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Effect of tetracycline dose and treatment-mode on selection of resistant coliform bacteria in nursery pigs

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Running title: Selection for tetracycline resistant coliforms

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ABSTRACT

This study describes results of a randomized clinical trial investigating the effect of oxytetracycline treatment dose and mode of administration on selection of antibiotic resistant coliform bacteria in fecal samples from nursery pigs. Nursery pigs (pigs of 4-7 weeks of age) were treated with oxytetracycline against *Lawsonia intracellularis* induced diarrhea in five pig herds. Each group was randomly allocated to one of five treatment groups: oral flock treatment with (i) high (20 mg/kg), (ii) medium (10 mg/kg) and (iii) low (5 mg/kg) dosage, (iv) oral-pen-wise (small group) treatment (10 mg/kg), and (v) individual intramuscular injection treatment (10mg/kg). All groups were treated once a day for five days. In all groups, treatment caused a rise in numbers and proportion of tetracycline resistant coliform bacteria right after treatment, followed by a significant drop by the time where pigs left the nursery unit. Counts and proportion of tetracycline-resistant coliforms did not vary significantly between treatment groups, except immediately after treatment, where the highest treatment dose resulted in the highest number of resistant coliforms. A control group treated with tiamuline did not show significant changes in number or proportion of tetracycline resistant coliforms. Selection for tetracycline-resistant coliforms was significantly correlated to selection for ampicillin- and sulfonamide-resistant, but not to cefotaxime-resistant strains. In conclusion, difference in dose of oxytetracycline and the way the drug was applied did not cause significantly different selection of tetracycline resistant coliform bacteria, under the conditions tested.

47 **IMPORTANCE**

48 Antimicrobial resistance is a global treat to human health. Treatment of livestock with
49 antimicrobials has a direct impact on this problem, and there is a need to improve the ways that
50 we use antimicrobial in livestock production. We hypothesized that antibiotic resistance
51 development following treatment of diarrhea in nursery pigs could be reduced by either lowering
52 the dose of oxytetracycline or by replacing the commonly used practice of flock treatment with
53 individual or small group treatments, since this would reduce the number of pigs treated.
54 However, the study showed no significant difference between treatment-groups with respect to
55 the number or proportion of tetracycline resistant coliforms selected. The most important
56 conclusion is that under the practical field conditions, there will be no added value in terms of
57 lowering resistance development by exchanging flock treatment with individual or small group
58 treatment of nursery pigs. The reason for lack of effect of single animal treatment is probably that
59 such animals share the environment with treated animals and take up resistant bacteria from the
60 environment.

61 **INTRODUCTION**

62 Antibiotic resistant bacteria are a recognized threat to public health. They cause increased
63 mortality of infectious diseases (1), higher cost of treatments due to prolonged recovery time and
64 use of more expensive antibiotics, and they increase the need for, and thus the cost of, biosecurity
65 in hospitals (2). The same is true in veterinary medicine, where resistant bacteria increase the cost
66 of treatment and may lead to animal welfare problems due to unsuccessful treatments (3, 4). For
67 these reasons, it is important to reduce selection of antibiotic resistant bacteria as far as possible.
68
69 Antibiotic resistance in the animal sector can reach humans through the food chain, the
70 environment, and by direct and indirect contact to animals and animal products (5, 6). While
71 antibiotic resistant pathogenic bacteria are the immediate threat, antibiotic resistance in
72 commensal bacteria of food animals is considered a reservoir of antibiotic resistance genes that
73 may aggravate the problem (7). For example, surveillance results show 36 % tetracycline
74 resistance in commensal *E. coli* from pigs in Denmark (8). Thus, minimizing resistance in the
75 commensal flora of food animals may be important in order to reduce the risk to human health
76 from use of antibiotics in the livestock industry.
77
78 Enteric disease is very common in industrial pig production, especially in the nursery period (9). As
79 a consequence, the highest single indication for use of antibiotics in the Danish livestock industry
80 is treatment of diarrhoea in pigs in this period, and 42 % of total antibiotic use for pigs in Denmark
81 is for this indication, with tetracycline as the most used drug class (8). In order to reduce the total
82 amount of antibiotics used in the pig industry, it is important to find more intelligent ways to treat
83 enteric diseases in the nursery period.

84

85 Treatment of nursery pigs against diarrhea is often carried out using oral flock-treatment, where a
86 full section of pigs is treated with antibiotic in the feed or water, when disease is seen in a pre-
87 fixed proportion of the population. The justification for this approach is that apparently healthy
88 animals in close proximity to diseased individuals are likely to be sub-clinically infected and will
89 progress to develop clinical disease(10, 11). This batch treatment regime exposes the commensal
90 intestinal flora of all pigs to a selective pressure, which is presumed to increase the total amount
91 of resistant bacteria in farms significantly, when compared to treatment of individual pigs (12, 13).
92 However, to the authors' knowledge, this has not been investigated under field conditions.

93

94 Apart from the treatment regime (flock versus individual treatment), selection of antibiotic
95 resistant bacteria are influenced by factors such as treatment-dose(14, 15), number of animals
96 housed together(16), and other management factors (17-21). Among these factors, mathematical
97 modeling suggests that dose may play a particularly important role for selection of resistant
98 coliform bacteria following tetracycline treatment (22). Such modeling predicts that consumption
99 of high doses of antibiotics is positively correlated to a subsequent high proportion of resistant
100 fecal coliforms and to a longer time required for the proportion of resistant bacteria to non-
101 resistant bacteria to return to pre-treatment equilibrium.

102

103 The aim of the present study was to determine the effect of five different oxytetracycline (OTC)
104 treatment regimens with varying doses and varying modes of treatment on occurrence of
105 antibiotic resistant coliform bacteria in nursery pigs in a randomized clinical field trial.

106

MATERIAL AND METHODS

Clinical field trial

The set-up of the randomized clinical field trial has previously been described in two studies measuring the efficacy of varying OTC treatment doses and treatment regimes (administration routes) for *Lawsonia intracellularis* diarrhea (11, 23), and the reader is referred to those two studies for a comprehensive description and for calculation of sample size. In brief, five herds with history of *L. intracellularis* induced diarrhea were pre-selected. Each herd had between 2300 and 3600 pen places, and an all-in all-out batch production in sectioned compartments. The flooring consisted of 1/3 solid floor and 2/3 slatted floor. In each herd 15 batches were included in the study after being weaned. At clinical signs of diarrhoea they were treated as described below and followed until at least the end of the seven-week nursery period. Where possible, pigs were also re-sampled in the week prior to slaughter. A batch was defined as a group of nursery pigs weaned at the same time and housed in a number of pens within one stable. In each batch 15 animals, randomly distributed over pens, were selected as trial pigs. The allocated treatment regimen, however, was applied to all pigs in the section as previously described (23). All trial pigs were ear tagged with a unique ID.

When a new batch was weaned, it was monitored once a week for outbreak of diarrhea. When an outbreak was detected, defined as at least 25 % pigs showing clinical signs of enteritis (watery feces, scouring of the back and/or a poor body score), pigs were subjected to one of five treatment regimens: oral flock-treatment in water with a standard dose of 10 mg/kg OTC (Terramycin®Vet. 20 %, Orion Pharma) for five days (ND, normal dose), oral flock-treatment in water with 20 mg/kg OTC for five days (HD, high dose); oral flock-treatment in water with 5 mg/kg

130 OTC for five days (LD, low dose), oral pen-wise (small group) treatment in water with a standard
131 dose of 10 mg/kg OTC for five days (PW) or individual intra muscular treatment (IM) of pigs with
132 diarrhea with a standard dose of 10 mg/kg OTC for five days. Pen-wise treatment was initiated
133 when more than 25% of pigs in a pen had clinical signs of enteritis, while intramuscular treatment
134 was initiated in animals showing clinical signs of enteritis. Flock treatment was administered
135 through the common water supply, whereas pen-wise treatment was administered in water in
136 troughs to pigs also having access to medicine-free water through the common water supply. Each
137 treatment was repeated three times in each herd, and the order of the treatments was chosen at
138 random. The number of pigs included from each farm in the different groups can be seen in Table
139 1. Outbreaks of diarrhea, and thus initiation of treatment, occurred from 2 to 6 weeks after
140 weaning.
141
142 In order to be able to estimate selection of tetracycline-resistant coliform bacteria in pigs not
143 exposed to tetracycline treatment, 25 pigs in one additional batch in herd A, suffering from an
144 outbreak of diarrhea, were treated by oral flock-treatment with a standard dose (8 mg/kg) of
145 tiamuline (Denagard®Vet, Novartis, Copenhagen, Denmark) for three days.
146
147 All pigs in the trial received 2500 ppm zinc-oxide supplement in the feed the first 14 days after
148 weaning. Farmers were asked to keep record on all antibiotic treatments carried out in the herd
149 before and during the field trial. This allowed controlling for confounding due to additional
150 antibiotics treatments. A total of 889 pigs received antibiotic treatment before T_1, and 402 pigs
151 received treatment during the trial period between T_2 and T_3 (Supplementary material, Table S1).
152 The treatments were farm specific: At one farm, pigs did very rarely received additional

153 treatments, neither before nor after the study treatment protocol. On three of the farms, the
154 farmer regularly treated pigs with colistin shortly after entering the nursery unit, i.e. shortly before
155 the trial period. On two of these three farms, other treatments than this was rare, while the
156 remaining farmer additionally treated some pigs with doxycycline between T_2 and T_3. Finally, on
157 one farm, pigs were often treated with amoxicillin before T_1, but with no other treatments
158 between T_2 and T_3. Antibiotic treatments between T_3 and T_4 were not consistently recorded and
159 were thus not taken into account in the analyses. When analyzing for the effect of pre- and post-
160 treatment with antibiotics there were no significant effect of the three largest additional
161 treatment groups (colistin treatment before T_1, amoxicillin treatment before T_1, and doxycycline
162 treatment after T_2) on absolute number of tetracycline resistant coliform bacteria, proportion of
163 tetracycline resistant coliforms or change in proportion of tetracycline resistant coliforms, and we
164 concluded that these treatments were not confounders in our study.
165
166 **Sampling**
167 Faecal samples were collected from all trial pigs between October 2011 and April 2013, either at
168 defecation or per rectum. Samples were collected from all pigs at three time points: Time point 1
169 (T_1) was the first day of treatment, immediately before antibiotic administration, Time point 2 (T_2)
170 was two days after the end of the five day treatment, and Time point 3 (T_3) was when pigs were
171 moved from the nursery stables to finisher stables, either in the same herd or in other herds.
172 When possible (n=296), a fourth sample (T_4) was collected from rectum 1-7 days before slaughter.
173 Samples were stored in 40 ml containers and shipped to the laboratory in cooled boxes.
174
175 **Bacterial quantification**

176 10^{-1} w/v suspensions were made from approximately 1 g of fecal sample in PBS, and one ml of this
177 suspension was used for preparation of 10-fold serial dilutions from 10^{-2} to 10^{-4}. Twenty µl of each
178 dilution was plated on four MacConkey agar plates (Oxoid Ltd, Thermo Scientific, Roskilde,
179 Denmark), containing different antibiotics (16 mg/L tetracycline, 16 mg/L ampicillin, 256 mg/L
180 sulfamethizole, or 2 mg/L cefotaxime), and on a MacConkey agar plate without added antibiotics,
181 using the principle of the drop plate method (24) with a 4x4 grid. Antibiotics were purchased from
182 Sigma (Sigma-Aldrich, Copenhagen, Denmark). Antibiotic concentrations were based on EUCAST
183 epidemiological cutoffs for *E. coli*, as recommended in (25).
184
185 Plates were incubated overnight at 37 ^{o}C followed by enumeration of dark red colonies with a size
186 >0.5 mm. To confirm that colonies counted were coliforms, 100 colonies were randomly picked
187 and subjected to species identification using Matrix-assisted laser desorption-ionization time-of-
188 flight mass spectrometry (MALDI-TOF MS) (Vitek MS RUO, bioMérieux, France). All colonies were
189 shown to belong to the species *E. coli* (data not shown). For each plate, a count expressed as
190 colony-forming units (CFU) per gram were determined using a weighed arithmetic mean based on
191 the two highest dilutions showing the separation between colonies, and finally CFU/g was Log_{10}
192 transformed. The detection limit for the method used was 500 colony forming units per gram of
193 feces, corresponding to $Log_{10} = 2.70$.
194
195 In order to validate that this method distinguished between tetracycline resistant and susceptible
196 isolates, at representative collection of commensal *E. coli* from Danish pigs, previously used to
197 model the growth response of *E. coli* to antimicrobials (26) were tested. They consisted of 32
198 isolates with MIC between 0.24 ug/ml and 2.0 ug/ml (sensitive isolates) and 16 isolates with MIC

199 between 16 and 512 ug/ml (resistant isolates). They were grown in LB broth (Oxoid Ltd, Termo-
200 Scientific, Roskilde, Denmark) at 37 °C overnight. Ten-fold dilutions were made in PBS, and
201 dilutions were plated on McConkey agar without tetracycline and McConkey agar containing 16
202 ug/ml tetracycline. CFU was counted after 20 hours of incubation at 37 °C and the difference
203 between CFU estimation on the two plates was determined for each strain.
204
205 **Statistics**
206 The clinical trial was set up as a five-treatment-trial, and the statistical analysis for differences
207 between groups with respect to selection for resistant coliform bacteria was therefore carried out
208 with all groups in one analysis. The effects of the different treatment protocols on the number of
209 antimicrobial resistant bacteria were analyzed using either Log_{10} transformed counts of resistant
210 bacteria or testing for significant changes in the square root of the proportion or change of
211 proportion of resistant bacteria, i.e $\sqrt{\frac{R_{Tx}}{C_{Tx}}}$ or $\sqrt{\frac{R_{Tx}}{C_{Tx}} / \frac{R_{Ty}}{C_{Ty}}}$ where *R* is the CFU/g count on the
212 antibiotic *R* plate at time *Tx* or *Ty*; and *C* is the total CFU coliforms at time *Tx* or *Ty*. Due to the
213 uncertainty of CFU counts, proportions could be higher than one; however, proportions above two
214 were considered outliers and excluded. The square root transformation was selected to improve
215 the normality of the residuals of the tests. Pigs with drop out data (data missing at any of the time
216 points T_1-T_3) were removed from the study, while drop out of data for T_4 had to be accepted
217 because only a small fraction was available for sampling.
218
219 Analyses were performed by Linear Mixed-Effects Models to determine significant differences in
220 resistant coliform bacteria and fraction of resistant bacteria from T_1-T_3 using lmer from the

package lme4 in R version 3.2.2 (27). When testing for the effect of treatment, farm ID and the interaction between farms and treatment were included as fixed effects, while batch of pigs was included as a random effect. To identify the significant effects, back wise elimination was performed using the step function and AIC (Akaike information criterion). Confidence intervals (CI) were found by bootstrapping using bootMer from the lmerTest package. Test of differences of multiple groups at single time points was done using Kruskal-Wallis Rank Sum Test (kruskal.test), while test for differences in numbers or proportions of resistant bacteria between different time points within group was done using Student's t-Test (t.test), and correlation was tested using Pearson's product moment correlation coefficient (cor.test), all in R (27).

Ethical statement

The clinical trial was approved by the Danish Medicines Agency (License no. 2011090862 / 2012053751), and the participating herd owners signed a written "Owner informed consent" explaining the scope of the field trial.

RESULTS

Effect of treatment-dose and treatment-regimes with OTC on selection of tetracycline resistant coliform bacteria

In total, 224 pigs received high dose as flock-treatment (HD), 241 pigs received normal dose as flock-treatment (ND) and 224 pigs received low dose as flock-treatment (LD). 241 pigs belonged to the pen-wise treatment (PW) group and 221 pigs to the individual intra muscular treatment (IM) group. In total, samples from 1167 animals were analyzed (Table 1).

244

245 The method used to count consisted of McConkey agar with added tetracycline. In order to
246 validate that this method distinguished between terracyline resistant and tetracycline sensistive
247 coliform bacteria, 49 coliform strains were plated on agar with and without antimicrobials. The
248 CFUs of cultures of sensitive strains were 7.0 ± 0.5 Log_{10} units lower on plates containing
249 tetracycline than on plates without antibiotic, and only one strain showed colonies. The
250 corresponding values for resistant strains were difference of 0.3 ± 0.5 Log10 units, and all strains
251 showed colonies (Supplementary material, Figure S1).

252

253 *Effect of OTC dose on selection of tetracycline resistant coliform bacteria*

254 As can be seen from figure 1, variation between pigs with respect to Log_{10} CFU/g tetracycline-
255 resistant coliform was large in all groups at all time-points. The average number of coliform
256 bacteria and tetracycline resistant coliform bacteria did not differ significantly between groups
257 before initiation of treatment (T_1) (Supplementary material, Figure S2 and Figure 1). On average,
258 pigs carried 6.0 ± 0.8 Log_{10} CFU/g total coliform bacteria and 5.5 ± 0.9 log_{10} CFU/g tetracycline
259 resistant coliform bacteria at T_1. Treatment irrespective of dose caused a significant rise in the
260 number of tetracycline-resistant coliforms at T2 followed by a significant drop towards the time
261 where pigs left the nursery unit (T_3) (paired one-sided t-test, $p<0.0005$). The rise from T_1 to T_2 was
262 highest in the HD group. In all three dose-groups, the average Log_{10} CFU/g tetracycline-resistant
263 coliform bacteria at slaughter were significantly below the T_1 value (paired t-test, one-sided
264 $P<0.05$). The proportions of tetracycline-resistant coliforms also increased significantly in all
265 groups following treatment (paired one-sided t-test, $p<0.005$), but dropped to below the starting

point at slaughter (T_4) (Figure 2). The differences between proportions at T_1 and T_4, however, were not significant.

We analyzed for the overall effect of treatment-dose on the change in proportion of tetracycline resistant coliforms between T_1 and T_3 using a mixed linear model. In this analyses farm was included as a fixed effect and batch as a random effect. We found no significant effect of treatment-dose. The only significant effect in the model was the random effect of batch.

Effect of treatment mode on selection of tetracycline-resistant coliform bacteria

The use of PW or IM treatment strategies, with the aim to treat fewer pigs than by flock-treatment, did not significantly affect the number of tetracycline-resistant coliform bacteria selected or the proportion of resistant coliforms at different timepoints. As for oral batch-treatment, the number and proportion of resistant bacteria at slaughter (T_4) was lower than before treatment (Figure 1 and Figure 2). The only significant effect in the logistic model here, too, was the batch effect.

In both the PW and the IM groups some pigs did not receive treatment (n=26 and n=79) (Table 1). The mean Log_{10} CFU/g tetracycline resistant coliforms in these groups at T_3 (5.0 Log_{10} CFU/g and 5.2 Log_{10}CFU/g) were lower than the mean Log_{10} CFU/g tetracycline resistant coliforms in the treated pigs (5.4 Log_{10} CFU/g and 5.3 Log_{10}CFU/g). The difference was significant in the PW group but not the IM group (two-sided t-test, p=0.01 and p=0.39) (Supplementary material, Figure S2). At T_4, there were no significant differences between treated and untreated pigs in PW group (p=0.06).

289 **Control treatment with tiamuline**

290 For animal welfare reasons, the clinical trial did not contain a non-treated, control group. Instead,
291 a control experiment, where pigs suffering from *Lawsonia intracellularis* induced diarrhea were
292 treated with an unrelated antibiotic, tiamuline, was conducted. As shown in Figure 3, treatment
293 with this drug did not result in a significant increase in the number of tetracycline-resistant
294 coliforms. Similarly, the proportion of tetracycline-resistant coliform bacteria did not change as a
295 result of treatment. This showed that the effects seen after OTC treatment were specifically
296 related to the use of this drug, and did not represent normal development in the coliform flora of
297 nursery pigs.

298

299 **Co-selection for other antibiotics**

300 In all treatment groups, there were no significant differences in number of AMP, SUL and CTX
301 resistant coliforms before initiation of treatment (data not shown). The counts showed a close,
302 highly significant correlation between the changes in proportion of tetracycline-resistant coliforms
303 from T_1 to T_2 and changes in proportion of ampicillin and sulfonamide resistant coliforms between
304 the same time points (Pearson's product moment correlation coefficient, $P<0.0001$), indicating
305 that these resistances were selected together. On the contrary, no significant correlation was
306 observed between tetracycline- and cefotaxime-resistant coliforms (data not shown).
307 Nevertheless, 282 out of the 1167 pigs analyzed were found to carry cefotaxime-resistant
308 coliforms at T_1 (average Log_{10} CFU in positive pigs was 3.2 with a range from 2.7 (detection limit) to
309 7.0 Log_{10} CFU/g), and at least one pig in all farms were positive for cefotaxime-resistant coliforms.

310

311 **Discussion**

312 The purpose of this study was to estimate the effect of OTC treatment dose and treatment
313 regimes on selection of tetracycline resistant coliforms in nursery pigs under field conditions. We
314 used an easy agar-dilution counting method, based on including breakpoint concentrations of OTC
315 to McConkey plates. This method has previously been validated for use with McConkey agar and
316 added tetracycline (28), however, with 8 ug/ml as the added concentration of tetracyline. We
317 performed our own method validation with 16 ug/ml tetracycline added to the plates, and found
318 that this, too, gave 100 % ability to distinguish between tetracycline sensitive and resistant
319 coliforms.
320
321 In accordance with a previous study (14), we observed a significantly higher number of
322 tetracycline resistant *E. coil* right after the treatment in the group receiving the highest dose, but
323 in contrast to the previous publication, the concentration and proportion returned to the starting
324 level within 3-4 weeks. Proportions of resistant coliforms at T_4, corresponding to shortly before
325 slaughter and thus the time where the pigs enter the food chain, was significantly below the
326 before treatment level. Thus, pigs receiving a high dose of tetracycline may shortly show higher
327 level of resistant bacteria, but according to our results, they do not possess a higher risk of
328 transfer of resistant bacteria to consumers.
329
330 Reports on proportion of tetracycline resistance in randomly collected *E. coli* from pigs in Denmark
331 have been published since the 1970ties (29). Comparison between these old studies and results of
332 the current surveillance program in Denmark (30) shows that the mean proportion of tetracycline
333 resistant commensal *E. coli* has varied over the years, however, it seems never to clime above
334 approximately 40 %. A possible reason for the minimal selective effect of dose in our study may be

335 the very high starting concentrations of resistant bacteria. While this is representative for
336 proportions of tetracycline resistant commensal *E. coli* in pigs in Denmark (30), it is much higher
337 than the 1-10 % chlortetracycline-resistant *E. coli* detected by Delsol et al (14) prior to their
338 experiment. Our results may thus not be representative for farms with an initial lower
339 concentration of tetracycline-resistant bacteria. Compared to previously published studies, a high
340 number of pigs were included in the present study, and conclusions must be considered strong.
341 Still, the trails were only conducted in five different herds with quit similar management practices.
342 We cannot rule out that under very different management practices, results would have been
343 different.
344
345 Previous studies on the effect of dose on selection of resistance have generally been concerned
346 with differences between therapeutic and sub-therapeutic concentrations of antibiotics (see
347 meta-analysis (31)). In contrast, we considered therapeutic doses. Putting results together, and
348 including studies from poultry as well, there seems to be minimal effect of treatment dose on
349 selection of resistant indicator bacteria (31, 32). This indicates that within quit broad ranges,
350 veterinarians might change dose to achieve a better treatment efficacy, without changing the
351 selection of resistant bacteria significantly. It should be noted that while 5 mg/kg, corresponding
352 to the low dose used in the current study, is sufficient to reduce *L. intracellularis* below the
353 threshold for pathological changes in the intestine of pigs, it takes 10 mg/kg to eliminate the
354 bacterium to non-detectable levels (23).
355
356 On a population level, there is a direct association between the intensity of use of antibiotics and
357 the proportion of bacteria resistant to such antibiotics. This has been demonstrated for clinical as

358 well as indicator bacteria and from both humans (33, 34) and farm animals (35), though the
359 relation is not always straight forward (36). As a consequence, there is a tendency to argue against
360 flock treatment of farm animals. A large proportion of the reduction in amount of antimicrobials
361 used in the Netherlands to treat farm animals has been reported to be due to restricted use of
362 flock treatment (37), and legal restrictions specifying certain pre-conditions on use of flock
363 medication have been gradually introduced in Denmark. Although phasing out oral flock-
364 treatment leads to less antibiotic usage, it has never been thoroughly investigated whether this
365 also leads to less resistance under field conditions, where untreated animals are housed in close
366 proximity to treated animals, and we tried to answer this question in the current study.
367
368 Surprisingly, we did not observe any significant differences in selection of tetracycline resistant
369 coliform bacteria when we compared oral flock to oral pen-wise (small group) and single animal
370 IM treatments. This is difficult to explain, given that the overall use of OTC was 15 % and 44 %
371 lower in the PW and IM treatment groups. A detailed analysis of our results showed that
372 untreated pigs in the PW group, but not in the IM group, had significantly lower counts of
373 tetracycline resistant coliforms than the treated pigs in the same groups. The most like
374 explanation for the lack of difference in in the individual treatment group is that they shared the
375 environment (the pen) with treated pigs, and thus were exposed to high number of tetracycline
376 resistant coliforms that were excreted from treated pigs. Contrary to this, untreated pigs in the
377 PW group always shared the pen with untreated pigs.
378
379 The lack of overall difference between PW and ND groups, we believe, is simply a matter of
380 numbers. The vast majority of pigs in the PW groups got treated, because the pen fulfilled the

criterion for treatment against diarrhoea. In that respect, our study confirms previous observations that once diarrhoea is observed in a fraction of the nursery pigs, there is a high risk that the remaining pigs are sub-clinically infected (10). Taken together, our results, nevertheless indicated that a form of treatment, where treated pigs are separated from untreated pigs, might be a better strategy for reducing antimicrobial resistance than individual treatment, where treated and untreated pigs share the same pen. PW and IM treatments with OTC have been shown to be ineffective compared to flock-treatment for treatment of *L. intracellularis* diarrhoea (11). When this observation is combined with our results, continued use of oral flock-treatment seems justified, at least as far as conditions are similar to those investigated in the current study. In the study of treatment efficacy (11), the authors argued that oral flock-treatment may be needed as long as there are no good, rapid and precise diagnostic methods for detection of individual pigs with intestinal disturbance, since pigs with intestinal disturbance may go unnoticed with current diagnostic procedures. This puts emphasis on improved diagnostics corresponding well to the WHO action plan against antimicrobial resistance, which emphasise the need for development of improved diagnostic tests in the fight against antibiotic resistance (38). The results of the current study might also indicate that measuring antibiotic consumption is not always a good surrogate for measuring antimicrobial resistance, even though this is currently one of the cornerstones in national surveillance programs on antibiotic resistance.

For animal welfare reasons, we could not leave pigs untreated when outbreaks of diarrhoea was present. To be able to control for natural development in the coliform flora, we chose instead to treat a batch with tiamuline, a drug belonging to the groups of pleuromutilins and used exclusively in veterinary medicine. As this drug does not select for tetracycline resistant coliforms, this group

could be used to create a baseline for natural fluctuation in numbers and proportions of tetracycline resistant coliforms in nursery pigs. The results showed that the fluctuations we observed in tetracycline treated pigs in the clinical trials were associated with the OCT treatment and were different from the fluctuations in pigs treated with tiamuline.

Langlois et al. (39) showed that pigs in herds with a history of previous routine use of antibiotics developed higher numbers of tetracycline-resistant coliforms following chlortetracycline treatment than pigs from another herd without such a history. During and before the current clinical trial, farmers were allowed to treat pigs for other diseases, when needed. Treatments between birth and T_1 may very well influence selection between T_1 and T_2 by having pre-selected for tetracycline resistant coliforms. However, we systematically collected data on consumption of antibiotics in the period from T_1 to T_3 and analysed for the effect of pre- and post-treatment with other antibiotics on selection for tetracycline resistant coliforms. The results showed no significant effect of the three most commonly additional treatments and we ruled out additional treatments as a confounding factor. After time point T_3, pigs were distributed to different fattening units, and only a fraction of pigs were re-sampled at T_4. No records on antibiotic use were available to us covering the time periods from birth to T_1 and between T_3 and T_4. We cannot rule out that treatment between T_3 and T_4 may be the reason for lack of differences between groups at T_4. However, in general, number of treatments in the fattening period are far below the number in the nursery period in Danish pig production (8), making this less critical for the current study.

The fact that flock and pen-wise (small group) treatment was carried out as water medication introduced an uncertainty with regard to dose obtained by the individual pig. We ensured that the

427 dose given to the flock and the pen was consumed (in total), but we could not ensure that all pigs
428 received equal treatment. This means that dose in flock treated and pen-wise treated groups is an
429 average of pigs, and there will be variation between pigs. Similarly, treatments (T_1) were initiated
430 when the clinical inclusion criterion was fulfilled, while T_3 (end of the nursery period) was a fixed
431 date for each pig. This introduced variation in the duration of the period between T_1 and T_3, and
432 this too may be a factor in lack of significant differences between treatments. On the other hand,
433 this is the situation in real life, and our results represent the naturally occurring variation in dosing
434 and treatment time under field conditions.
435
436 Besides being tetracycline resistant, commensal *E. coli* from food animals in Denmark are
437 commonly resistant to ampicillin and sulphonamides (8), indicating co-selection, and a study from
438 the United States indicated that tetracycline treatment of calves could lead to co-selection for
439 resistance genes encoding 3rd and 4th generation cephalosporin resistance (40). It has been
440 reported that commensal tetracycline-resistant *E. coli* are often resistant to ampicillin and further
441 they may carry class-1 integrons encoding sulfonamide resistance genes (41). To test whether
442 tetracycline treatment resulted in specific increase of coliforms with other resistance markers, all
443 samples were also cultured on MacConkey agar containing ampicillin, sulfonamide or cefotaxime.
444 The latter drug was included to investigate possible selection of extended-spectrum beta-
445 lactamase (ESBL)-producing bacteria, which constitute a growing health concern (42).
446 In the current study, selection of tetracycline-resistant coliforms from T_1 to T_2 was significantly
447 associated with selection for ampicillin- and sulphonamide-resistant coliforms. Since we have not
448 characterized the bacteria counted in the current study, we cannot prove that this is co-selection
449 caused by co-localization of the resistance genes, but the observation is hard to explain by any

450 other mechanisms. One of the most prominent antibiotic resistance threats to human health is the
451 growing prevalence of ESBL producing Gram-negative bacteria (43). In the current study we found
452 that ESBL producing coliforms could be identified in all farm and on average approximately 20 % of
453 the pigs were shown to be carriers. However, there is currently no indication that pigs are and
454 important reservoir for ESBL infection in humans in Denmark (8), and based on our results, the use
455 of tetracycline can be ruled out as a (co)selection factor for such bacteria. The Danish pig industry
456 does not use cephalosporin drugs, and due to this the prevalence of ESBL has decreased rapidly in
457 recent years (35).
458
459 Several studies have been published recently, modelling development of tetracycline resistance in
460 pigs following different treatment scenarios (22, 44-46). Such models have been fed with data on
461 growth responses in *E. coli* to different concentrations of tetracycline. In relation to our study, the
462 multi-strain, multi-pig model by Græsbøll et al. (22) is the most relevant. This model predicts, that
463 high dose will results in a higher proportion of tetracycline resistant bacteria than low dose. In that
464 sense our field study is in agreement with the results of the model. However, the modelling also
465 predicts that the proportion will return to pre-treatment level in a dose dependent manner. This
466 prediction was not confirmed by our field study. At T_3 there was no significant difference between
467 treatment groups.
468
469 Measuring resistance in coliform bacteria is a widely used method for studies of development of
470 antibiotic resistance in bacterial populations, both in the society in general and in intervention
471 studies (47), but it is a narrow approach. It is therefore indicated to make follow up studies where
472 one looks at the changes in the microbiome in general, since not only coliform bacteria will be a

473 risk for transfer of resistance genes to human pathogenic bacteria through the food chain. Such
474 studies should preferably be carried out using culture independent techniques.
475
476 In conclusion, the current study showed that dose of oxytetracycline during flock treatment and
477 mode of application did not have a significant influence on the selection of coliform bacteria in the
478 intestine of nursery pigs, under the conditions tested. This means that doses can be set putting
479 emphasis on consideration to efficacy and prize of treatment, and that, from an antibiotic
480 resistance point of view, there appears to be no benefits from using single animal treatment,
481 unless treated animals are separated from non-treated pen-mates.
482

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488

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617

618

619 **Table 1.** Overview of number of pigs included in the study in each treatment group, as distributed on the

620 five participating farms

	Treatment													
	Oral batch-treatment high dose HD		Oral batch-treatment normal dose ND		Oral batch-treatment low dose LD		Oral pen-wise treatment PW Treated pigs		Oral pen-wise treatment, untreated pigs		Individual injection treatment IM treated pigs		Individual injection treatment untreated pigs	
Farm	T1-T3[a]	T4[b]	T1-T3	T4	T1-T3	T4	T1-T3	T4	T1-T3	T4	T1-T3	T4	T1-T3	T4
A	45	19	46	17	45	20	40	20	21	6	24	10	21	6
B	60	33	30	23	45	29	37	23	8	5	26	11	19	17
C	44	18	59	30	44	12	43	20	1	1	22	11	18	11
D	45	5	45	13	45	0	46	6	0	0	24	1	21	1
E	46	0	61	1	45	0	38	0	7	0	28	0	18	0
Total	240	75	241	84	224	61	204	69	37	12	124	33	97	35

621 T1 – T4 refer to the time points where samples were obtained. T_1 was immediately before treatment, T_2

622 was to days after end of treatment, T_3 corresponded to the time where pigs left the nursery unit, and T_4

623 was 1-4 days before slaughter.

624

625 **Legend to figures.**

626

627 **Figure 1.** Box plot illustrating Log_{10} CFU/g tetracycline resistant coliforms in fecal samples from pigs
628 at different time points relative to treatment with different doses of OTC or given OTC by different
629 modes of treatment. Normal, Low and High refer to groups of pigs subjected to five days of oral
630 OTC batch treatment using 10 mg/kg (ND), 5 mg/kg (LD), and 20 mg/kg (HD) dosages, respectively.
631 Injection (IM) and Pen (PW) refer to groups treated with 10 mg/kg OTC for five days individually by
632 injection and pen-wise. T1-T4 refers to the time points where fecal samples were obtained: T1:
633 immediately before treatment, T2: two days after end of treatment, T3: when pigs left the nursery
634 unit, T4: 1-7 days before slaughter. The boxes indicate the interquartile range. The open circles
635 indicate data points more than 1.5 times the interquartile range from the median.

636

637 **Figure 2.** Box plot illustrating the square root of proportions of tetracycline resistant coliforms in
638 fecal samples from pigs at different time points relative to treatment with different doses of OTC
639 or with different treatment modes. Normal (ND), Low ((LD) and High (HD) refer to groups of pigs
640 subjected to five days of oral OTC batch treatment using 10 mg/kg, 5 mg/kg, and 20 mg/kg
641 dosages, respectively. Injection (IM) and Pen (PW) refer to groups treated with 10 mg/kg OTC for
642 five days individually by injection and pen-wise treatment, respectively. T1-T4 refers to the time
643 points where fecal samples were obtained: T1: immediately before treatment, T2: two days after
644 end of treatment, T3: when pigs left the nursery unit, T4: 1-7 days before slaughter. The boxes
645 indicate the interquartile range. The open circles indicate data points more than 1.5 times the
646 interquartile range from the median.

647

Figure 3. Log_{10}CFU/g tetracycline-resistant coliforms (A) and proportion of tetracycline resistant coliforms (B) in fecal samples from pigs treated orally as batch-treatment with tiamuline for three days. T_1-T_3 refers to the time points where fecal samples were obtained: T_1: Immediately before treatment, T_2: Two days after end of treatment, T_3: When pigs left the nursery unit. The boxes indicate the interquartile range. The open circles indicate data points more than 1.5 times the interquartile range from the median.