CAN DIET BE USED AS AN ALTERNATIVE TO ANTIBIOTICS TO HELP CONTROL ENTERIC BACTERIAL INFECTIONS OF PIGS?

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Abstract

In response to a need to develop alternative methods to control the major enteric bacterial infections of pigs, studies have been undertaken to investigate whether or not it is possible to reduce susceptibility to colonisation by pathogens through the use of specific diets. These diets are intended to alter the intestinal environment, including the resident microflora, such that conditions are no longer conducive to growth of the pathogens. In the case of swine dysentery, caused by the spirochaete *Brachyspira (Serpulina) hyodysenteriae*, it has been shown that diets with very low levels of soluble non-starch polysaccharides and resistant starch offer complete protection against experimental disease. The only fully protective diet identified to date comprises cooked white rice and animal protein, but substituting the rice with steam-flaked maize or sorghum, or finely ground sorghum, gives a diet that tends to reduce susceptibility to experimental infection. To date the application of exogenous enzymes to standard pig diets has not produced intestinal conditions that inhibit colonisation by the spirochaete. In the case of the related intestinal spirochaete *Brachyspira (Serpulina) pilosicoli*, the aetiological agent of porcine intestinal spirochaetosis, feeding the rice-based diet retards the rate of colonisation of the large intestine but does not completely prevent either colonisation or the development of disease in pigs after experimental challenge. The same rice-based diet reduces colonisation of the small intestine by enterotoxigenic *Escherichia coli* after experimental infection of weaners, whilst addition of a source of soluble non-starch polysaccharide to the rice diet results in greater colonisation by the *E. coli* strain. Finally, the stomachs of weaner pigs fed a finely ground wheat-based diet have been shown both to have severe ulceration of the *pars oesophagea* and to be colonised by *Helicobacter* spp. Feeding finely ground extruded wheat resulted in no ulceration and an absence of the bacteria. It is possible that the *Helicobacter* spp. are involved in the aetiology of the ulceration, and that their presence is influenced by the treatment of the diet consumed.

From these studies it is clear that a number of important enteric bacterial infections can be modified by the use of specific diets. The main challenges are to understand how these effects work and to develop cost-effective diets that can be applied in the field to help supplement current control measures for these and other enteric infections of pigs.

Introduction

Antibiotics are an important management tool for the pig industry. They are used to treat overt bacterial diseases, to provide a level of prophylaxis in situations where disease is liable to occur, and, to a lesser extent, to improve growth rates in the absence of disease. Unfortunately the pig industry faces mounting difficulties over its use of antimicrobials. The reason for this is that their long term use eventually selects for the survival of resistant bacterial species or strains, and furthermore there are a variety of mechanisms whereby the genes encoding this resistance can be transferred to other bacteria, thus also making them resistant. This scenario has resulted in a situation where a variety of important bacterial pathogens of pigs are showing resistance to a range of antimicrobial drugs. On an immediate practical level this drug resistance is reducing the number of available antimicrobials that can be reliably used to control diseases caused by these bacteria in pigs. Although this is an obvious problem, it is unlikely to induce legislative intervention. In contrast the potential risks to human health that may arise are leading to mandatory changes being imposed on the industry. These risks include the transfer of multidrug resistant zoonotic pathogens such as *Salmonella* spp. and

Campylobacter spp. from pigs to humans, the direct or indirect transfer of resistance genes from members of the porcine intestinal microflora to human bacterial strains, and the presence of antimicrobial drug residues in pig meat. Public concern about these issues is being translated into reduced meat consumption, tightening of restrictions on antimicrobial residues in meat, and legislation reducing the availability of antimicrobial agents for use in animal production. Consequently there is a clear and urgent need to investigate alternative means both of controlling bacterial infections and promoting growth in pigs.

There are a number of common and important enteric bacterial infections of pigs, and much of the antimicrobial usage in the pig industry is directed at controlling these infections. Clearly alternative methods of control that do not require antimicrobials would greatly reduce the need to use these drugs. Accordingly efforts are being directed at modifying management practices so as to limit exposure to pathogens and to minimise stress, at improving vaccines for enteric infections, at selective breeding of animals for resistance to infectious diseases, at improving the pig's local immune responses, and at strategies to inhibit or kill pathogenic bacteria in the gut by the use of organic acids, inorganic chemicals such as zinc oxide, bacteriophages or bacteriocins. A slightly different approach being developed focuses on excluding the growth of pathogens in the gut by encouraging the growth of other bacteria which are believed to take up microniches in the intestine and compete with the pathogens at those sites. The idea of "competitive exclusion" of *Salmonella* serovars by components of the normal intestinal microflora has long been accepted (Nurmi and Rantala, 1973), and the principle has recently been extended to *Yersinia* spp. infecting pigs (Asplund *et al.*, 1996). One form of this approach is to feed specialised strains of certain bacteria, especially *Lactobacillus* spp. and *Bifidobacterium* spp., that are selected because they are considered to promote gut health and exclude pathogens. The use of these so-called probiotic bacteria is reviewed elsewhere in this volume. Probiotics probably have most promise for use in controlling infections in young pigs, for example in the period immediately after weaning, when the resident intestinal microflora is not yet stable enough to exclude probiotic strains.

An extension of the probiotic approach to control of enteric infections has been to feed specific dietary components that act as substrate for natural populations of "protective" bacteria, such that these proliferate and more effectively exclude pathogens. For example, in the case of *Clostridium difficile* infection, different dietary fibre sources have been investigated to optimise inhibition by the resident microbial flora through its production of specific short chain fatty acids (May *et al.*, 1994). Similarly so-called "prebiotic" dietary supplements such as fructose-containing oligosaccharides have been used to selectively increase numbers of *Bifidobacterium* spp. in the large intestine, the presence of which in turn results in an inhibition of colonisation by certain pathogens (Gibson *et al.*, 1995). Recently specific metabolites from plants have been identified which when fed may interact with short chain fatty acids to create inhibitory conditions for pathogens such as *E. coli* O157 (Duncan *et al.*, 1998).

The resident intestinal microflora of the pig is extremely diverse and complex, and varies quantitatively and qualitatively at different intestinal sites and at different stages in the life of the pig. The main bacterial biomass is found in the large intestine, where dietary fibre serves as the major bacterial growth substrate. Dietary fibre is defined as plant materials that are not digested in the small intestine, and can be broadly divided into material that is fermented rapidly and material this is fermented slowly. There have been relatively few detailed studies on the intestinal microflora of pigs (e.g., Robinson *et al.*, 1981, 1984), and because of a lack of appropriate culture techniques suitable for many of the fastidious anaerobic microorganisms that inhabit the large intestine, the exact composition of the intestinal microflora of the pig is not known. There is a body of literature to show that different forms of fibre in the diet can broadly influence the composition and metabolic activity of the large intestinal microflora in pigs (Varel *et al.*, 1982; Varel and Pond, 1985; Bach Knudsen *et al.*, 1991; Jensen and Jorgensen, 1994; Reid and Hillman, 1999). Unfortunately little is known about how the different groups of resident bacteria which are stimulated to proliferate in this way themselves interact with pathogenic species of bacteria. This lack of information makes it difficult to predict how a given dietary component could be used to indirectly influence a given enteric pathogen.

It should also be borne in mind that the diet could have other influences on colonisation by pathogens, for example by modulating the amount of specific substrate available at a given site for the pathogen itself, by altering intestinal viscosity and hence intestinal motility, and by direct or indirect effects on the intestinal mucosa such that changes occur in specific colonisation sites or receptors on enterocytes. For example, different cereal types and particle size have been shown to alter epithelial cell proliferation and lectin binding patterns of the epithelium in the large intestine of pigs (Brunsgaard, 1998).

Despite a lack of detailed knowledge, the general contention that dietary components can in some way influence colonisation by pathogens is consistent with reports from the field, where it is often observed that changes to the diet result in either increased or decreased enteric disease. For example, it has been reported that units adopting liquid feeding of by-products or using fermented wet feed have a lower incidence of Salmonellosis than herds using dry feed (Stege et al., 1997; van der Wolf et al., 1999). Information from such field studies, although obviously important because it reflects conditions in the field, does need to be confirmed by careful experiments conducted under controlled conditions. This is because other issues apart from specific dietary components may be contributing to the effects. In the case of Salmonellosis the relative hygiene of the various diets may be influencing the infectious dose presented to the pigs.

In view of the effects that diet can have on the intestinal environment, including its resident microflora, and because of the need to develop new means for control of specific enteric bacterial pathogens, attempts have been made to select or manipulate pig diets under experimental conditions so as to help control some of these important infections. The approach assumes that the diet to be used has the correct optimal balance of macro- and micro-nutrients to support normal pig growth, and does not contain any toxic components (e.g., mycotoxins) which may increase susceptibility to pathogenic bacteria.

It should be borne in mind that many different sorts of pathogenic bacteria infect pigs, and these have different physiological requirements for colonisation and growth. Different pathogens also colonise different sites within the gastrointestinal tract, and the environmental conditions generated at these sites in response to the diet vary enormously. Given these complexities it would be optimistic to seek one simple dietary solution that could be used for the control of all enteric infections at different stages of a pig's life.

This review focuses on four important enteric bacterial diseases of pigs: swine dysentery, porcine intestinal spirochaetosis, post-weaning colibacillosis and ulceration of the *pars oesophagea* of the stomach. These conditions involve different sorts of bacteria that colonise different areas of the intestinal tract. These diseases have been selected for study both for their economic importance to the pig industry and because they illustrate some of the general principles involved in using diet to help control enteric bacterial infections.

Swine dysentery

Swine dysentery (SD) remains a major recurrent problem for the pig industry in many parts of the world. The disease is caused by infection with the anaerobic intestinal spirochaete *Brachyspira (Serpulina) hyodysenteriae,* which colonises the crypts of the large intestine and induces a severe mucohaemorrhagic colitis and dysentery (Hampson et al., 1997; Ochiai et al., 1997). Experimental infection studies in gnotobiotic pigs have shown that colonisation by the spirochaete and lesion formation are enhanced by the presence of other species of anaerobic bacteria, particularly certain *Bacteroides* spp. and *Fusobacterium* spp. (Meyer et al., 1975; Whipp et al., 1979). Vaccines developed to prevent the infection have been relatively ineffective, and control of SD on infected piggeries mainly is achieved through the prophylactic and/or therapeutic use of antimicrobials, or by eradication through depopulation and/or medication (Hampson et al., 1997).

According to Harris and Lysons (1992), in the era before antimicrobials were developed, pigs with SD were treated by feeding them oats soaked in salt water or sodium hydroxide solution, with the assumption that the high fibre content of the diet was beneficial. Prohaszka and Lukacs (1984) reported a field study where the diet of pigs with SD was changed from one based on corn to one based on corn silage. This

change lowered the pH of the digesta in the large intestine, and resulted in an inhibition of growth of *B. hyodysenteriae* and protection against disease. These field observations led Siba *et al.* (1996) to test the hypothesis that diets rich in highly fermentable fibre would generate an acidic environment in the large intestine which would protect from colonisation by *B. hyodysenteriae*. Groups of weaner pigs were fed either a typical Australian wheat/lupin diet that contained rapidly fermentable fibre sources, or an experimental diet composed of cooked white rice and animal protein that contained low levels of dietary fibre. Judging from the pH of the digesta in the large intestine, the cooked rice diet apparently reduced the extent and rate of bacterial fermentation in the large intestine compared to the standard diet. Contrary to expectations nearly all the pigs fed wheat/lupin developed SD after experimental challenge, whilst none of the pigs fed the rice diet were colonised by the spirochaete or developed SD. When either the cooked rice or the animal protein were mixed with either lupin or wheat, disease occurred after challenge (Table 9). This indicated that neither the rice nor the animal protein contained specific components that inhibited growth of the spirochaete. The authors considered that the protective effects of the rice diet were most likely due to reduced fermentation in the large intestine, and associated suppression of members of the resident microflora which normally facilitate colonisation by the spirochaete. The authors did not exclude the possibility that the protection was associated with other physical changes in the large intestine associated with reduced fermentation (e.g., drier digesta). In a subsequent study of pigs fed the "protective" rice-based diet, an analysis of the bacterial flora in the large intestines showed some evidence for there being reductions in populations of bacteria which have been reported to act synergistically with *B. hyodysenteriae* - notably *Fusobacterium necrophorum* and *F. nucleatum* (Durmic *et al.*, 1998b).

Subsequent work showed that parboiled rice was not a suitable substitute for cooked rice, and that it was important for the rice to be fully cooked with a ratio of two volumes of water per volume of rice in order for fermentation in the large intestine to be minimised (Siba, 1997). Recently, workers in Canada (R.N. Kirkwood, personal communication) and Denmark (R.H. Lindecrona, personal communication) have reported difficulty in reproducing the protective effect of the rice diet. This apparent failure to obtain protection may be associated with the way the rice was processed, or alternatively it may be a reflection of differences in the intestinal microflora of pigs at the study sites. If the latter is the case it adds a further dimension of complexity to the use of diet to control SD.

Table 9. Pooled results displaying shedding of spirochaetes and the incidence of swine dysentery in pigs fed different diets following oral challenge with *B. hyodysenteriae* (after Siba *et al.*, 1996).

Item	Diet Type[1]			
	RA	RL	WA	WL
No. of pigs challenged	16	6	6	16
No. of pigs shedding *S. hyodysenteriae* in faeces	3	6	5	13
Mean duration (days) of shedding in faeces	4.6	5.4	5.6	8.5
No. of pigs that developed SD	0	5	3	10
Incidence of disease, %	0	83.3	60	62.5

[1]Diets: RA: 77% cooked white rice + 18% animal protein; RL: 64% cooked white rice + 13% animal protein + 15% dehulled Australian sweet lupins; WA: 75% wheat + 17% animal protein; WL: 62% wheat + 11.5% animal protein + 15% dehulled Australian sweet lupins.

In most parts of the world it is neither practical nor economically viable to feed pigs cooked rice, except for example for a short period during an attempt to eradicate SD from

a piggery. A study therefore was undertaken to examine a variety of different cereal grains either heat-processed or not, in order to identify practical alternatives to feeding rice, and to help identify components of the diet which might predispose to colonisation by the spirochaete (Pluske *et al.*, 1996). Two cereals, maize and sorghum, were identified which when steam-flaked reduced the incidence of disease amongst groups of pigs after experimental infection with *B. hyodysenteriae*. An analysis of all the diets tested identified soluble non-starch polysaccharide (sNSP) and resistant starch (RS) as being two important dietary components that promoted fermentation in the large intestine and were associated with a high incidence of SD.

The importance of sNSP and RS in generating conditions that allowed the spirochaetes to proliferate were then investigated by adding them in pure form either by themselves, or together, to the original protective cooked rice diet (Pluske *et al.*, 1998). Retrograde maize starch was used as a source of RS, and guar gum was used as a source of sNSP. Pigs fed these supplemented diets became colonised and developed dysentery, whilst those on the base rice diet did not. Consistent with the hypothesis that rapid fermentation associated with sNSP and/or RS is required to facilitate colonisation and disease, when a source of predominantly insoluble NSP (oaten chaff) was added to the protective rice diet, this diet remained protective. Based on measured fermentation parameters (pH of digesta, gut weight and VFA and ATP content) the chaff was poorly fermented such that the correct predisposing conditions for colonisation by *B. hyodysenteriae*, for example VFA concentrations and balance of microflora, were absent.

As wheat remains an important cereal grain for feeding pigs in Australia, attempts have been made to increase the digestibility of wheat in the small intestine by the addition of exogenous enzymes and/or cereal grain extrusion (Durmic *et al.*, 1997, 1998a). Dietary enzymes used with wheat included xylanase to reduce the viscous effects of sNSP, and various mixtures of amylase and/or protease to help increase digestion of starch in the small intestine. Extrusion was used to assure complete starch gelatinisation and near complete digestion of starch in the small intestine. These manipulations failed to reduce the fermentability of the diet such that it prevented colonisation by *B. hyodysenteriae*. In this case addition of enzyme actually resulted in an increased rate of fermentation in the caecum, with reduced fermentation only being recorded in the distal part of the colon. The increased caecal fermentation presumably was a result of liberation of smaller highly fermentable oligosaccharides from the NSP in the wheat. Extrusion of the wheat also failed to significantly reduce the expression of SD with a 57 ± 7 % (mean $\pm$ sem) expression in pigs fed either extruded or hammer-milled raw diets (8 mm screen) formulated with wheat and animal protein. This high incidence of disease occurred despite the presence of reduced indices of fermentation in the large intestine of pigs fed extruded diets. One possible explanation may be that the relatively high temperatures associated with extrusion may have strengthened bonds within the starch granules, making them less susceptible to enzyme action. Alternatively, heating may have decreased the ratio of insoluble NSP : soluble NSP (Pluske *et al.*, 1996) that exacerbated expression of the disease.

The effects of grain processing and addition of dietary enzymes to sorghum-based diets currently are being investigated in our laboratory. Sorghum grain has a very low sNSP content but a relatively high starch content, so treatments aimed simply at increasing starch digestion in the small intestine might cause reduced fermentation in the large intestine and result in a reduced expression of SD. In preliminary experiments the inclusion of dietary enzymes based on xylanase, amylase and protease have had no effect on fermentation parameters in the large intestine nor on the expression of SD in infected pigs. Extrusion of sorghum actually increased the expression of SD ($P<0.05$) with 59 ± 8 vs 19 ± 2% of pigs (n=24) expressing the disease when fed diets based on extruded versus raw sorghum (with animal protein as the protein source). For these experiments the sorghum grain was finely milled through a 1.2 mm screen using an air assisted hammer-mill compared to an 8 mm screen in a traditional hammer-mill. Further analysis comparing different experiments showed a response to fine grinding ($P<0.05$), with 63 ± 8 vs 35 ± 8% of infected pigs (n=54) expressing SD when fed coarse versus finely ground wheat or sorghum. The basis of this response is still to be investigated, but the known improvement to digestibility in the small intestine of finely ground diets (Wandra *et al.*,

1995; Mavromichalis and Hancock, 1999) should result in the reduced availability of substrate for fermentation in the large intestine. Certainly in these experiments, various fermentation indices (weight of the large intestine, pH and ATP, VFA and starch content of the digesta) suggested that finely ground sorghum resulted in rates of fermentation as low as those found with extruded sorghum.

Collectively, how do these data improve understanding of the relationships between diet, fermentation and SD? Simple linear regression analyses were conducted between dietary characteristics and indices of fermentation recorded in the large intestine and the percentage of pigs showing clinical expression of the disease (Table 10). This was based upon data from 204 pigs, 102 of which were slaughtered for measurement of fermentative indices after being fed different diets or dietary treatments (described above), and 102 of which were identically fed, but then inoculated with a virulent strain of *B. hyodysenteriae* and monitored for SD. A multiple regression model was also developed.

The percentage of variation in SD in the infected pigs explained by individual indices of fermentation in the uninfected pigs was generally low (0.3 to 18%) (Table 10). However, a multiple regression model incorporating these individual indices of fermentation explained 51% (P<0.001) of the total variation in the percentage of experimentally-challenged pigs that developed SD, as follows: -

Percentage of experimentally-challenged pigs that developed SD=151.4 + 7.1 (sNSP in diet, %) + 39.3 (weight of full caecum, % body weight) – 21.7 (pH caecum) + 3.8 (ATP in proximal colon, nmol/g digesta) – 0.14 (total VFA in large intestine, mmol); r^2=0.51. NB Indices of fermentation were derived from the uninfected pigs.

Table 10. Individual correlations between diet characteristics and fermentative indices in the large intestine, the multiple regression model, and the percentage of experimentally-challenged pigs that developed SD.

Model component	Individual correlation with % disease expression		Multilinear regression	
	Correlation (r^2)	P value	% contribution to final r^2	P value for model
Dietary sNSP	0.17	0.001	42	<0.001
Full caecum	0.18	<0.001	17	<0.001
pH caecum	0.16	<0.001	11	0.001
ATP proximal colon	0.04	0.04	5	0.029
Total [VFA] in large intestine	0.003	NS	25	<0.001

The resultant model is heavily driven by the sNSP level of the diet (Table 10). Given that dietary interventions designed to counter some of the effects of sNSP were not effective in protecting against SD, the model clearly points to the selection of grains (diets) inherently low in sNSP to achieve protection against the disease. The other components of the model mainly relate to fermentation indices in the caecum and proximal colon (Table 10). It would appear, therefore, that controlling or reducing fermentation in the first part of the large intestine is critical for reducing the expression of SD. Reducing fermentation in this part of the large intestine is difficult, however, since even small amounts of undigested material passing from the terminal ileum will be available for fermentation.

Although a cheap and easy means of treating all common cereal grains to make them "protective" against SD has not been identified, some progress has been made, and sorghum and maize have been identified as being the best grains on which to concentrate investigation. Further work will be needed to verify the effects on large intestinal fermentation and disease of grind size with these and wheat-based diets. The cooked rice diet stands out in that it can completely protect infected pigs from expressing SD. In addition it clearly results in the lowest rates of fermentation in the large intestine when compared to all other diets that have been examined so far. Although expensive, it could

be used prophylactically in outbreaks of SD, or to reduce shedding of *B. hyodysenteriae* prior to medication and/or destocking, as part of a SD eradication programme.

Porcine intestinal spirochaetosis

Porcine intestinal spirochaetosis (PIS) is a chronic diarrhoeal disease of weaner and grower/finisher pigs, resulting from colonisation by the anaerobic intestinal spirochaete *Brachyspira (Serpulina) pilosicoli* (Trott *et al.*, 1996; Ochiai *et al.*, 1997). As with the closely-related *B. hyodysenteriae*, *B. pilosicoli* colonises the caecum and colon, but unlike *B. hyodysenteriae*, which is chemotactic to mucus and moves deep into the crypts, *B. pilosicoli* remains largely in the lumen of the intestine, or may attach by one cell end to the epithelium adjacent to the intestinal lumen (Hampson and Trott, 1995).

For some time before the description of PIS and its association with *B. pilosicoli*, certain cases of what were almost certainly PIS were described as "grower scour/non-specific colitis" (Smith and Nelson, 1987). This condition was reported to be influenced by diet, with pelleting of the diet being said to predispose to the condition (Connor, 1992). Finely ground pelleted food is also believed to predispose to Salmonellosis (Schwartz, 1999), and ulceration of the *pars oesophagea* (Friendship, 1999).

In view of the close similarity between *B. pilosicoli* and *B. hyodysenteriae*, their very similar habitats in the large intestine, and reports from the field of dietary influences on PIS, an investigation was made into whether the cooked rice diet that protects from SD might also protect from PIS (Hampson *et al.*, 1998). In this study two groups of weaner pigs were fed either a standard commercial wheat-lupin weaner diet (n=8), or the rice-based diet described above (n=6) for three weeks after weaning. All pigs were then challenged orally over three days with 10^{10} active mid-log phase cells of a Western Australian field strain of *B. pilosicoli* (strain 95/1000). The pigs were killed 3-4 weeks post inoculation (pi).

All animals became colonised with *B. pilosicoli* strain 95/1000, but this occurred significantly later (mean of 14 days pi compared to 3.6 days), and lasted for significantly less time (mean of 13 days compared to 20 days), in the pigs fed rice compared to those fed wheat. One pig fed the wheat diet developed an acute and severe erosive colitis with severe watery diarrhoea within three days pi, and was euthanased. *B. pilosicoli* cells were observed attached to the colonic epithelium adjacent to the areas of erosion. All the other pigs on both diets developed a mild transient diarrhoea, lasting only 2-3 days. At post-mortem examination small areas of mild patchy colitis were observed grossly, but no spirochaete attachment to the epithelium was detected.

This study demonstrated that, as with *B. hyodysenteriae*, colonisation by *B. pilosicoli* can be influenced by diet. In this case the rice-based diet did not prevent colonisation, but only retarded the process. From this finding it seems that the two spirochaete species have different environmental requirements and constraints on their ability to colonise the large intestine of pigs. The details of these differences are completely unknown, and may or may not be associated with the different micro-niches that they occupy in the large intestine, with differences in their metabolism and physiological requirements, or with other factors. The generally mild nature of PIS, together with the lack of complete protection using the rice-based diet, means that the prospects for an economically-viable means of controlling PIS in piggeries by using the rice-based diet alone are poor. Given the differences between the response of the two spirochaete species, however, it might still be worth investigating whether other dietary changes have a relatively greater influence on the proliferation of *B. pilosicoli*, perhaps acting via different mechanisms than those postulated for *B. hyodysenteriae*.

Post-weaning colibacillosis

The occurrence of growth checks and diarrhoea in the first 5-10 days after weaning remains a serious problem in many piggeries. Colonisation of the small intestine with enterotoxigenic strains of *E. coli* in this period results in a severe secretory diarrhoea (post-weaning colibacillosis: PWC), and, besides mortalities and the requirement for

antimicrobial medication, the associated growth checks can result in overall increases in time taken to reach market weight (Hampson, 1994).

It is well-established that PWC is a multifactorial condition, and that there are dietary influences on the disease (Hampson, 1987). For example, "high" concentrations of dietary protein (21%) have been shown to predispose to the condition (Prohaszka and Baron, 1980). Some highly digestible and milk-based weaner diets have been associated with reduced post-weaning diarrhoea (English, 1981), whilst conversely it has been suggested that the inclusion of fibre sources to weaner diets will reduce the incidence and severity of PWC (Bertschinger et al., 1978; Bolduan et al., 1988).

To investigate these contradictory observations further, the growth rates and recovery of haemolytic E. coli from the faeces of pigs fed a highly-digestible cooked rice/animal protein diet, or the same diet supplemented with guar gum as a source of additional sNSP, were examined (McDonald et al., 1997; 1999). Pigs fed the basic rice diet for two weeks after weaning were heavier, and had lighter large intestines and less fermentation at this site, than the pigs fed the diet containing guar gum. When pigs on the two diets were challenged with enterotoxigenic E. coli, significantly more of these organisms were recovered from the small intestine of the pigs on the rice diet supplemented with sNSP than on the other diet (Table 11). Pigs fed a commercial wheat-lupin based diet had significantly more of the pathogens isolated than did the pigs on the basal rice diet (data not shown).

Table 11. The recovery of haemolytic *Escherichia coli* from the intestinal tract of infected weaner pigs (after McDonald *et al.*, 1999).

Item	Diet Type[1] RA	Diet Type[1] RAGG	Statistics[2]
Mean CFU[3]/g in small intestine	1.3×10^4	8.0×10^9	*
No. of positive sites in SI[4]	0.53	1.63	**
CFU/g in colon	1.4×10^7	3.7×10^{10}	NS
No. of positive sites in colon	1.71	1.69	NS

[1]Diets: RA: 74% cooked white rice + 20% animal protein + 4% soya bean meal; RGG: 64% cooked white rice + 10% guar gum + 20% animal protein + 4% soya bean meal. [2]*P< 0.05; **P<0.01; NS, not significant. [3]CFU: colony-forming units. [4]Maximum number of possible positive sampling sites in small intestine (SI) was 3.

This experiment suggests that the presence of sNSP in weaner diets is detrimental in terms of both piglet growth and proliferation of enterotoxigenic E. coli in the small intestine. It also points to the benefits of feeding a highly-digestible, rice-based diet to weaners. The mechanism(s) involved in the protection from PWC is not certain, but may be related to the reduced availability of substrate for the bacteria in the small intestine of pigs fed the rice-based diet. Apparently it is not necessary to feed sources of fibre to stimulate the development of the large intestine as a means to promote good health and production in the immediate post-weaning period. Furthermore, diets that promote development of the large intestine do this by diverting growth away from the rest of the carcass. If dietary sNSP is confirmed as a predisposing factor in PWC, then careful selection of ingredients to minimise these components and/or treatment with exogenous enzymes may be helpful in controlling the condition.

Ulceration of the *pars oesophagea*

Ulceration of the *pars oesophagea* of the stomach is a common finding in pigs at slaughter, with advanced lesions being associated with reduced weight gain (Ayles *et al.*, 1996). The condition is well known to be responsive to diet, with many factors such as the fineness of dietary grind, pelleting, cornstarch content, gelatinisation, and unknown factors in wheat all having been implicated in its aetiology (Friendship, 1999). More recently, workers in Brazil have demonstrated a link between the presence of *Helicobacter*

heilmannii in the stomach and the occurrence of stomach ulcers (Barbosa *et al.*, 1995; Queiroz *et al.*, 1996) - a situation which parallels the involvement of *Helicobacter pylori* in human stomach ulceration.

To study possible interactions between *H. heilmannii* and diet in the aetiology of ulceration, a weaner model of stomach ulceration was developed (Accioly *et al.*, 1998). In this model, weaners fed finely ground wheat developed quite severe ulceration after 2-3 weeks, and there was evidence of a urease-producing helical bacteria being naturally present in the lesions (these bacteria were thought to be *H. heilmannii*). In this model, pigs fed wheat that had been extruded remained healthy, and there was no evidence of the urease-producing organisms being present. By some as yet unknown mechanism, extrusion of the wheat resulted in the absence of the organism. At this stage it is unclear whether *H. heilmannii* is causal, and the possibility that the organism proliferates secondarily to the presence of an ulcer cannot be excluded. For example a recent study in gnotobiotic swine failed to produce ulceration of the *pars oesophagea* when the animals were inoculated with *H. heilmannii* and fed a carbohydrate-enriched liquid diet (Krakowa *et al.*, 1998). In contrast pigs fed this diet and inoculated with *Lactobacillus* and *Bacillus* spp. developed ulcers. Fermentation by these bacteria was most likely encouraged by the presence of readily available dietary substrate, and the acidic short chain fatty acids produced as end-products of the fermentation were damaging to the epithelium. Whether or not *H. heilmannii* is a primary pathogen in the stomach, or whether other bacteria may contribute to damage to the epithelium of the stomach, both possibilities provide links between diet, enteric bacteria and disease. Knowledge about such links provides new opportunities for the control of ulceration of the *pars oesophagea* in pigs.

Conclusions

The studies described above provide four examples where there are connections between the pig's diet, and the presence and/or extent of proliferation of pathogenic enteric bacteria. These pathogens inhabit very different parts of the gastrointestinal tract (stomach; small intestine; large intestine), and are themselves quite distinct. Nevertheless, in each case feeding diets that are low in soluble NSP and/or resistant starch can reduce their proliferation. Such dietary effects on infection may not be restricted to bacterial enteric pathogens, as there is evidence that carriage of the parasitic nematode *Oesophagostomum dentatum* in pigs is enhanced by diets rich in insoluble fibre (Petkevicius *et al.*, 1997).

The basis of the protective effects that have been observed is not known, nor is it clear whether different mechanisms with the same outcome are involved in the different infections in different parts of the gut. The protection may be related to reduced availability of substrate for the pathogen, or physicochemical changes in the intestinal environment, such as reduced viscosity of the digesta. Under these changed circumstances the exogenous pathogenic zoonotic bacteria may face increased constraints in colonising and proliferating. Even though no clear explanation has been found for the protection achieved, this work suggests the possibility of new approaches to the control of enteric pathogens. The principles involved may also apply to other bacterial populations in the gut, for example, by reducing sNSP levels in the finisher diet it may be possible to minimise the subclinical intestinal carriage of pathogenic bacterial species which can contaminate meat, and which present a threat to human health. The work may also be relevant to intestinal infections in other monogastric species, particularly poultry and human beings.

In summary, to answer the question posed by the title of this paper, there is evidence that the occurrence and severity of certain enteric infections can be influenced to a greater or lesser extent by the use of diet. The cost-effectiveness of this approach for direct control of diseases in production animals does however require careful consideration. Whilst it may be economically viable to feed highly refined diets to pigs for a short period after weaning, or during a disease clean-up operation, it is not something which can be universally applied. Current efforts are directed at adding exogenous enzymes to the diet or fermenting the diet before it is fed as relatively cheap methods of

reducing sNSP concentrations in the diet. The expectation is that this will help limit colonisation of the intestinal tract by pathogenic bacteria.

Acknowledgments