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Effect of lysozyme or antibiotics on faecal zoonotic pathogens in nursery pigs

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Abstract

Aims: The objective of this study was to determine the effect of lysozyme and antibiotics on zoonotic pathogen shedding in faeces from nursery pigs housed without and with an indirect disease challenge.

Methods and Results: Two replicates of approximately 650 pigs each were weaned and randomly assigned to one of 24 pens in either a nursery room that had been fully disinfected or a nursery room left unclean. Pigs were randomly assigned to control diet (Control), control diet + antibiotics (Antibiotic; chlortetracycline and tiamulin), or control diet + lysozyme (Lysozyme; 100 mg kg⁻¹ diet). Rectal swab samples were collected on day 0 and 28 of treatment, and enriched and cultured for Campylobacter spp. and shiga-toxigenic Escherichia coli (STEC). Enrichments from rectal swab samples also were analysed for presence of enterohaemorrhagic E. coli (EHEC) virulence genes (hlyA, eae, stx1 and stx2). Room hygiene had little effect on day 28 results. Percentage of samples culture positive for Campylobacter spp. was lowest for lysozyme diets (P < 0·01), but similar for control and antibiotic diets (43·2, 83·7, and 84·8% respectively). Diet had little effect on the EHEC virulence genes hlyA or eae (P > 0·1), but there was a tendency for fewer samples positive for stx1/stx2 in antibiotic or lysozyme diet groups (P < 0·07) compared to control diet (1·2, 2·1 and 5·8% respectively). Salmonella spp. and specific STEC types tested were rarely detected in the study.

Conclusions: In nursery swine, room hygiene had little effect on pathogen shedding. Dietary chlortetracycline and tiamulin did not reduce pathogen shedding but dietary lysozyme reduced faecal shedding of Campylobacter.

Significance and Impact of the Study: Lysozyme can effectively replace antibiotics in the diet of nursery swine and can be effective for pathogen control.

Introduction

Antibiotics have been fed to farm animals at sub-therapeutic levels for nearly 60 years to improve animal performance (Cromwell 2001). The young piglet benefits from dietary inclusion of antibiotics (Pluske et al. 2002; de Lange et al. 2010). However, public pressure has increased in recent years to remove antibiotics from food animal’s diets and as a consequence there is an urgent need to identify alternatives.

Lysozyme is a 1,4-β-N-acetylmuramidase and this enzyme cleaves N-acetyl-glucosamine and N-acetylmuraminic acid linkages in bacterial cell wall peptidoglycan. The activity is antimicrobial and occurs widely in nature, and in mammals the enzyme is secreted in tears, saliva, and mucosa. In the gastrointestinal tract, the protein can modulate anti-inflammatory response (Goldman et al. 1986) and immune response (Kawano et al. 1981). As a naturally occurring antimicrobial, there is interest in determining the efficacy of the compound as a dietary supplement.

Early research utilizing transgenic vectors to deliver lysozyme indicated that piglets had improved intestinal morphology (Brundige et al. 2008), as well as metabolic
profile (Brundige et al. 2010). Recent research with egg-
white lysozyme observed a performance benefit when fed
to young piglets (May et al. 2012; Oliver and Wells
2013). However, these studies have been with small
groups and determining the potential effect on pathogen
shedding of naturally infected animals has been limited.

In pigs fed milk supplemented with lysozyme, changes
in the intestinal microflora were observed (Maga et al.
2006, 2012), and in a small study with 10-day old piglets
the Campylobacter prevalence was reduced (May et al.
2012). When pigs were challenged with enterotoxigenic
Escherichia coli (ETEC), supplemented lysozyme reduced
ETEC colonization and concentrations in the digesta
(Nyachoti et al. 2012) and improved the recovery from
clinical signs of infection (Cooper et al. 2013). Nonethe-
less, the potential benefit for dietary lysozyme to reduce
pathogens in nursery piglets is unknown. This study
was designed to evaluate lysozyme in nursery piglets in a typi-
cal production environment and evaluate its ability to
control pathogens excreted in faeces.

Materials and methods

Animals, design and management

The experimental protocol was approved by the US Meat
Animal Research Center Animal Care and Use Commit-
tee. Two replicates of approximately 650 pigs each (1287
pigs total) were weaned from the sow at 26 days of age.
Pigs were blocked by litter and gender, and then ran-
domly assigned to either a nursery room that had been
fully cleaned and disinfected or a nursery room left
uncleaned since the previous group of pigs (Bassaganya-
Riera et al. 2001; Renaudeau 2009; Oliver et al. 2014).
Within a room (24 pens per room), pigs were randomly
assigned to a pen (experimental unit) with either control
diets (Control; 2-phase nursery regime, Oliver et al.
2014), control diets + antibiotics (Antibiotic; chlortetra-
cycline, 55 mg kg$^{-1}$ diet and tiamulin hydrogen fumarate,
38 mg kg$^{-1}$ diet (added as Denagard 10 premixed sup-
plement per label at 1-65 g kg$^{-1}$ diet; Novartis Animal
Health, Basel, Switzerland) or control diets + control
Lysozyme (Lysozyme; 100 mg kg$^{-1}$ in diet, sourced from egg whites;
Entegard, Neova Technologies, Abbotsford, BC, Canada)
and pigs in each pen were allowed to consume diets
ad libitum for 4 weeks. The pigs were distributed across a
total 96 pens in the study (averaged 13-4 piglets per pen;
32 pens per dietary treatment), with pen as the experi-
mental unit for all statistical analyses. All diets met or
exceeded NRC recommendations for required nutrients
(NRC 1998). Animals were evaluated for performance,
gain, intake, and gain to intake) and this data were
reported previously (Oliver et al. 2014).

Sample collection

Piglets were sampled at day 0 (weaning), 14 and 28 of
the study. A rectal swab was taken from each piglet and
was placed in a 15-ml conical centrifuge tube containing
2 ml sterile Difco buffered peptone water (BPW; Becton
Dickinson Co., Sparks, MD). After collection, tubes were
immediately transported to the lab for processing. Tubes
were vortexed vigorously and sample processing was done
as described below for pathogen detection. A 500 µl ali-
quot was used for stx and shiga-toxigenic E. coli (STEC)
detection, a 750 µl aliquot was used for Salmonella
detection, and remainder in tube with swab was used for
Campylobacter detection.

Microbiological analyses

Salmonella analyses

To determine Salmonella, a 750 µl volume was taken
from swab sample tube and transferred to 15-ml conical
tube containing 13 ml tetrathionate broth (Becton Dick-
inson) and capped (Wells et al. 2010, 2012). Tubes were
incubated for 24 h at 37°C. Tubes were mixed well and a
50 microliter aliquot was transferred to 3 ml Rappaport–
Vassiliadis Soya Peptone broth (RVS; Oxoid Ltd, Basing-
stocke, UK) in a deep well 48-well plate. The RVS deep
well plates were covered and incubated at 42°C for 24 h.
A 10 µl aliquot of the RVS enrichment was plated onto
Difco Hektoen-Enteric agar (nHE; Becton Dickinson)
supplemented with 20 µg per ml novobiocin (Sigma-
Aldrich, St. Louis, MO). The nHE plates were incubated
for 24 h at 37°C. Black colonies were picked and plated
onto fresh nHE plate. Isolated colonies were grown in
TSB and confirmed Salmonella by PCR for invA gene (Zi-
emer and Steadham 2003).

Shiga-toxigenic Escherichia coli and virulence genes
analyses

A 500 µl volume was taken from swab sample tube and
transferred to deep well 96-well plate containing 500 µl
of 50% glycerol for determination of stx and STEC. The
samples in glycerol were held for up to 48 h at 2°C. A
500 µl volume was transferred to deep well 48-well plate
containing 2.5 ml brain heart infusion broth (BHI; US
Biological, Swampscoft, MA, USA) for enrichment. The
BHI enrichment plates were covered and incubated for
8 h at 37°C while shaken at 150 rev min$^{-1}$ (Innova 44
Shaking Incubator; New Brunswick Scientific, Edison,
NJ). A 10 µl sample of the BHI enrichment was added to
100 µl of BAX lysis buffer (Dupont Qualicon, Wilming-
ton, DE), 25 µl screened for enterohaemorrhagic E. coli
(EHEC) virulence factors eae, hlyA, stx1, and stx2 using
multiplex PCR in a 50 µl reaction as described previously.
for 23S rRNA gene PCR assays (Eyers et al. 2013) and pen within room being the experimental unit. This experiment was designed as a split-plot with pen as the sub-plot and pen within room being the experimental unit and prevalence for pathogens or pathogenic genes was calculated as a percentage of positive samples per pen. Data were analysed as a 2 × 3 factorial arrangement of treatments within the split-plot design using the GLIMMIX procedure (SAS Institute, Cary, NC). The effects of day, hygiene and dietary treatment, and the interactions, were included in the model as fixed effects. The effects of replication and replication*room were included in the model as random effects. The significance level for all tests was set at \( P < 0.05 \) and tendencies at \( P < 0.10 \).

**Results**

Swab samples from 1287 piglets in 96 pens were collected on 0 day as animals were sorted into pens going into the swine nursery and again on 28 day at the end of the nursery phase for this study. No significant interactions were observed for any of the statistical analyses. *Campylobacter* spp. prevalence in pens was 43.8% at the start of the study, and increased to 70.6% after 28 days in the nursery (\( P < 0.05 \); Fig. 1). More than 90% of the *Campylobacter* spp. positive samples tested positive as *Campylobacter coli*. Samples were screened for *E. coli* O-serogroups O26, O45, O103, anti-*E. coli* O103, anti-*E. coli* O111, anti-*E. coli* O121, anti-*E. coli* O145 and anti-*E. coli* O157:H7 beads; SDIX, Newark, DE, USA). The IMS beads were suspended into 100 \( \mu \)l phosphate buffered saline (Sigma-Aldrich) and diluted 10-fold, and 50 \( \mu \)l of the diluted bead suspension was plated onto STEC differential agar (SDA; Kalchayanand et al. 2013). The SDA plates were incubated for 24 h at 37°C then allowed to rest at room temperature for 30 min prior to evaluation. Presumptive isolated STEC colonies were picked into deep well 96-well blocks with 1 ml TSB and grown 24 h at 37°C. Each putative STEC isolate was confirmed by PCR for specific O-serogroup and virulence factor genes as described above without BAX lysis buffer preparation. For each isolate, 1 \( \mu \)l of culture is heated to 100°C for 15 min in a sealed tube and PCR is performed directly on this preparation.

**Campylobacter analyses**

*Campylobacter* was determined by enrichment from remainder of sample (750 \( \mu \)l) with swab in sample tube. A 10 ml volume of Bolton selective enrichment broth with supplement (Oxoid Ltd) and lysed horse blood cells (Lampire Biological Labs, Pipersville, PA) was added to the sample tube (Wells et al. 2010). Tubes were gently mixed, capped tightly, and incubated 4 h at 37°C followed by 20 h at 42°C. A 20 \( \mu \)l aliquot was plated onto Campy-Cefex agar (Stern et al. 1992) and incubated using MicroAero Pack in AnaeroPack System (Mitsubishi Gas Chemical, New York, NY) for 48 h at 42°C. Presumptive colonies were verified *Campylobacter* positive by agglutination (*Campylobacter* Test Kit; Oxoid) and PCR for 23S rRNA gene PCR assays (Eyers et al. 1993; Fermér and Olsson Engvall 1999). Species assignments were made to the *Campylobacter* isolates using lpxA multiplex PCR assays (Klena et al. 2004).

**Statistical analyses**

This experiment was designed as a split-plot with pen being the experimental unit for dietary treatment (sub-plot) and pen within room being the experimental unit for the room hygiene treatment (whole plot). Pen was the experimental unit and prevalence for pathogens or pathogenic genes was calculated as a percentage of positive samples per pen. Data were analysed as a 2 × 3 factorial arrangement of treatments within the split-plot design using the GLIMMIX procedure (SAS Institute, Cary, NC). The effects of day, hygiene and dietary treatment, and the interactions, were included in the model as fixed effects. The effects of replication and replication*room were included in the model as random effects. The significance level for all tests was set at \( P < 0.05 \) and tendencies at \( P < 0.10 \).
spp. for the piglets in the lysozyme-treated pens, whereas the control- and antibiotic-treated pens increased significantly over the course of the treatment period ($P < 0.05$). Presence of *Campylobacter* spp. was not affected by room hygiene at beginning of the study and similar levels for *Campylobacter* spp. were observed in clean room pens and dirty room pens at the end of the 28-day study (Fig. 3).

The average pen prevalence specifically for STEC O-serogroups O26, O45, O103, O111, O121, O145 and O157 were each $<1\%$ and no effect of treatment was observed ($P > 0.1$; data not shown). The average presence of the STEC virulence genes in pens for *hly*A (haemolysin) and *eae* ( intiminin) in faecal swabs were similar across treatments on 0 day and 28 day (Fig. 4). The average presence in pens of *stx*1/*stx*2 genes was also similar on 0 day across treatments (Fig. 5), but at end of the study on 28 day the average prevalence for these STEC virulence genes in pens differed between control and antibiotic treatment pens ($P < 0.05$) and tended to be lower in the lysozyme-treated pens compared to the control pens ($P < 0.1$). However, when the pen data were analysed as a difference between 0 and 28 days to account for slight differences in initial levels across treatments, no significant differences were observed for *stx*1/*stx*2 genes over the course of the study.

Piglets sorted into clean and dirty rooms had similar percentages of pen samples testing positive for haemolysin and intiminin genes (Fig. 6). The percentage of pen samples testing positive for haemolysin or intiminin did not differ statistically by day 28, nor did the pen values when calculated by difference from 0 to 28 days ($P > 0.1$). Similarly, piglets sorted into clean and dirty rooms had similar percentages of pen samples testing positive for *stx*1 alone or both *stx*1/*stx*2 on 0 day ($P > 0.1$; Fig. 7), and no difference in the percentage of pen samples positive was observed on 28 days or when calculated by difference from 0 to 28 days ($P > 0.1$).
Inclusion of lysozyme in diets of young swine has been shown to improve performance (May et al. 2012; Oliver and Wells 2013; Oliver et al. 2014). The nursery piglets in the current study were fed a control diet or a diet supplemented with lysozyme or with the antibiotic combination chlortetracycline and tiamulin, and animals fed lysozyme or fed antibiotics performed better for weight gain and feed efficiency than the animals fed the control diet (Oliver et al. 2014). In addition, the animals were housed in either clean or dirty (left uncleaned from previous nursery batch) rooms to provide an indirect immune challenge and hygienic stress that reduced weight gain in control piglets but dietary treatments with lysozyme or antibiotics unaffected.

In this study with piglets fed control diets without treatment supplementation, Campylobacter spp. were detected in more than 40% of the faecal samples of piglets at weaning and nearly doubled to 80% following the 4-week nursery period. More than 95% of the Campylobacter spp. isolated was determined to be Camp. coli. We have previously observed high levels of Campylobacter in nursery piglets fed diets without supplemented antimicrobials (Wells et al. 2010). Quintana-Hayashi and Thakur (2012) observed nearly identical results to our current study in faecal samples from piglets at end of farrowing (i.e. weaning; 41%/C13%) and nursery (83%/C17%) phases for piglets in antibiotic-free production systems, and 99%/C18% of Campylobacter isolates were Camp. coli.

Campylobacter have been recovered throughout the gastrointestinal tract and from internal lymph node tissues (Nesbakken et al. 2003) and this pathogen appears to colonize animals at weaning (Harvey et al. 1999). However, the nursery phase appears to be an important phase for Campylobacter transmission as piglets from different litters are comingled. In older pigs sampled after the nursery phase, where Campylobacter prevalence was negligible, increases in Campylobacter prevalence were slow and the herd prevalence was <20% prevalence positive after 8-weeks of growing phase (Wells et al. 2012).

When piglets were monitored for faecal Campylobacter with repeated sampling over time, piglets that were recurr-
Dietary lysozyme in piglets

As noted above, the antibiotic dietary treatment with chlortetracycline and tiamulin did not affect Campylobacter prevalence. Chlortetracycline is a tetracycline derivative with broad-spectrum antimicrobial activity commonly used in swine production but may have little effect against Campylobacter since most isolates harbour resistance (Quintana-Hayashi and Thakur 2012). Tiamulin is a pleuromutilin antibiotic fed to reduce swine dysentery caused by Brachyspira (Treponema) hyodysenteriae (O’Connor et al. 1979; van Duijkeren et al. 2014). Resistance against tiamulin is not widespread but Campylobacter appears to harbour resistance (Lykkeegberg et al. 2007). It would appear from the current study that neither chlortetracycline nor tiamulin impact Campylobacter in nursery swine.

Shiga-toxigenic E. coli, including EHEC are known zoonotic pathogens, and can impact human health (Mathusa et al. 2010; Friedrich et al. 2002). In previous research with older growing pigs possible STEC O-serogroups O26, O103 and O145 were found in 35% of the samples, whereas STEC O-serogroups O111 and O121 were not observed (Wells et al. 2012). In nursery piglets in this current study, 0.5% of the piglets were STEC positive at weaning and <0.1% were STEC positive at the end of the nursery phase. Because the STEC prevalence was low, diet effects could not be demonstrated. In the nursery piglets, we only observed STEC O-serogroup O103 at weaning and O-serogroup STEC O111 at end of nursery phase. It would appear from this current research that STEC O-serogroups O26, O103, O111, O121, O145 and O157 types might not be significant inhabitants in the

Figure 5 Average percentage of animal rectal swab samples in pen testing positive for stx1 (shiga toxin 1) gene or stx1/stx2 (shiga toxin 1 and shiga toxin 2) genes at weaning (day 0), at end of the nursery phase (day 28), and by difference from weaning (day 28-day 0). Control diet (white bars), antibiotic-supplemented diet (light grey bars), and lysozyme-supplemented diet (dark bars). Error bars denote the standard error, and treatment significant differences are signified by different letters above the error bars.

Figure 6 Average percentage of animal rectal swab samples in pen testing positive for hlyA (STEC haemolysin) gene or eae (STEC intimin) gene in pens cleaned (Clean, light bars) or not cleaned (Dirty, dark bars) prior to being housed with piglets. Error bars denote the standard error, and room hygiene significant differences are signified by different letters above the error bars. STEC, shiga-toxigenic Escherichia coli.
piglet during the nursery phase. However, based on the prevalence for stx genes detected in the faecal samples, other STEC serogroups may be present and abundant in the weaned piglet, but decrease after weaning. A recent report regarding swine in China did not observe these specific STEC serogroups, but did observe a significantly high prevalence for stx genes indicating that swine could be a significant reservoir for other STEC O-groups (Meng et al. 2014).

The eae gene encodes intimin, a virulence protein associated with pathogenic E. coli, and as such can be used as an indicator for EHEC and enteropathogenic E. coli (EPEC). The presence of this gene increased significantly in the faeces during the nursery phase. As EHEC bacterial grouping include STEC, and the presence of stx genes decreased over the nursery phase, much of the increase in eae is likely attributable to the EPEC pathogen groups. The role that EPEC might have in the young piglet is not well defined and this is the first research to indicate that, based on eae presence, EPEC might be present in many young piglets. Neither antibiotic nor lysozyme treatment affected this eae prevalence and thus unlikely to have affected EPEC.

Cleanliness of the room the piglets were weaned into had little effect on the specific pathogens monitored, even though gain was reduced in the control animals (Oliver et al. 2014). Although dietary treatments with lysozyme or antibiotics ameliorated the reduction in gain observed with control piglets in the dirty rooms (Oliver et al. 2014), we did not see an increase in pathogens in the dirty rooms for the control animals when we collected our bacterial samples after 4 weeks of housing. Rooms that were cleaned before animals were penned had numerical reductions in pathogen indicators such as hlyA and stx genes, but neither reduction was statistically significant. However, we must note that room hygiene on day of animal placement may have had a greater impact on pathogen load in animals earlier in the nursery phase (e.g. weeks 1 and 2) when we did not sample.

Lysozyme previously has been shown to reduce ETEC in challenged piglets (Nyachoti et al. 2012). However, in a small study with young piglets, lysozyme did not reduce E. coli in the ileum (Maga et al. 2012), so lack of an effect on some of our pathogenic E. coli indicators was not unexpected. Maga et al. (2012) also noted an elimination of Campylobacter in their small microbiome study with piglets fed lysozyme, and our study specifically shows that Campylobacter are significantly reduced with lysozyme. Campylobacter spp. are likely resistant to the enzymatic action of lysozyme (Hughey and Johnson 1987), so the potential mechanisms likely involve changes in the microbial ecology that affects Campylobacter (Maga et al. 2012).

Campylobacter annually account for 2-4 million illnesses, and c. 80% of these illnesses are foodborne transmissions (Mead et al. 1999). Campylobacteraceae were isolated from 15% of retail pork tested in a recent study from Ireland (Scanlon et al. 2013), and Camp. coli was species most often observed. Campylobacter were observed in 6.7% of plant samples and 1.3% of retail pork in the United States (Duffy et al. 2001) and Camp. coli in 1.3% of retail pork in New Zealand (Wong et al. 2007). Reduction in Campylobacter shedding early in the swine production cycle with lysozyme when animals appear most susceptible to colonization could reduce pathogens at harvest.

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Conflict of Interest

The authors declare that no conflict of interest exists.
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