Animal 15 (2021) 100218

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

Lysine requirements of finishing boars and gilts: A meta-analysis

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ARTICLE INFO

Article history:
Received 26 August 2020
Revised 23 February 2021
Accepted 25 February 2021
Available online 23 May 2021

Keywords:
Female
Male
Pig
Sex
Uncastrated

ABSTRACT

The expected increase in boar (pig entire male) production while societal concerns for castration increase requires good estimations of their nutrient requirements. In this work, a meta-analytical approach was used to overcome the inconsistent results between studies that compared lysine requirements of boars and gilts. For this meta-analysis, data from 14 different studies analysing the effect of increasing dietary lysine on growth performance of finishing pigs, 70–100 kg average body weight, were extracted from 11 publications. Those studies represented 128 different treatments (53 for boars and 75 for gilts). Diets were reformulated based on NRC (2012) ingredient values to calculate standardized ileal digestible lysine to net energy ratio (**SID Lys:NE**) and daily SID Lys intake using average daily feed intake (**ADFI**). As expected, no evidence for differences in ADFI ($P = 0.303$) was observed between boars and gilts. However, boars grew faster ($P < 0.001$) and had higher gain to feed (G:F; $P < 0.001$). The divergent effect of SID Lys:NE on average daily gain (**ADG**) and G:F was analysed in a quadratic polynomial model showing different parameters for each sex ($P < 0.001$). Although performance between sexes was similar at low SID Lys:NE, differences were greater at higher SID Lys:NE. Furthermore, broken-line linear, broken-line quadratic (**BLQ**) and quadratic polynomial (**QP**) models were fitted to each sex to determine SID Lys:NE and SID Lys daily intake requirements to maximize ADG and G:F. Overall, QP models showed the best fit, and reported that to reach maximum ADG 0.88 (95% CI: [0.82–0.94]) or 1.01 (95% CI:[0.91–1.11]) g SID Lys/MJ, NE was required for gilts and boars, respectively. However, boar ADG was best fitted by BLQ using SID Lys daily intake as independent variable, with the requirement for maximum ADG at 24.2 (95% CI:[21.3–27.2]) g SID Lys/day. The three models reported wide confidence intervals for the requirements at maximum performance, and consequently those were overlapped when comparing boars and gilts. Maximum boars' productive performance when dietary lysine was not limiting was 116% of gilts, and at those levels the amount of SID Lys intake required per kg gain was similar between both sexes. Thus, because ADFI and Lys efficiency of gain was similar, the requirement differences were driven by the increased growth rate and gain to feed ratio between boars and gilts. In conclusion, the present study confirmed a greater productive response of boars compared to gilts when increasing dietary lysine.

Implications

Feed cost is the largest cost in swine production, and amino acids are considered the second major cost after energy. This work provides evidence that boars and gilts have a different response to increasing dietary lysine, as a reference of dietary amino acid content. Because boars have a greater growth performance potential and a similar lysine efficiency, they require more lysine than gilts. Therefore, in some price contexts, feeding boars and gilts, different feeds tailored to their requirements could improve feed efficiency and reduce feed costs, while reducing the environmental impact of swine production, as less nitrogen would be excreted.

Introduction

Increasing societal pressure in some countries to stop surgical castration of male pigs will increase the relative production of

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https://doi.org/10.1016/j.animal.2021.100218
1751-7311/

entire male pigs in future years (Bee et al., 2015). Male pigs that are not castrated have improved feed efficiency and leaner carcasses than barrows (Dunshea et al., 2013), and better feed efficiency than gilts (Cámara et al., 2014) because of a greater lean deposition potential (King et al., 2000; Giles et al., 2009). Several studies have shown that growth differentiation between boars and gilts starts around 40–70 kg body weight (BW) (Campbell et al., 1988; Moore et al., 2013; Cámara et al., 2014). Because boars have a leaner (Carabús et al., 2017) and higher growth, and lysine is the first limiting amino acid for lean tissue deposition, boars need more lysine intake than gilts to maximize growth performance (Aymerich et al., 2020). Some modelling studies have assumed a lower average daily feed intake (**ADFI**) for boars than for gilts (NRC, 2012; Dunshea et al., 2013; van der Peet-Schwering and Bikker, 2018), other work has not found evidence of these ADFI differences (Moore et al., 2013; Rikard-Bell et al., 2013; Aymerich et al., 2020). Furthermore, those works reported greater differences in average daily gain (**ADG**) than the assumed inputs in the models when sufficient lysine was available. For instance, NRC (2012) assumed that entire male ADG was only 2.8% greater than gilts between 75 and 100 kg BW whereas Aymerich et al. (2020) reported on average a 9.2% greater ADG in the period 70–105 kg and O'Connell et al. (2006) a 17.6% greater ADG.

Available studies comparing lysine requirements of boars and gilts to maximize growth performance have indicated inconsistent results. Whereas Moore et al. (2013) reported that boars and gilts maximized ADG at the same lysine level, Rikard-Bell et al. (2013) and Aymerich et al. (2020) found different requirements for each sex. O'Connell et al. (2006) reported different responses depending whether pigs were housed in pairs or in groups. In addition, most of these studies have modelled the requirements for each sex and posteriorly compared the estimates without considering the associated standard error. Recent works have shown the wide confidence intervals of those estimates, which make the comparison between sexes difficult (Aymerich et al., 2020). It could be that differences in BW range or genetic lines are partly responsible for these disagreements. In addition, the different models used to describe the response to the dietary standardized ileal digestible lysine to net energy ratio (**SID Lys:NE**) in each study might also be responsible for the inconsistencies (Pesti et al., 2009). In a situation of lack of clarity in individual studies, meta-analysis is considered a reasonable and powerful tool to improve the understanding of the response (Kelley and Kelley, 2019) and determine nutritional requirements (van Milgen et al., 2012). Therefore, the aims of this meta-analysis were to compare the response to increasing dietary lysine between finishing boars and gilts (65–100 kg BW), and, if different, determine dietary SID Lys:NE and SID Lys intake requirements for each sex to maximize growth performance.

Material and methods

This study did not require ethical approval as the data were collected from studies already published in the literature. The methodology outlined by Kelley and Kelley (2019) for meta-analysis in nutrition research was used as a reference to develop a protocol for obtaining meta-data (Supplementary Material S1). Thus, the following section was divided into study eligibility, data sources, study selection, data abstraction, and statistical analyses.

Study eligibility

Only randomized controlled dose–response experiments analysing the effects of dietary lysine on growth performance of finishing boars or gilts were included. The literature search was limited to articles from 2000 onwards to limit differences related to genetic improvements and nutrition advances. In addition, only studies in which initial BW was between 50 and 85 kg and final BW was between 85 and 120 kg were considered. Publications were excluded when there were less than four dietary lysine levels or when dietary SID Lys was not constant throughout the study. Other reasons for exclusion were not meeting amino acid ratios (ideal protein) after reformulation, based on NRC (NRC, 2012), or only providing mixed sex data.

Data sources

The literature search was performed on April 18, 2020, by searching with PubMed and Web of Science using prespecified search terms like lysine and pig and boar or gilt (Supplementary Material S1). References in the identified eligible articles were checked and some authors were contacted for further information if data were only available as figures. Finally, a publication detected after revising cross-references in the selected articles was also included, although not published in a peer-reviewed journal (Moore et al., 2015).

Study selection

A total of 1 473 publications were initially identified after removing the duplicates between both data sources. To determine whether studies fulfilled the eligibility criteria, first, the title was checked to discard studies focusing on other topics. Afterwards, the abstracts of the remaining studies were carefully analysed, and if sufficient data were not provided there, the full text was also checked. At the end, there were only eleven publications that fulfilled all inclusion criteria, including nine studies for boars and thirteen for gilts, of which eight included results for both sexes.

Data abstraction

The data from the selected studies represented 6 654 pigs (1 588 boars and 5 066 gilts) in 128 different treatments (53 for boars and 75 for gilts), each one used as an experimental unit. Diet information in each study was entered into a single database to reformulate the diets based on NRC (2012) ingredient values. This approach was preferred instead of using the dietary values provided by the studies because of the large impact of different energy evaluation systems and digestibility values. The authors acknowledge that this approach might miss some information only known by the other researchers but are confident that it is a more objective approach. For all studies except King et al. (2000), differences in diet SID Lys content between published and reformulated composition were $\leq$0.05% SID Lys. Next, a database was created including (1) study reference (first author name, year of publication, locations and experiment number), (2) animal characteristics (sex, genetics, initial BW and final BW), (3) experimental design characteristics (pigs per treatment, replicates per treatment), (4) diet characteristics (main energy and protein sources, crude protein, metabolizable energy, net energy, SID Lys and SID Lys:NE, after reformulation), (5) growth performance (ADG, ADFI and gain to feed), and (6) measures of variability for the response variables (standard error of the mean, standard error of the difference, standard deviation or the coefficient of variation). The latter were recorded to provide a measure of the consistency of the means to be used as weights in the regression model (St-Pierre, 2001). All variability measures were transformed to standard error of the mean (SEM). Each row in the dataset corresponded to a treatment of one specific sex. The ADFI and SID Lys content of the diet was used to calculate daily SID Lys intake.

Statistical analyses

A reduced dataset with the eight experiments including both boars and gilts was analysed to compare performance of both sexes. The highly suspected heterogeneity was corroborated comparing null models and heterogeneity models using the Bayesian information criteria (BIC). Initially, growth performance of both sexes was compared in a linear mixed model including sex as a fixed effect and study as a random effect using the *nlme* package (Pinheiro et al., 2019) of R (R Core Team, 2019). In addition, the SEM of the specific variable tested was specified as a variance covariate using the *VarPower* function in the weight statement (Pinheiro and Bates, 2000), representing the inverse of the variance as suggested by St-Pierre (2001). Finally, model validity was examined using standardized residual scatterplots to observe whether the distribution of residuals was more homogeneous after accounting for the random study effect and the variance covariate adjustment. The sex effect significance was determined by the F-test in the ANOVA when *P*-value was $\leq$0.05. Least square means and SEM were estimated with the *emmeans* package (Lenth, 2020). Furthermore, the differential response to SID Lys:NE between boars and gilts was analysed in a quadratic polynomial function ($Y_i = L_{QP} + B_{QP} \times X_i + A_{QP} \times X_i^2$) in which the parameters L_{QP}, B_{QP} and A_{QP} were interacted with sex. Posteriorly ANOVA with *F*-tests was used to assess the significance of the interactions, and only the ones that reduced BIC were considered for the final model.

Next, each sex was modelled independently to determine the response to dietary lysine on growth performance using the complete dataset. Regression models to predict growth performance, ADG or gain to feed (G:F), depending on SID Lys:NE and SID Lys daily intake were built using the nlme package (Pinheiro et al., 2019). Broken-line linear (**BLL**), broken-line quadratic (**BLQ**), and quadratic polynomial (**QP**) models were built following Robbins et al. (2006). Furthermore, the quadratic parameter of the BLQ model (A_{BLQ}) was included as a function of B_{BLQ} and the requirement at maximum performance (R_{BLQ}):

$$A_{BLQ} = -B_{BLQ}/(R_{BLQ} \times 2)$$

Initially, a random component was included for all fixed effect parameters using a diagonal variance–covariance structure to determine which did not account for the between subject model variability. The parameters which had a near zero standard deviation (SD) were removed starting by the one with the lower SD and a model with a general positive variance–covariance structure was fitted. Subsequently, the complex and simpler models were compared using BIC, and the one with the lowest BIC was selected. Over parametrization was assessed analysing the correlation between random parameters in the model, and if present, the model was tested with and without each parameter, selecting the model with the lowest BIC. Only the best fitting model, the ones reporting the lowest BIC, was finally considered (Supplementary Table S2). 95% confidence intervals (CIs) of the fixed effects were calculated for the parameter estimates of the models. The CIs of the parameters representing the level at which maximum performance was achieved in BLL and BLQ models were used to compare requirements of boars and gilts. Furthermore, the CI at the inflection point in the QP models was estimated using the delta method in the msm package (Jackson, 2011).

Results

Study characteristics

The 14 studies included in the meta-analysis are summarized in Table 1. Initial BW ranged from 49.6 to 84.1 kg, whereas final BW from 86.2 to 120 kg. The minimum SID Lys:NE was 0.38 for gilts and 0.45 for boars whereas the maximum was 1.23 g/MJ for both sexes. Net energy ranged from 9.7 to 11.7 MJ/kg, but the diets with higher energy density (>10.6 MJ NE/kg) were only from gilts studies (Main et al., 2008; Shelton et al., 2011). The differences in NE within some studies were related to formulating diets based on digestible energy or metabolizable energy, instead of NE, and to using different ingredient composition tables than NRC (2012). Median year of publication was 2008, and of the 14 studies, five were from Australia, four from Europe, four from North America and one from South America. Finally, the median number of replicates per study was six and seven, for boars and gilts, respectively.

Sex differences

The effect of sex on growth performance and carcass composition variables is reported in Table 2. The effects of sex on BW were not statistically analysed because for some studies, BW data were only reported as mixed sex, while others only reported the study average initial and final BW. Nevertheless, on average initial BW was 68.9 and 69.1 kg, average BW was 85.6 and 85.4 kg, and final

Table 1
Summary of the studies included in the meta-analysis to predict the effect of sex on the growth performance response to dietary lysine of finishing boars and gilts.

Study	Publication – Experiment (Exp.)	Sex	Average BW (kg)		Dietary treatments	Dietary range		Ingredients used to increase the dietary SID Lys
			Initial	Final		SID Lys:NE[1]	NE[2]	
1	Aymerich et al. (2020)[3]	Boars/Gilts	69.6	105.5	5	0.63–1.00	10.6–10.6	SBM + Lys + AA
2	Cline et al. (2000)	Gilts	53.6	116.4	5	0.62–1.16	10.1–10.6	SBM
3	Kill et al. (2003)[3]	Gilts	66.3	95.5	4	0.65–0.92	10.5–10.6	SBM
4	King et al. (2000)[3]	Boars/Gilts	80.0	120.0	6	0.45–0.92	10.1–10.5	SBM + Lys + AA
5	Main et al. (2008) – Exp. 2	Gilts	59.8	86.2	6	0.50–0.92	11.1–11.6	SBM + AA
6	Main et al. (2008) – Exp. 3	Gilts	78.4	102.9	6	0.38–0.74	11.4–11.7	SBM
7	Moore et al. (2013) – Exp. 2[3]	Boars/Gilts	49.6	103.3	5	0.55–1.12	10.0–10.4	SBM + Lys + AA
8	Moore et al. (2015)[3]	Boars/Gilts	63.6	100.5	7	0.60–1.12	9.7–10.2	SBM + AA
9	Moore et al. (2016)[3]	Boars	60.1	105.1	5	0.46–1.06	9.9–10.3	SBM + CM + MM + Lys + AA
10	O'Connell et al. (2006) – Exp. 1	Boars/Gilts	60.0	91.0	6	0.68–1.12	9.8–10.3	SBPC + AA
11	O'Connell et al. (2006) – Exp. 2	Boars/Gilts	81.0	102.0	8	0.59–1.23	9.7–10.4	SBPC + AA
12	O'Connell et al. (2006) – Exp. 3	Boars/Gilts	80.0	99.0	6	0.59–1.09	9.9–10.4	SBPC + AA
13	Rikard-Bell et al. (2013)[3]	Boars/Gilts	60.0	90.0	5	0.55–1.11	9.8–10.3	SBM + MM + AA
14	Shelton et al. (2011) – Exp. 3	Gilts	84.1	110.5	6	0.46–0.78	11.0–11.3	SBM + AA

Abbreviations: SID Lys = standardized ileal digestible lysine; SBM = soybean meal; Lys = synthetic lysine; AA = synthetic amino acids different to Lys; CM = canola meal; SBPC = soybean protein concentrate; MM = meat meal.

[1] Standardized ileal digestible lysine to net energy ratio (SID Lys:NE, g/MJ) calculated after reformulating the diets (NRC, 2012).

[2] Net energy (NE, MJ/kg) calculated after reformulating the diets (NRC, 2012).

[3] Reported backfat thickness measurements.

Table 2
The effects of sex (boars vs. gilts) on growth performance and carcass composition of finishing pigs from the eight studies included in the meta-analysis that studied both boars and gilts.

Item	Boars	Gilts	*P*-value
n (observations)	48	48	–
Initial BW, kg[1]	68.9	69.1	–
Average BW, kg[1]	85.6	85.4	–
Final BW, kg[1]	102.4	101.6	–
Average daily gain, g	1 000 ± 33.0	889 ± 33.1	<0.001
Average daily feed intake, g	2 448 ± 55.2	2 433 ± 55.2	0.303
Gain to feed, g/kg	408 ± 12.0	365 ± 12.0	<0.001
Backfat thickness, mm[2]	11.0 ± 0.98	11.7 ± 0.98	<0.001

Least square means ± SEM.
[1] For BW, the value represents the arithmetic mean of all the observations.
[2] Replicates were 33 and 32, for boars and gilts, respectively.

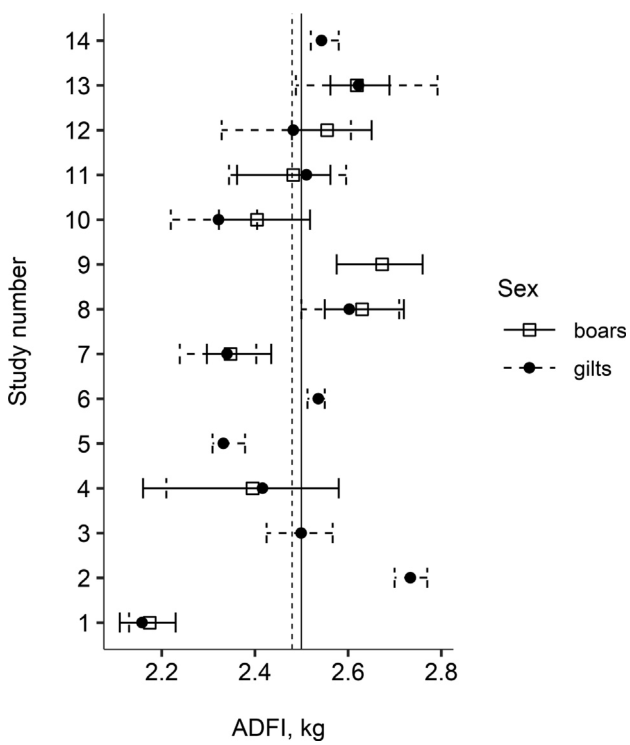

Fig. 1. Variation in average daily feed intake (ADFI) of finishing boars and gilts within each study and sex. Error bars represent the minimum and maximum reported values while the vertical dashed and solid lines represent the mean of each sex.

BW was 102.4 and 101.6 kg, for boars and gilts, respectively. As expected, boars compared to gilts had greater ADG ($P < 0.001$) with no evidence for differences in ADFI ($P = 0.303$). Therefore, boars had an improved G:F ($P < 0.001$). In addition, Fig. 1 shows the variation in ADFI between treatments within each study by sex and visually confirms the similar ADFI between boars and gilts. Regarding carcass composition, only backfat thickness was abstracted from the studies because it was the most frequently reported parameter. As expected, backfat thickness was greater in gilts than in boars (11.7 vs. 11.0 mm, $P < 0.001$).

To assess whether the response to increasing SID Lys:NE differed between boars and gilts, a quadratic model including the interaction between sex and each of the three parameters was built and each interaction was evaluated. The best fitting models to predict ADG and G:F accounting for the interactions are shown in Fig. 2. Best fitting models for both ADG and G:F included a different slope (B_{QP}, $P < 0.001$), intercept (L_{QP}, $P < 0.001$) and a different quadratic parameter (A_{QP}, $P = 0.074$) for each sex. These differences suggested that boars require more SID Lys:NE to reach maximum performance, and that gilt performance is significantly reduced when fed at high SID Lys:NE. Summarizing, both ADG and G:F models confirmed a different response to increasing SID Lys:NE between boars and gilts.

Lysine requirements by sex

The different response to SID Lys:NE between boars and gilts suggested fitting models to determine the requirements to maximize performance for each sex separately. The best fitting BLL, BLQ and QP regression equations to describe the effect of SID Lys:NE and SID Lys intake in boars and gilts ADG and G:F and each model BIC are reported in Table 3. In addition, the final models in response to SID Lys:NE and the observations from each study are illustrated in Fig. 3. Similarly, Fig. 4 illustrates the models explaining the effect of SID Lys intake on ADG and G:F and all the observations included in the meta-analysis. Quadratic polynomial models were the best fitting ones except for boars ADG that was best predicted by BLQ using SID Lys intake as explanatory variable. Nevertheless, the differences in BIC between boars BLQ and QP for both ADG and G:F were at most two units with SID Lys:NE as explanatory variable.

As expected, the three models reported different SID Lys:NE and SID Lys intake to maximize growth performance, with the lowest being always the BLL. Although the 95% confidence intervals of the requirement (R_{BLL}) were overlapped between sexes, the slope of the effect of increasing SID Lys:NE on ADG was greater in boars than in gilts. Besides, maximum performance (L_{BLL}), for both ADG and G:F was greater in boars than in gilts regardless of the explanatory variable used. On average, boars' maximum performance using BLL was 16% greater than gilts. Broken-line quadratic models did neither report different SID Lys:NE nor SID Lys intake requirements (R_{BLQ}) because of the wide confidence intervals. However, boars' requirement was always numerically greater than gilts. For instance, boars required 0.926 g SID Lys/MJ NE (95% CI: [0.826, 1.026]) or 24.2 g SID Lys/d (95% CI: [21.3, 27.2]) to maximize ADG whereas gilts required 0.872 g SID Lys/MJ NE (95% CI: [0.728, 1.016]) or 22.6 g SID Lys/d (95% CI: [19.1, 26.2]).

The QP models reported the highest requirement to reach the maximum performance, calculated at the inflection point of the function. Regarding boars, maximum ADG and G:F were reached at 1.01 (95% CI:[0.91–1.11]) and 1.06 (95% CI:[0.97–1.15]) g SID Lys/MJ NE, whereas gilts at 0.88 (95% CI:[0.82–0.94]) and 0.91 (95% CI:[0.84–0.98]) g SID Lys/MJ NE, respectively. Table 4 shows the dietary SID Lys required to reach different relative target performances (95–100%) in 10.47 MJ NE/kg diets. To increase one point of relative performance between 95 and 99% of the maximum performance, dietary SID Lys had to increase around 0.03–0.05%, whereas to increase from 99% to 100%, it required 0.12–0.13% higher dietary SID Lys. Although QP and BLQ SID Lys:NE models fitted similarly for boars, QP reported a greater requirement for maximum ADG that could be related to maximum ADG being slightly greater in the QP than in the BLQ (1 063 vs. 1 054 g). Finally, as for the BLL, QP reported boars maximum ADG and G:F to be 116% of gilts.

Discussion

The increasing importance of entire male production requires good estimations of their nutrient requirements. As lysine is the first limiting AA for protein deposition (NRC, 2012) and boars have a greater potential for protein deposition than gilts (King et al.,

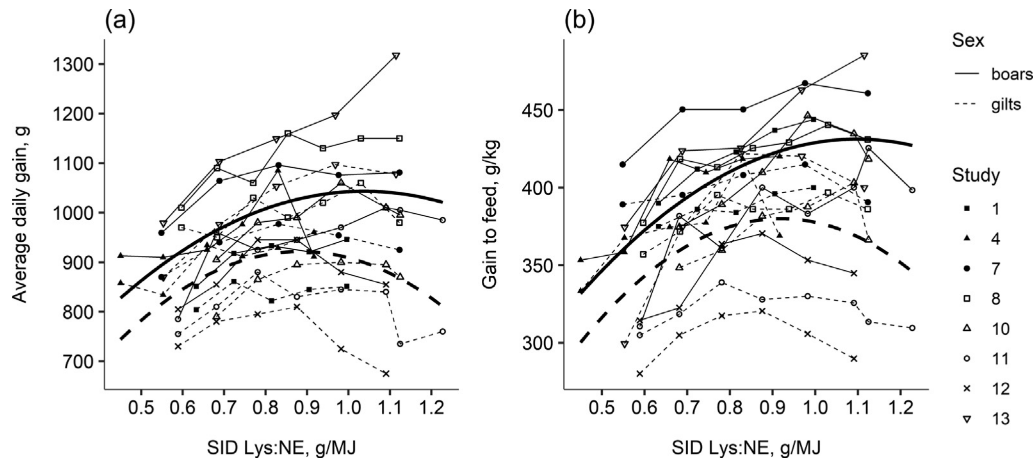

Fig. 2. Best fitting quadratic polynomial models to predict average daily gain (a) and gain to feed (b) from dietary standardized ileal digestible lysine to net energy ratio (SID Lys:NE) for boars (—) and gilts (- -). The regression equations for growth were $Y = -623 \times X^2 + 1295 \times X + 371$ and $Y = -944 \times X^2 + 1669 \times X + 184$, for boars and gilts, respectively. The regression equations for feed efficiency were $Y = -238 \times X^2 + 522 \times X + 145$ and $Y = -362 \times X^2 + 665 \times X + 74$, for boars and gilts, respectively. Each plot is based on 96 observations from eight different studies.

Table 3
Parameter estimates of different models to predict average daily gain (ADG, g) and gain to feed (G:F, g/kg) from the dietary standardized ileal digestible lysine (SID Lys) to net energy (NE) ratio and SID Lys daily intake for boars (B) and gilts (G).

Explanatory variable (Y_i)	Response variable (X_i)	Sex	Parameter estimates[1]			BIC[2]
Broken-line linear[3]			L_{BLL}[3]	U_{BLL}[3]	R_{BLL}[3]	
SID Lys:NE (g/MJ)	ADG	B	1 045 [979, 1 112]	851 [618, 1 084]	0.736 [0.702, 0.770]	581
		G	913 [871, 956]	380 [231, 530]	0.715 [0.654, 0.776]	795
	G:F	B	429 [408, 450]	196 [149, 244]	0.882 [0.822, 0.941]	478
		G	371 [352, 390]	136 [78, 195]	0.736 [0.665, 0.806]	667
SID Lys/day (g/day)	ADG	B	1 060 [988, 1 135]	20.3 [12.7, 27.9]	21.9 [20.4, 23.4]	587
		G	915 [873, 957]	14.4 [8.9, 19.8]	19.2 [17.7, 20.7]	793
	G:F	B	431 [408, 454]	7.31 [5.53, 9.10]	22.9 [21.1, 24.7]	484
		G	371 [352, 390]	4.95 [2.93, 6.96]	19.5 [17.8, 21.2]	667
Broken-line quadratic[4]			L_{BLQ}[4]	B_{BLQ}[4]	R_{BLQ}[4]	
SID Lys:NE (g/MJ)	ADG	B	109 [−239, 458]	2 040 [1 084, 2 997]	0.926 [0.826, 1.026]	574
		G	490 [296, 685]	977 [395, 1 558]	0.872 [0.728, 1.016]	791
	G:F	B	117 [23, 210]	607 [371, 842]	1.033 [0.910, 1.156]	468
		G	174 [83, 265]	476 [205, 747]	0.824 [0.704, 0.944]	663
SID Lys/day (g/day)	ADG	B	79.2 [−191, 349]	81.5 [52.3, 110.6]	24.2 [21.3, 27.2]	573
		G	424 [181, 668]	43.5 [16.2, 70.9]	22.6 [19.1, 26.2]	789
	G:F	B	127 [24, 230]	22.9 [12.7, 33.1]	26.6 [22.7, 30.5]	478
		G	174 [65, 283]	18.0 [5.7, 30.3]	21.8 [18.2, 25.4]	665
Quadratic polynomial[5]			L_{QP}[5]	B_{QP}[5]	A_{QP}[5]	
SID Lys:NE (g/MJ)	ADG	B	260 [71, 450]	1 589 [1 138, 2 040]	−787 [−1 063, −511]	567
		G	407 [278, 536]	1 172 [860, 1 485]	−664 [−854, −473]	765
	G:F	B	131 [57, 206]	567 [391, 743]	−267 [−372, −163]	458
		G	165 [106, 224]	463 [326, 599]	−254 [−337, −171]	648
SID Lys/day (g/day)	ADG	B	235 [42, 429]	64.6 [46.2, 83.1]	−1.27 [−1.73, −0.81]	581
		G	393 [250, 536]	46.5 [32.4, 60.5]	−1.02 [−1.38, −0.66]	789
	G:F	B	147 [59, 235]	20.7 [12.4, 29.1]	−0.375 [−0.573, −0.177]	487
		G	207 [157, 257]	14.3 [9.8, 18.7]	−0.308 [−0.412, −0.205]	673

[1] Estimate [95% confidence interval].
[2] Bayesian information criteria.
[3] Broken-line linear: $Y_i = L_{BLL} - U_{BLL} \times (R_{BLL} - X_i);\ if\ X_i \le R_{BLL}$; $Y_i = L_{BLL};\ if\ X_i > R_{BLL}$.
[4] Broken-line quadratic: $Y_i = L_{BLQ} + B_{BLQ} \times X_i - B_{BLQ} \times X_i^2/(R_{BLQ} \times 2);\ if\ X_i \le R_{BLQ}$; $Y_i = L_{BLQ} + B_{BLQ} \times R_{BLQ}/2;\ X_i > R_{BLQ}$.
[5] Quadratic polynomial: $Y_i = L_{QP} + B_{QP} \times X_i + A_{QP} \times X_i^2$.

2000; Giles et al., 2009), this study focused on the differential response of boars and gilts to increasing SID Lys:NE ratio. In the last decade, the publication of different nutrient requirements for boars and gilts evidenced the increasing concern on this issue. For instance, NRC (2012) provided different requirements for boars and gilts, whereas the previous version did not (NRC, 1998). Similarly, more recent work also gave different requirements for each sex (van der Peet-Schwering and Bikker, 2018). These publications were based on models which consider ADFI and ADG or protein deposition as input parameters. Although these approaches might provide reliable estimations, it is necessary to validate the values provided by these models with experimental data to determine whether those approaches are valid or need further revision.

Consistent with the literature, this meta-analysis confirmed that boars grow more rapidly and with a better feed efficiently than gilts, and without evidence of differences in ADFI, similar to results reported by Cámara et al. (2014). The variation in ADFI between studies could be related to the differences in dietary NE

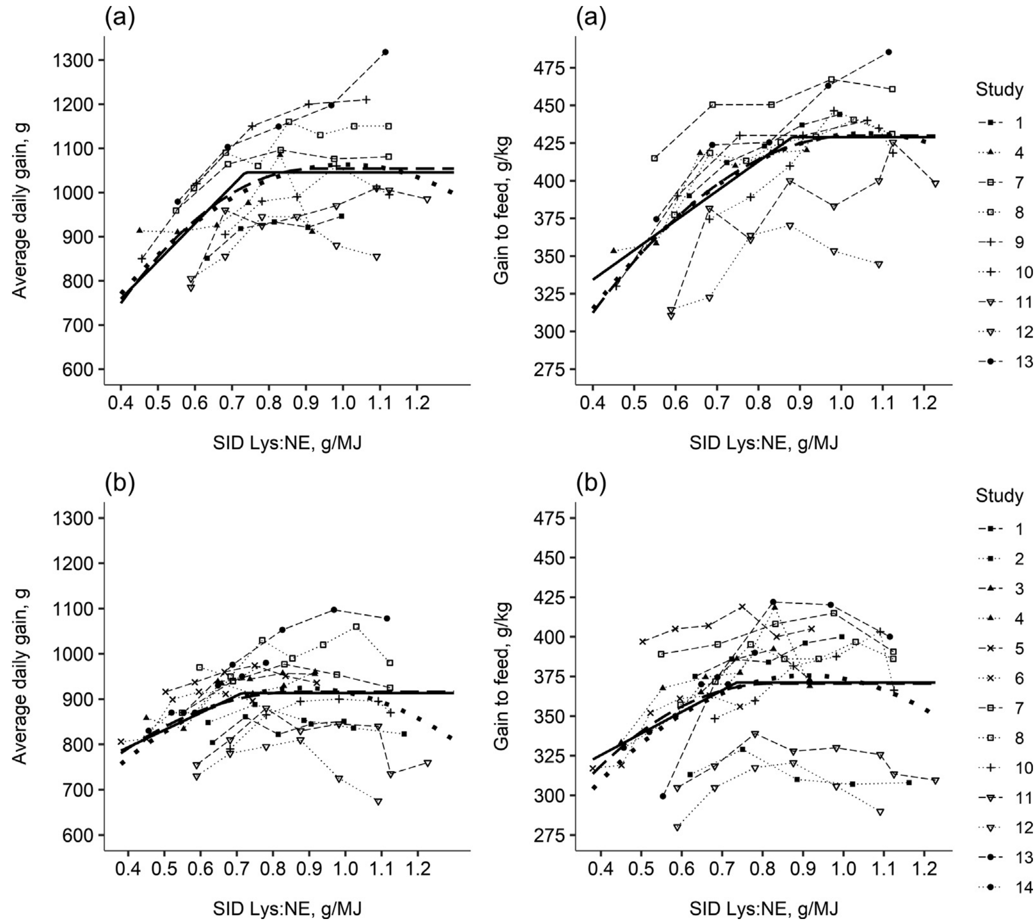

Fig. 3. Best fitting broken-line linear (BLL, —), broken-line quadratic (BLQ, - - -) and quadratic polynomial (QP, · · ·) models to predict boars (a) and gilts (b) growth performance from the dietary standardized ileal digestible lysine to net energy ratio (SID Lys:NE). Each number represents a different study, as summarized in Table 1. The boar's plots (a) are based on 53 observations from nine different studies, and the gilt's ones (b) on 75 observations from 13 different studies.

concentration or to the feed intake potential of the genotype used. The reduction in BFT for boars might be the result of less energy available for fat deposition as a greater fraction is used for protein deposition (Moore et al., 2013). Nevertheless, some publications have not reported evidence for different BFT between boars and gilts (Gispert et al., 2010; Moore et al., 2013; Trefan et al., 2013) whereas others have (Cámara et al., 2014; Aymerich et al., 2019). In addition, this study confirmed a different response to dietary SID Lys:NE between both sexes, with boars showing a positive reaction up to higher SID Lys:NE levels.

The different requirements to maximize ADG and G:F reported by BLL, BLQ and QP models might be the result of the model itself (Pesti et al., 2009), but also for which fixed effect parameters, a random component was included in the model (Robbins et al., 2006). Moreover, as the meta-data only included studies in a specific BW range, it was not considered necessary to account for the variation in requirements related to BW as implemented by van Milgen et al. (2012). Moreover, because the BLL and BLQ did hardly ever include a random component for the requirement parameter (R_{BLL} and R_{BLQ}), it could be concluded that there was almost no variation in the dietary lysine requirement between the studies included. The different slope before reaching the plateau in the BLL models for ADG suggested that although the requirement estimate was not different for those models, the marginal efficiency was greater for boars. The low requirement for boars ADG could be related to the requirement underestimation of BLL model outlined by some authors.

Commonly, models with a quadratic shape are preferred for being "biologically meaningful" (Remmenga et al., 1997) or because they better represent the "diminishing marginal productivity". However, the concept of a nutritional requirement consists in assuming that a plateau is reached, and therefore, models which combine a plateau but with an ascending quadratic part (BLQ) might be a good combination of both concepts. However, the greater standard error for the requirement estimate of BLQ models as outlined by Pesti et al. (2009) might rise concerns around the precision of that estimate. Generally, the best fit in this study was provided by the QP models, probably related to accounting for the reduction in performance at dietary lysine above the requirement. This reduction could be the result of a reduced energy available for fat deposition when fed high CP diets, as part of it is used to deaminate excess amino acids (Bender, 2012) or of a negative correlation between dietary SID Lys and ADFI (Aymerich et al., 2020).

The outputs of the QP models showed that to increase the performance of both boars and gilts from 99 to 100%, the required increase in dietary SID Lys was of similar magnitude to that required to increase performance from 96 to 99%. Therefore, in some price contexts, it might not be economically feasible to feed finishing boars and gilts at their maximum performance. Nutritionist can use the QP equations provided to decide the most optimal diet for their production goal and whether it is feasible or not to feed boars and gilts separately. For instance, to reach 99% of maximum ADG, it would be necessary to feed diets with 3.75 or 3.20 g SID Lys/Mcal NE for boars and gilts, respectively. Similarly, in the 2

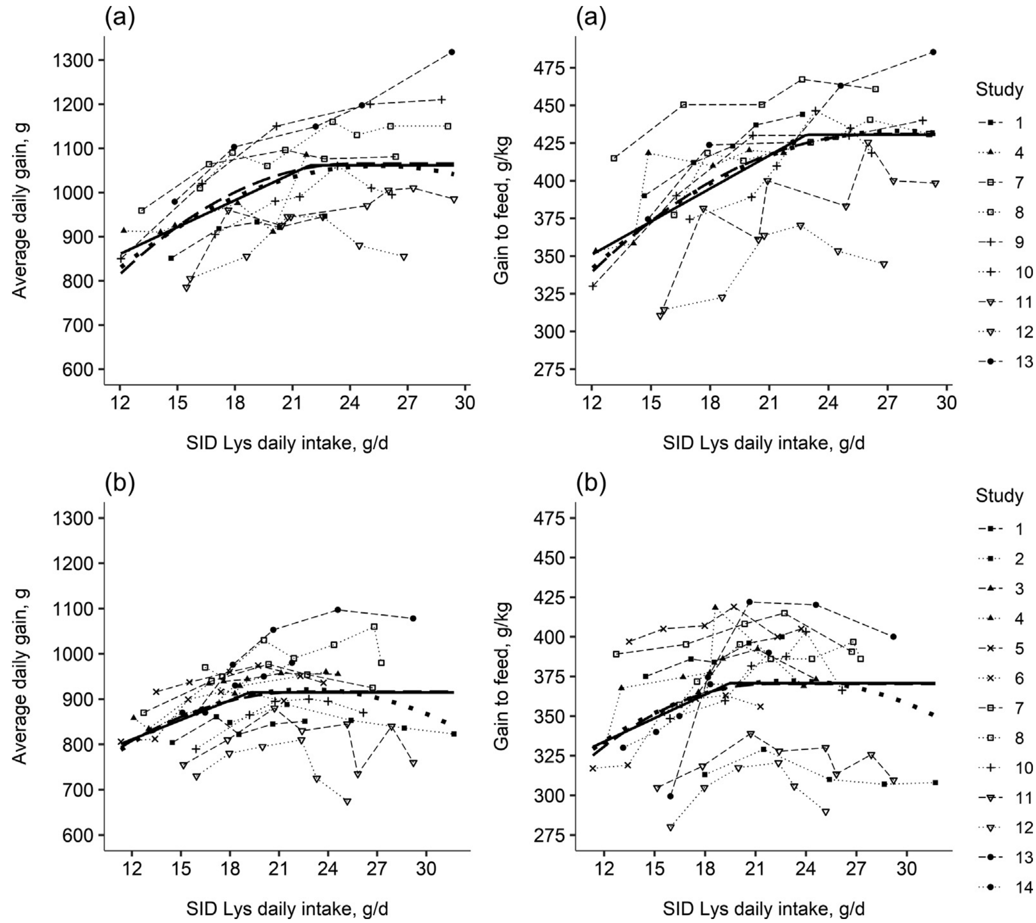

Fig. 4. Best fitting broken-line linear (BLL, —), broken-line quadratic (BLQ, - - -) and quadratic polynomial (QP, ···) models to predict boars (a) and gilts (b) growth performance from the standardized ileal digestible lysine (SID Lys) daily intake. Each number represents a different study, as summarized in Table 1. The boar's plots (a) are based on 53 observations from nine different studies, and the gilt's ones (b) on 75 observations from 13 different studies.

Table 4
Dietary standardized ileal digestible lysine (%) required to reach target average daily gain (ADG) and gain to feed (G:F) in relation to their maximum for finishing boars and gilts using quadratic polynomial models.[1]

	% of maximum performance					
Item	95	96	97	98	99	100
ADG						
Boars	0.79	0.82	0.85	0.89	0.94	1.06
Gilts	0.65	0.68	0.71	0.75	0.80	0.92
G:F						
Boars	0.81	0.84	0.88	0.92	0.98	1.11
Gilts	0.67	0.70	0.73	0.77	0.82	0.95

[1] Standardized ileal digestible lysine (SID Lys) calculated assuming a diet with 10.47 MJ net energy/kg.

500 kcal NE/kg diet example, boars required between 0.14 and 0.16% more dietary SID Lys than gilts to reach between 95and 100% of maximum ADG or G:F.

Models describing the effect of SID Lys intake could be more useful for practical feed formulation when feed intake is well characterized, but because feed intake is difficult to predict, SID Lys:NE is usually preferred. Moreover, in this meta-analysis, BLQ was the best fitting model for boars ADG when using SID Lys intake as explanatory variable, but gilt fit was rather poor. The BLQ predicted a requirement for maximum ADG at 24.2 g and 22.6 g SID Lys/d, for boars and gilts, respectively. Both values were relatively high compared to NRC (2012) between 75 and 100 kg BW, 19.0 and 18.4 g SID Lys/d, for boars and gilts, respectively. The lower values in NRC (2012) were the result of assuming an ADG of 922 and 897 g/d, and protein deposition at 156 and 144 g/d when modelling boars and gilts, respectively. On the contrary, our models reported greater differences in ADG between both sexes that explain the differences in SID Lys requirements.

The SID Lys intake models might also be used to calculate the efficiency of use of SID Lys per kg gain at the maximum performance. Main et al. (2008) found a constant efficiency of around 20 g total ileal digestible Lys/kg gain for grow-finishing pigs at the level at which growth performance was maximized. In the present study, considering the SID Lys intake and the performance at the breakpoint (BLL and BLQ) or the inflection point (QP), there were some differences between models, but the value was similar between sexes. Sex related variation in lysine efficiency was between 20.7and 21.0 for BLL, 22.7 and 24.6 for BLQ, and 24.1 and 24.7 g SID Lys/kg gain for QP, for boars and gilts, respectively. Thus, relevant differences in SID Lys efficiency of utilization for growth at maximum performance between sexes were only reported by BLQ. Unexpectedly, boars did not require more SID Lys per kg gain, although protein deposition represents a greater fraction of their growth. These results would be further supported by Heger et al. (2009) that suggested that there was no evidence of differences on SID Lys utilization between pigs with different protein deposition potential. Future studies might aim to compare SID Lys digestibility and maintenance requirements of finishing boars and gilts.

The relative maximum performance of boars for the different SID Lys:NE models was around 115–116% of gilts, for both ADG and G:F. If there are no differences in SID Lys efficiency for growth between sexes, then the requirements of boars relative to gilts would be directly related to their relative performance. Therefore, assuming finishing boar SID Lys requirement to be around 115% of gilts might be useful for practical feed formulation. Dunshea et al. (2013) suggested that SID Lys:NE requirements of boars relative to gilts might be 108% from 50 to 95 kg BW and 114% from 95 to 125 kg BW when modelled with InraPorc (van Milgen et al., 2008) using previously published data (Quiniou et al., 2010) as inputs. Thus, the relative requirements were the result of the observed differences in performance, which were small during the first 42 days in the grow-finishing facilities. In addition, the single phase diet used in that study might have been initially limiting boars' growth.

Summarizing, this study provided evidence of a different response of finishing gilts and boars to increasing dietary lysine. In this meta-analysis, the maximum performance of boars relatively to gilts when dietary lysine was not limiting was around 115–116% between 70 and 100 kg BW. Thus, the requirements of boars can be expected at around 115% of gilt requirements until further studies compare the efficiency of use of lysine between sexes. However, basing boar requirements on gilts requires good estimates of gilts' dietary lysine requirements. The equations provided in this work, especially the quadratic polynomial, can be used to evaluate the effects of different dietary strategies in boars and gilts in the body weight range studied.

Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.animal.2021.100218.

Ethics approval

Not applicable.

Data and model availability statement

None of the data were deposited in an official repository.

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Declaration of interest

The authors declare no conflict of interest.

Acknowledgements

The authors would like to acknowledge K. L. Moore for providing the numeric values reported in figures in Moore et al. (2016).

Financial support statement

This research was supported by the Catalan Industrial Doctorates Plan of the Department for Universities and Research, Ministry of Business and Knowledge of Generalitat de Catalunya (Ref: 2017 DI 046).

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