation of feces in the pens, hence minimizing the contact between animals and their waste. French researchers found that emptying the pit below slatted floors before the next batch of pigs was placed was a protective factor against *Salmonella* (Beloeil and others 2004). They also found frequent removal of the sow's manure during the lactation period is protective. Early studies in the United States found that *Salmonella* prevalence was lower in pigs raised on slatted floors compared with all other types of floors, and it was higher for pigs raised on "dirt lots" (pens with earth floors) (Davies and others 1997a,b). Similar to this, a reduced prevalence of *Salmonella* in pigs housed on fully slatted floors was found more recently in Germany (Hotes and others 2010) and Belgium (Nollet and others 2004), and slatted floors have also been cited as a protective factor by other authors (Zheng and others 2007). This is also substantiated by the fact that solid floors are usually cleaned by means of scrape-through systems which facilitate transmission of feces between pig pens, as opposed to slatted systems in which each pen is usually self-contained (Twomey and others 2010).

Since the most likely route of transmission of *Salmonella* is fecal–oral, any system that would prevent the spread of manure between pens would prevent the spread of infection. This was found in Denmark where closed pen separations prevented fecal contact between adjacent pens and, therefore, the spread of the infection (Dahl and others 1996). However, when investigated in several other European countries, open pen separations were not found to be a significant risk (Lo Fo Wong and others 2004).

Other Control Measures Against *Salmonella* Infection

There are many studies available that have explored different alternatives and approaches to control *Salmonella*, but for the purpose of this review, the focus is put broadly on 3 particular areas: feed, additives to water and feed, and vaccination.

Feed

Feed-based interventions are believed to be of utmost importance when trying to reduce *Salmonella* prevalence. Studies are diverse, but the most frequently reported ones relate to the feed form, its formulation, and the feed particle size.

It has been reported by a considerable number of authors that the feed form given to pigs has a great influence in their *Salmonella* status, and particularly meal and wet feed as opposed to pellets. It is believed that meal results in more acidic conditions in the intestinal tract, making that environment more inhospitable to *Salmonella*. It has been said that many types of wet feed also have an intrinsically low pH, making it resistant to contamination during storage and feeding (Belluco and others 2015). But it is important to clarify that liquid or wet feed alone is not sufficient to provide protection, as it requires a low pH that is achieved by fermentation (Rajic and others 2007). In fact, adding water to feed with no fermentation step has been associated with an increased risk of having *Salmonella*-positive samples in swine herds in the Netherlands (van der Wolf and others 2001a). The lower pH also promotes the proliferation of other bacteria, such as *Lactobacilli,* which can competitively exclude *Salmonella* (Prohaszka and others 1990). The protection provided by *Lactobacilli* and other lactic acid bacteria has also been reported when whey is added to the wet feed, where an enhanced protection was observed and it was speculated that whey stimulates the proliferation of that protective flora more strongly (Lo Fo Wong and others 2004). Today it is generally accepted that wet feed is preferred to dry feed (van der Wolf and others 1999; Beloeil and others 2004; Farzan and others 2006) and dry meal feed preferred over pelleted feed (Dahl and others 1999; Lo Fo Wong and others 2004), as long as the feed particle size of meal is not too small. German authors also concur, since they found that coarse-grinding was able to influence positively the intestinal flora and was capable to reduce *Salmonella* excretion of infected piglets, with this protective action being enhanced when potassium diformate was also added to the feed (Papenbrock and others 2005). In contrast to this, other authors in Germany were unable to find the protective effects of a coarsely ground diet, but it should be said that the ingredients were pelleted, resulting in a considerable proportion of fine particles (Taube and others 2009).

In addition to these protective feeding factors, it has also been reported that rations with a minimum of 25% barley have been shown to reduce *Salmonella* colonization in pigs (Blanchard and Kjeldsen 2003), and it appears that replacing the high wheat content in most rations with almost anything else, for example, beet, barley, maize, manioc, various starchy coproducts, is likely to be protective (Hansen and others 2001; Jørgensen and others 2001a).

Numerous studies have concluded that feeding pigs with pelleted compound feed was a risk factor for *Salmonella* infection (Beloeil and others 2004; Kich and others 2005; Farzan and others 2006; Rajic and others 2007; García-Feliz and others 2009; Hotes and others 2010), while others have reported a protective effect when coarsely ground feed or fermented liquid feed was given to the pigs (van der Wolf and others 1999; Lo Fo Wong and others 2004; Farzan and others 2006; Hautekiet and others 2008; Poljak and others 2008; Twomey and others 2010). The principle behind this is that pellets have to be made from very finely ground ingredients to maintain their integrity and this reduces the transit through the digestive tract and therefore does not achieve a protective low intestinal pH. This has been observed by other authors who claim that coarsely ground meal decreases the survival of *Salmonella* during stomach passage, possibly because of a slower gastric passage and a lower gastric pH (Mikkelsen and others 2004; Canibe and others 2005). Heat-treated pellets also have fewer indigenous yeasts and bacteria that can promote gastric fermentation (Mikkelsen and others 2004). Opposite to this, pelleting can provide a protective factor since it involves a heating step that helps to reduce the potential *Salmonella* contamination level which may be in the primary ingredients (Himathongkham and others 1996; Jones and Richardson 2004).

It has been said that the downside of offering coarsely ground meal compared with pellets is an increased cost because of reduced feed efficiency due to greater feed wastage of meal (Ball and others 2011). Other factors which are also advantageous when feeding the pigs with pellets are superior feed conversion, convenience and easier use in automatic handling systems, as well as lower cost as it has been discussed in a previous literature review (Belluco and others 2015). Danish researchers found, however, that adding coarsely ground barley (or even wheat) to pelleted diets, it appeared to improve the protective effect against *Salmonella*, while only reducing feed conversion efficiencies by a small proportion (Dahl 2008).

Previous reviews have attempted to study and analyze the quality of published evidence regarding the effect of the feed form on *Salmonella* control and found it weak, recommending further prospective studies (O'Connor and others 2008). This is clearly reflected in the way that U.K. experts feel about the viability of feed-based interventions to reduce *Salmonella* infections in pigs. However the general perception is that these interventions could have a high impact, but there are concerns because of the capital costs of implementing a change in the feeding practice and the potential reduction in performance parameters that such changes may incur (Brunton and others 2013). Less intensive feed formulations may, however, also provide important protection against other intestinal disorders, thus enhancing the overall economic viability. Such holistic approaches to formulations of pigs rations require more detailed consideration.

It is important to note that, although feed can be a vehicle for *Salmonella* to reach the pigs (Harris and others 1997), it is usually contaminated with other "exotic" *Salmonella* serovars, rather than *S. typhimurium*, although this may occur rarely (Harris and others 1997; Funk and others 2001b). Such contamination has a particular importance in farms where grains and cereals used to make homemade meals are temporarily stored in livestock areas where they can get contaminated (Davies and Wales 2013); but in most countries, other than those where *Salmonella* is controlled by an elimination policy for all serovars, feed is not a major source of persisting infection in pigs.

Additives to water and feed

There are numerous references and studies that have investigated the actions of substances added to the feed or drinking water. From those the acidification with organic acids seems to be the most popular intervention. These work not only by suppressing the contamination of feed or water with *Salmonella*, but also by further reducing the pH within the digestive tract. Although such acidification may appear to be beneficial in terms of reducing *Salmonella* prevalence, the results from 8 studies were reviewed and found to be inconsistent (Friendship 2009), and there are associated problems, such as clogging of drinkers, fungal growth, and corrosion of the equipment (van der Wolf 2004) when drinking water is acidified. A more recent literature review on the addition of chemicals to the feed and water of livestock for the control of *Salmonella* (Wales and others 2010) highlighted that, due to the wide array of products available with contrasting modes of action, the need for standardized tests of efficacy is obvious. The 1st acid compound to be approved in the EU for the use in pigs was a salt of formic acid that was reported to significantly reduce the incidence of *Salmonella* in the pig's gut (Blanchard and Kjeldsen 2003). A more recent study in Spain suggested that the administration of organic acidic compounds in both drinking water and feed during the last part of the finishing period was associated with a reduction in the seroprevalence and, to a lesser extent, a reduction in the prevalence of *Salmonella* shedders at the end of that period (Arguello and others 2013b).

The analysis of the antibacterial effects of acid products is rather complex as it depends on the type of organic acid, the bacterial species, the concentration used, and the physical form in which it is administered to the animals. The composition of the currently used products seems to be largely empirically determined (Boyen and others 2008).

In summary, the findings from different studies are highly variable and dependent on the age of the pigs in which they are tested and the product, or combination of products, used. It is important to mention that these types of treatment are preventive and not curative; if they are taken out, breakdowns will occur (Burch 2007). For example, providing lactic acid to weaners (Jørgensen and others 2001b) and growers (Tanaka and others 2010) and formic acid to finishers (Vanderwal 1979) seemed to have a beneficial effect, but in another study, when weaners were given acid-supplemented feed, it did not have any effect on the presence of *Salmonella* in feces (Walsh and others 2007). Several reasons have been given in the literature as to why the treatment with organic acids can fail to show a beneficial effect. It could be as a consequence of other concurrent health problems in the herd, as it was hypothesized by a study in the United Kingdom where the high incidence of Post Weaning Multisystemic Wasting Syndrome (PMWS) could have contributed toward the failure (Cook and others 2006) or because of the level of challenge being too high (Davies and Cook 2008), or because the so-called "acid tolerance response" in which adaptation to lower pH enables the organisms to survive periods of severe acid stress (Bearson and others 1998), or because the administration of the compound was not done for a sufficiently long period, as it was reported by a study in Belgium (De Busser and others 2009). The acid tolerance response is a very complex matter which involves several regulatory systems that result in reversible upregulation of tolerance mechanisms (Bearson and others 1998). There is a lack of data on selection of *Salmonella* strains that have survived treatment with acid from a wider population of organisms and this represents a greater risk to humans either by lowering the infectious dose or association with additional virulence mechanisms (Aviv and others 2014).

In the field, introductions of commercial products for acidification of feed or water often appear to have little or no effect, or may even lead to increased shedding of *Salmonella*. This can sometimes be related to the use of unsuitable formulations at insufficient concentrations, but there is a great uncertainty regarding effective programs, thus making advice difficult. Protected butyric acid salt-based products are claimed to survive the digestive tract and inhibit attachment of *Salmonella* to the large intestinal mucosa, but more evidence of efficacy in commercial farm situations is required (Brosse and others 2013; De Ridder and others 2013).

Vaccination

It is generally accepted that vaccination can play a role in reducing the prevalence of *Salmonella* in pigs and could become an adjunct to on-farm control (Denagamage and others 2007) by preventing *Salmonella* colonizing the gut and reducing the subsequent shedding and the development of a carrier state (Haesebrouck and others 2004). Vaccination, therefore, has the potential to reduce the infection cycle at the farm level by increasing the threshold to infection. But the antigenic complexity of the microorganism, due to its multiple serovars, the different response in terms of age and host species, as well as the intracellular phases of *Salmonella* infection result in most of the vaccines being serovar specific (Wallis 2001). Despite the fact that it has been reported that vaccination against *S. choleraesuis* can cross-protect the pigs against other strains, such as *S. typhimurium* (Nnalue and Stocker 1987; Maes and others 2001), and there may be a certain degree of cross-protection between serovars (Foss and others 2013) it is generally accepted that serovar-specific vaccines are more likely to be effective, as antibodies induced by different *Salmonella* serovars show only a low level of cross-protection (Wallis 2001; Foss and others 2013). The reduction of cross-protection against heterologous serovars has already been recently observed (Farzan and Friendship 2010), and it is possible to say that in farms with multiple serovar infection, the control by vaccination will be compromised. It has been said that the use of serovar-specific vaccines could create a niche for the emergence of new serovars of *Salmonella* (Gast 2007; Singh 2009) and this has been already described in poultry, where control programs for *Salmonella pullorum* were theorized as being partially responsible for the emergence of *S. enteriditis* (Foley and others 2011). However, the most important aspect currently is that serovars that pose the highest risk to humans are controlled while a more wide-ranging solution is sought. Nonetheless, it is hypothesized that any vaccine that confers a certain degree of protection against *S. typhimurium*, together with good biosecurity practices, could have the potential to reduce prevalence of *Salmonella* in pigs and result in a reduction of human cases attributed to pork. A recent study carried out in Spain found that shedding was up to 6 times higher in unvaccinated groups than those vaccinated with an inactivated *S. typhimurium* vaccine, while the prevalence of the samples taken at slaughter was also lower in those pigs coming from vaccinated groups (Arguello and others 2013c).

It has been proposed that live vaccines are generally considered to provide the best protection (Haesebrouck and others 2004) and should be the ones to be considered as a control measure (Ball and others 2011). This is due to the fact they can be mass-administered by oral or mucosal routes rather than by multiple injections and they generally produce a better cell-mediated and mucosal immunity than killed vaccines (Lindberg and Robertsson 1983; Detmer and Glenting 2006). A promising recent study has tested an attenuated vaccine against *S. typhimurium* and found that it prevented clinical salmonellosis, reducing the intestinal colonization and fecal shedding (Gradassi and others 2013), although the authors have not mentioned that this vaccine protects against monophasic *S. typhimurium*. There are too few data on the cross-protection toward monophasic variants when using a vaccine against *S. typhimurium*, so it is difficult to say what level of protection the available vaccines may confer against monophasic strains. However it has been reported in poultry that although there was little or no effect of vaccination on the proportion of birds shedding *Salmonella* for either biphasic or monophasic strains in a short-term study after a very high challenge dose, vaccination was effective at reducing egg contamination (Arnold and others 2014). In practice, live vaccines tend to be over-attenuated so as to avoid the vaccine strain persistence in the food chain or environment (Leyman and others 2012), and this can result in poorer immunity than would be expected (De Busser and others 2013), especially on large commercial farms as to ensure that all pigs receive an adequate dose of vaccine at suitable times when they get administrated in drinking water (Wales and others 2011).

A previous literature review carried out by BPEX in the United Kingdom found that out of 15 vaccination studies which were investigated, 14 of them reported a beneficial effect, although not achieving total protection (Friendship 2009). However, this reported beneficial effect is expressed in different ways (like reduction of prevalence, reduction in number of deaths, reduction of *Salmonella* shedding, and reduction of *Salmonella* in the lymph nodes) which makes it difficult to compare the different strategies used. As expected, the results varied from 1 study to another with reductions in the prevalence between 20% and 85%. Most studies reported a significant decrease in shedding and clinical signs, but another review concluded that the design and reporting deficiencies in most of these studies meant that the association between vaccination and *Salmonella* reduction in finishers was promising but needed further proof [(Denagamage and others 2007) as cited by (De Ridder and others 2013)]. It has also been hypothesized that the overall benefit of the vaccination might depend on how many farms within a geographical area use the vaccine, which could be difficult to achieve if the antibodies derived from vaccination cannot be distinguished from those originating from natural infection, and this interferes with monitoring programs (Hotes and others 2011). A recent study has tested a DIVA vaccine with promising results in which the sera from vaccinated animals can be differentiated from the sera from animals infected with the wild-type strain (Leyman and others 2011). Until this type of vaccine is commonly available, the preferred option in those countries where serological monitoring of slaughter pigs forms the basis of surveillance and control programs would be to vaccinate sows rather than finishing pigs, so their progeny acquire a certain level of maternal antibody protection without interfering with any monitoring programs that can be in place. Piglets can get a good level of protection that has the potential to reduce the *Salmonella* prevalence at farm level (Matiasovic and others 2013), as long as exposure to infection after maternal immunity has waned is minimized.

What is clear is that an ideal, safe, and efficient vaccine should prevent clinical symptoms, colonization, and the development of carriers, reduce shedding by infected pigs (hence reducing spreading to other pigs and the environment), increase the threshold for infection of susceptible animals, and induce a response that is distinguishable from that produced by natural infection (Haesebrouck and others 2004; Boyen and others 2008). On the other hand, vaccination is not a cheap strategy, especially if weaners are also required to be vaccinated. It has been reported that when sows were vaccinated with an inactivated vaccine, the prevalence of *Salmonella* shedders, as well as the prevalence of seropositive pigs within the progeny, was reduced and it was suggested that vaccination with an injectable vaccine to breeding sows could be an easy-to-apply and cheaper way to reduce *Salmonella* transmission to progeny and enhance maternal immunity (Roesler and others 2006). There is a risk, however, that pig producers may become more complacent if an effective vaccine was available, and by depending on it they may neglect the other important biosecurity aspects of *Salmonella* control.

Synergy Between Controls for *Salmonella* and Controls for Other Pathogens

As previously stated, most *Salmonella* infections are subclinical and this results in the pig farmers not being aware that their herds have a potential foodborne disease problem; and it is difficult to change their attitude toward *Salmonella* control as this is considered to be a consumer's responsibility via "proper cooking." Nonetheless, if by acting against *Salmonella,* other serious pig pathogens could also be better controlled, it is thought that the swine sector might be persuaded to improve *Salmonella* controls. Equally, by controlling some of the other pathogens the farmer can achieve a higher control of *Salmonella* infections too. Nonetheless, the association of *Salmonella* prevalence with other health conditions may be difficult to communicate, since many management factors may be different in high-health herds when compared to conventional herds, and high health herds may still have high levels of *Salmonella* (Funk and Gebreyes 2004; Wales and others 2009, 2013) but the economic reward due to improved performance and lower disease costs should become an important driver to adhere to *Salmonella* controls.

Herds of high health status have been described as having a lower risk of *Salmonella* infection (van der Wolf and others 1999; Kranker and others 2001), which clearly points out that the same sort of measures used to keep certain pathogens out could also be working to protect against *Salmonella*. Other studies have reported that herds experiencing diarrhea outbreaks during the growing phase were at higher risk of getting infected by *Salmonella* [(Moller and others 1998) as cited by (Funk and Gebreyes 2004)]. It has been discussed that poor biosecurity measures have been linked to the contamination status of pig herds, not just with *Salmonella* but also by other important zoonotic pathogens, such as *Campylobacter* spp., *Clostridium perfringens*, *Listeria monocytogenes, Y. enterocolitica*, and *Staphylococcus aureus* (Fosse and others 2009; Fosse and others 2011).

Salmonella shedding can also be affected by other infections that pigs may be suffering from. It was seen by French researchers that pigs which were seropositive for *Lawsonia intracellularis* or porcine reproductive and respiratory syndrome virus were at higher risk of shedding *Salmonella* (Beloeil and others 2004), which supports the added value of controlling such endemic diseases.

Many pathogens have been identified in animals or animal products, and by controlling them we can assist in controlling the introduction of those organisms into the herd (Amass 2005a). For example, *Salmonella* has been isolated from people, manure, domestic and feral animals, birds, rodents, and insects, so if measures are in place to control them, it could also protect from other potential pathogens; *Brachispyra hyodysenteriae* (manure, domestic and feral animals, birds, and rodents), *Brucella suis* (people, domestic and feral animals, and birds), *E. coli* (people, manure, rodents, and insects), porcine reproductive and respiratory syndrome virus (people, manure, domestic and feral animals, birds, and insects), *S. suis* (people, manure, domestic and feral animals, birds, and insects), and classical swine fever virus (manure, domestic and feral animals, and insects). Within this concept, it is noteworthy that a good biosecurity program that includes an effective rodent control could also be beneficial in terms of preventing the introduction/spread of other zoonotic pathogens that can be carried by rodents, such as *Leptospira*, hantavirus, MSRA, *Campylobacter*, and *Y. enterocolitica*, but also for important swine pathogens, such as *L. intracellularia* and *Y. enterocolitica* (Backhans and Fellstrom 2012). Contrary to this, a recent study in Germany has shown that *Campylobacter* and *Yersinia* were more often found in samples from herds within a low *Salmonella* risk category, although the number of herds analyzed in the study was rather limited (Nathues and others 2013). Another recent German study also found that *Salmonella* seroprevalence in herds was negatively associated with *Yersinia* seroprevalence (von Altrock and others 2011). It should be noted that these associations are based upon serology, which reflects past exposure to the pathogens, therefore the results could have been different if bacteriological samples had been taken. Despite these findings, the authors (Nathues and others 2013) pointed out that biosecurity and hygiene measures dedicated to the control of *Salmonella enterica* might have inhibiting effects on the other 2 pathogens, as hypothesized by other studies (Skjerve and others 1998; Fosse and others 2011). This suggestion is substantiated by the fact the simultaneous occurrence of these pathogens in fattening pigs was observed. It is also observed that, in many ways, *Yersinia* and *Salmonella* may behave in a very similar way, so the controls for one can also benefit the control of the other, and this is of particular importance in relation to the practice of mixing batches of pigs, notably in fattening herds (Rossell and others 2006; Fosse and others 2009). Some of the methods for spatial and temporary separation of populations of pigs to control *Salmonella* also appear to be effective in controlling some other infectious diseases of swine, although no study of the prevalence of foodborne agents in these systems has been reported (Davies and others 1997b).

The studies that investigated the use of isolated weaning to raise *Salmonella*-free swine were based on similar experiments for *M. hyopneumoniae,* which introduces the idea that both organisms, and perhaps other important swine diseases, could be eliminated without depopulation by placing animals in various stages of production into isolated locations (Harris 1988; Fedorka-Cray and others 1997).

If acidification of feed and water is used to control *Salmonella*, other acid-intolerant bacteria, such as *E. coli* and *Campylobacter* could also be affected by it (Wang 2012). Wet feeding is a protective factor against *Salmonella*, but unfortunately it increases the risk of pigs becoming infected with *L. monocytogenes*, an important zoonotic agent (Fosse and others 2009), although *L. monocytogenes* infection at the farm level has a lower relevance to human infection as this is primarily a postharvest processing contaminant (Nightingale and others 2004) that increases in prevalence during cutting and chilling (Thévenot and others 2006). Cleaning and disinfection of pipelines was notably associated with a higher prevalence of *L. monocytogenes* [(Beloeil and others 2003) as cited by (Fosse and others 2009)] because disinfection may destroy the bacterial pipeline biofilm which may inhibit the development of *L. monocytogenes* [(Royer and others 2004) as cited by (Fosse and others 2009)].

Finally, a recent and promising study in Belgium has found that the internal biosecurity (measures to reduce the within-herd spread of pathogens) was negatively associated with disease treatment incidence, suggesting that improved biosecurity might help in reducing other bacterial infections and the amount of antimicrobials used to treat them, with the consequent benefit of reduced cost and less development of antimicrobial resistance (Laanen and others 2013). However, the authors reported that no significant associations could be found between *Salmonella* seroprevalence and the scores for overall, external, or internal biosecurity. This contrasts with what other authors have reported (Baptista and others

2010a; Twomey and others 2010) whose studies showed a negative association between *Salmonella* herd prevalence and the level of biosecurity. It was hypothesized that this could be because the Belgian study excluded herds with high *Salmonella* seroprevalence and because of the different ways in which *Salmonella* infection was assessed in all those studies. It has been speculated that factors relating to feeding, pig mixing, and routine blanket medication practices on farms may have a much greater impact on the within-herd prevalence than biosecurity measures in a high herd prevalence situation (Belluco and others 2015).

Cost–Benefit Analysis

Salmonella controls are generally perceived as an operational and economic burden by most pig producers, with increased costs without obvious economic benefit. Unless compulsory reductions in farm prevalence are imposed, with penalties for farms failing to achieve the targets, or incentives to those who have very low prevalence, it will be difficult to engage pig producers to apply *Salmonella* controls. Another route would be to have a solid cost–benefit analysis that proves to the swine sector that, in the long term, *Salmonella* controls can be economically beneficial, and if those controls reduce the number of human outbreaks, the benefit would be greater and wide-spread for the overall population and the reputation of the pig industry. A recent cost–benefit analysis by EFSA interpreted the results as a potential failure to demonstrate a positive economic benefit from setting targets to reduce *Salmonella* in slaughter pigs based on the reduced cost of human infections alone. Nonetheless, it was reported that it would be premature to conclude that the cost–benefit will always be negative under all circumstances, and it is worthwhile continuing the investigations to explore possible ways forward (DGSANCO 2010). Contrary to this, studies in Denmark and the Netherlands concluded that the cost of *Salmonella* in pigs and humans is high without an intervention or control program in place (Wegener and others 2003; van der Gaag 2005). High farm standards, good pig feeding practices, and medication in those countries have resulted in low within-herd prevalence compared to many other northern and southern European countries (EFSA 2009).

A study in the United Kingdom showed that the attitude and willingness toward an adoption of on-farm biosecurity measures was proportionally inverse to the costs of implementing those measures (Fraser and others 2010), thus providing evidence that profit considerations are an important factor influencing the attitude of pork producers toward the adoption of such practices.

Good biosecurity, with herd health monitoring using clinical signs, serology, and postmortem examinations can be used to detect clinical and subclinical exposure to specific pathogens. This, complemented by good health and production records and feedback from other sources, such as slaughterhouses, can result in improved performance and profit, and also provide evidence-based justification for making changes to improve the herd status (Amass 2005a).

A review of studies on cost–benefit analysis was conducted by BPEX, concluding that there was a general lack of data on the cost and benefits associated with the implementation of single or multiple interventions or *Salmonella* control programs (Friendship 2009). A study in the United States concluded that postharvest interventions are cheaper than those at the farm level, quoting about $0.20 for carcass treatment compared with $0.85 per pig for vaccination (Miller and others 2005). A similar conclusion was established in Denmark where they concluded that only hot-water decontamination at the abattoir appeared to be socioeconomically profitable, although they only assessed acidification and feed formulation as preharvest interventions (Goldbach and Alban 2006).

In contrast, research demonstrated that there can be a financial payback as a result of good management practices required to control *Salmonella*. Improved performance benefits can outweigh the cost of effective acid treatment in feed/water and a comprehensive program of cleaning and disinfection (Blanchard and Kjeldsen 2003) and maintenance of minimal *Salmonella* on a national basis can have a positive cost–benefit (Hultén and others 2011).

The vast majority of the economic benefits will be achieved through better herd performance, for example, by improving the feed conversion efficiency and daily live weight gain. Alongside that, there may be reduced veterinary costs due to the avoidance of other infections. Expensive veterinary bills and increased culling rates can accompany some clinical *Salmonella* outbreaks (Blanchard and Kjeldsen 2003) and initiatives to reduce disease, antibiotic use, and consequent selection of antimicrobial-resistant bacteria are more relevant today than ever. It is in this context that a recent study has revealed that among many interventions, improved biosecurity ranked very high as an effective way of reducing the usage of antibiotic but also ranked very high in terms or return of investment (Postma and others 2015).

Preventive antibiotic treatment, with its associated cost, during the fattening period has also been shown to enhance the risk of *Salmonella* shedding (Rossell and others 2006) and a Dutch study found that the use of Tylosin as an antimicrobial growth promoter in finishing feed was associated with a higher risk of *Salmonella* seroprevalence (van der Wolf and others 2001b). In contrast, a study in the United States showed a higher prevalence of *Salmonella* in antimicrobial-free production systems than in conventional ones (Gebreyes and others 2006), but this could be explained by the variability in husbandry and treatments between sectors. Improved biosecurity and farm hygiene management might help to reduce the amount of antimicrobials used prophylactically, with consequent savings for the farmer and reduction of development of antimicrobial resistance (Laanen and others 2013).

Salmonella infection as such does not necessarily impact herd performance, and high levels of infection are often found in fast-growing pigs, as demonstrated by a study in the United States that found that feed conversion rates for groups of finishers with high *Salmonella* prevalence was above median when compared with herds with lower prevalence (Funk and others 2001a).

Despite numerous studies, there is still no compelling evidence to show that farms with a lower *Salmonella* prevalence have higher productivity once all the confounding variables have been considered (Fraser and others 2010), despite the fact that some diseases, such as postweaning systemic wasting syndrome, that are often associated with *Salmonella* infection, result in poor pig health and productivity (Cook 2004). This conflicting evidence should be resolved by more intensive intervention studies that also consider medium and long-term economic aspects in sufficient detail to be definitive.

Finally, another aspect of the cost/benefit discussion could be extended to *Salmonella* monitoring. Surveillance programs in several countries are dependent on intensive sampling schemes (Alban and others 2002; Blaha 2004; Cortinas Abrahantes and others 2009). These surveillance programs represent a considerable cost due to the manpower needed to collect/analyze the samples and the materials used. Alternative ways to categorize risk should be further investigated. One way of improving efficiency would be to simultaneously test the surveillance samples for multiple pathogens, which has been achieved in human medicine by using a luminex-based array system (Liu and others 2012). An interesting Danish–Portuguese study found that herds with poor biosecurity had a higher probability of testing positive for *Salmonella*. Based upon that, they suggested that there is potential for using herd information to classify herds according to their *Salmonella* risk, rather than actual testing, and this represented a considerable saving for surveillance programs. This could be a cost-effective tool for future development of risk-based approaches to surveillance, targeting monitoring on interventions to high-risk herds or designing appropriate sampling strategies for herds with different levels of infection (Baptista and others 2010a). It would not be the 1st time this has been done as farm data have already been used to classify cattle herds according to the risk profile for disease presence (Ortiz-Pelaez and Pfeiffer 2008).

Conclusions

When trying to control *Salmonella* infection in pig herds, particularly by means of improved biosecurity, there is no such thing as a "one size fits all" strategy. It is important that the main risk factors which are identified for a given farm are effectively assessed, and this information can then be used to develop a tailored control plan. To succeed, the control plan will normally need to combine several of the biosecurity measures discussed in this review.

Although control strategies based around feeding practices are reported as the most successful when trying to control Salmonella in pigs, there are also concerns about lower productivity and performance, which will normally have to be balanced by cost reductions, improved health or financial incentives. Therefore, more holistic research in this area is needed to establish overall benefits and costs. Considerations should also include reduction of antimicrobial medication and the associated development of antimicrobial resistance.

There is a general consensus that maintaining a closed herd with AIAO production and minimizing mixing of pigs from different sources can help to prevent cross-contamination and infection. Current pig farming practice, such as a continuous animal flows and disparity between breeding herd outputs and rearing farm capacities is one of the biggest problems that the industry may face in adhering to the real principles of AIAO. This can be at least in part be resolved by batch farrowing, but large batches may also create a need for on-farm lairage before movement of weaned pigs or finishers, which introduces a new opportunity for spread of infection. There is also a need for meaningful monitoring of the *Salmonella* status of herds, in particular to avoid the introduction of *S. typhimurium* into farms that are currently free of this invasive serovar.

Acidification of feed and water and *Salmonella* vaccination can assist with the reduction of infection in the herd but there is a need for more complete evaluation of effective programs under field conditions in different countries and for a DIVA vaccine in those countries which rely on immune-surveillance.

It is clear that the most effective control strategies are those that involve a financial penalty for failure to achieve the designated *Salmonella* prevalence. Even when productivity benefits can be demonstrated, it can still be difficult to motivate farmers to apply improved standards, particularly in the face of messages promoting postharvest interventions as the sole control option. There is therefore a need for a greater understanding of the drivers and barriers involved in promotion of voluntary improvement of farm standards.

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