Effect of water-to-feed ratio on feed disappearance, growth rate, feed efficiency, and carcass traits in growing-finishing pigs

Fiona M. O'Meara,[†,‡] Gillian E. Gardiner,[‡] John V. O'Doherty,[‖] and Peadar G. Lawlor[†,1]

[†]Teagasc Pig Development Department, Animal and Grassland Research and Innovation Centre, Moorepark, Fermoy, County Cork, Ireland; [‡]Department of Science, Waterford Institute of Technology, Waterford, Ireland; and [‖]School of Agriculture and Food Science, University College Dublin, Belfield, Dublin 4, Ireland

ABSTRACT: The optimum proportion of water for preparing liquid feed to maximize growth and optimize feed efficiency (FE) in growing-finishing pigs is not known. The aim of the current study was, using an automatic short-trough sensor liquid feeding system, to identify the water-to-feed ratio at which growth was maximized and feed was most efficiently converted to live-weight. Two experiments were conducted in which four commercially used water-to-feed ratios were fed: 2.4:1, 3.0:1, 3.5:1, and 4.1:1 on a dry matter (DM) basis (the equivalent of 2:1, 2.5:1, 3.0:1, and 3.5:1 on a fresh matter basis). Each experiment comprised 216 pigs, penned in groups of 6 same sex (entire male and female) pigs/pen with a total of 9 pen replicates per treatment. The first experiment lasted 62 days (from 40.6 to 102.2 kg at slaughter) and the second experiment was for 76 days (from 31.8 to 119.6 kg at slaughter). Overall, in Exp. 1, FE was 0.421, 0.420, 0.453, and 0.448 (s.e. 0.0081 g/g; $P < 0.01$) for pigs fed at 2.4:1, 3.0:1, 3.5:1, and 4.1:1, respectively. Overall, in Exp. 2, average daily gain was 1,233, 1,206, 1,211, and 1,177 (s.e. 12.7 g/day; $P < 0.05$) for pigs fed at 2.4:1, 3.0:1, 3.5:1, and 4.1:1, respectively. At slaughter, in Exp. 1, dressing percentage was 76.7, 76.6, 76.7, and 75.8 (s.e. 0.17%; $P < 0.01$) for 2.4:1, 3.0:1, 3.5:1, and 4.1:1, respectively. There were no differences between treatment groups for DM, organic matter, nitrogen, gross energy, or ash digestibilities. These findings indicate that liquid feeding a diet prepared at a water-to-feed ratio of 3.5:1 maximizes FE of growing-finishing pigs without negatively affecting dressing percentage. Therefore, preparing liquid feed for growing-finishing pigs at a water-to-feed ratio of 3.5:1 DM is our recommendation for a short-trough liquid feeding system.

Key words: dry matter, liquid feeding, sensor feeding, swine

Transl. Anim. Sci. 2020.4:1-11
doi: 10.1093/tas/txaa042

INTRODUCTION

The optimum proportion of water-to-feed to use for liquid feeding of growing-finishing pigs is not well known. Limited research has been conducted on this topic and there are no clear guidelines. Pigs limit their voluntary water intake in order to maximize dry matter (DM) intake (Geary et al., 1996; Yang et al., 1981). Consequently, high water-to-feed ratios are likely to prevent pigs adjusting their water intake to maximize DM feed intake. Water-to-feed ratio in the context of increased feed wastage associated with liquid feeding compared with dry feeding

[1]Corresponding author: peadar.lawlor@teagasc.ie
Received December 6, 2019.
Accepted April 2, 2020.

(l'Anson et al., 2012; Russell et al., 1996) must also be considered. Liquid feeding from long troughs normally involves restricted feeding and according to Hurst et al. (2008), feed efficiency (FE) is improved when liquid feeding is restricted compared with ad libitum. However, more modern liquid feeding involves ad libitum feeding from short troughs. O' Meara et al. (2019) found water-to-feed ratios ranging from 2.4:1 to 4.0:1 DM are used, whereas 3.1:1 to 5.9:1 DM are used in Ontario (Braun and de Lange, 2004b). Recommendations of 2.9:1 DM (English et al., 1988) and 2.3:1 DM (Pond and Maner, 1984) have been made but research has shown optimal FE in growing pigs fed at 4.1:1 DM (Gill et al., 1987) and 3.4:1 DM (Hurst et al., 2008). Conflicting reports exist regarding the effect of water-to-feed ratio on nutrient digestibility, with some showing differences (Barber et al., 1991) and others not (Sol Llop, 2016). Our objective was to examine the effect of four commercially used water-to-feed ratios in an ad libitum short-trough liquid feeding system on the growth rate, FE and carcass traits of finisher pigs and the apparent total tract digestibility (ATTD) of nutrients. Voluntary water intake of pigs that were provided with ad libitum access to feed has been reported to be ~3:1 DM (Cumby, 1986). The null hypothesis was that water-to-feed ratio would not affect the growth, FE or carcass traits of growing-finishing pigs.

MATERIALS AND METHODS

Animal Care and Ethics

Ethical approval for this study was granted by the Teagasc Animal Ethics Committee (approval no. TAEC 107/2015). The experiment was conducted in accordance with Irish legislation (SI no. 543/2012) and the EU Directive 2010/63/EU for animal experimentation.

Animals and Experimental Design

The effect of water-to-feed ratio on the growth and FE of growing-finishing pigs was examined in two experiments.

Experiment 1 involved 216 Danavil Duroc × (Landrace × Large White) female and entire male pigs with an initial body weight of 40.6 kg ± 4.56 SD and its duration was 62 days. Experiment 2 involved 216 pigs with an initial body weight of 31.8 kg ± 3.84 SD and its duration was 76 days. In each experiment, pigs were penned in same gender pens of six pigs/pen with a total of nine pen groups/treatment. Pen groups were given a 1 week adaptation period to liquid feeding prior to the start of both experiments during which they were all fed a liquid diet prepared at 2.5:1 (DM). Pen groups were blocked by sex and weight and assigned to one of four dietary treatments, as follows: 1) Water mixed with the feed at a ratio of 2.4 kg water per kg feed DM, (2.4:1; 29.4% DM); 2) Water mixed with the feed at a ratio of 3 kg water per kg feed DM, (3.0:1; 25.0% DM); 3) Water mixed with the feed at a ratio of 3.5 kg water per kg feed DM, (3.5:1; 22.2% DM); and 4) Water mixed with the feed at a ratio of 4.1 kg water per kg feed DM (4.1:1; 19.6% DM).

Pen groups were housed in pens (2.37 m × 2.36 m) with concrete slatted floors and solid PVC partitions. Each pen group had access to a water bowl (DRIK-O-MAT, Egebjerg International A/.S, Egebjerg, Denmark) as per regulation Council Directive 2008. Air temperature was maintained at 20–22°C and was recorded daily. The room was mechanically ventilated with fans and inlets controlled by a Steinen PCS 8100 controller (Steinen BV, Nederwert, The Netherlands). Pigs were observed closely twice daily and any pigs showing signs of ill-health were treated appropriately. All veterinary treatments were recorded, including identity of pig, symptom, medication, and dosage administered.

Each pen was equipped with a solenoid valve and a short trough fitted with an electronic sensor. The electronic sensors were checked three times per day increasing to six times per day, after 4 weeks, and additional feed was dispensed into troughs where the residual feed in the trough was below the level of the sensor. Feeding was according to a feeding curve to provide ad libitum access to feed. The feed curve provided 23 MJ digestible energy (DE)/pig/day at the start of the experiment, increasing to 42 MJ DE/pig/day in a curvilinear fashion during the experiment. Feed level in the trough was manually inspected daily before and after feeding and feed allocation per pen increased or decreased accordingly. The short steel troughs (100 cm × 32.5 cm × 21 cm) were located on top of a rubber mat (1.5 m × 1 m) which helped to minimise liquid feed wastage. However, liquid feed wastage could not be measured.

Diet Preparation, Storage, and Feeding

A common diet based on wheat, barley, and soybean meal was used for all treatments in each experiment. The diet was manufactured in meal form at the Teagasc feed mill. Ingredient and chemical composition of the diet is shown in Table 1. Celite (2 g/kg) was added to the feed during the manufacturing process in order to measure the coefficient of ATTD of nutrients using the acid insoluble ash (AIA) technique (McCarthy et al., 1977). The diet was stored in a steel bin adjacent to the liquid feeding system prior to use.

The dietary treatments were prepared and fed using an automatic sensor liquid feeding system (HydroMix, BigDutchman, Vechta, Germany). The liquid diets were prepared in a mixing tank with a six pale agitator and agitated for ~5 min prior to feed-out. A high-pressure air system delivered liquid feed from the mixing tanks to troughs which were fitted with electronic feed sensors. If feed was above the sensor in a trough, feed was not dispensed to that particular trough; if the feed was below the level of the sensor, feed was dispensed to that trough and sensors were checked automatically before each scheduled feeding.

Table 1. Ingredient and chemical composition of the experimental diet (on an air dry basis, g/kg)[a]

	Experimental diet[a]
Ingredient composition	
Wheat	400.0
Barley	382.7
Soy bean meal	183.0
Limestone flour	11.0
Fat, soya oil	9.7
Lysine HCl	3.8
Salt	3.0
L-Threonine	1.7
Celite	2.0
Vitamin and mineral premix[b]	1.0
Mono DiCalcium phosphate	1.0
DL-Methionine	0.9
L-Tryptophan	0.2
Phytase[c]	0.1
Chemical composition	
Dry matter	879.0
Crude protein	179.0
Ash	39.0
Oil	28.7
Neutral detergent fiber	190.0
Gross energy, MJ/kg	16.1
Lysine	10.6
Methionine	6.6
Threonine	7.3
DE[d], MJ/kg	13.8
Net energy[d], MJ/kg	9.8
SID lysine[d,e]	10.0
Total calcium[d]	6.6
Digestible phosphorus[d]	2.6

[a]Values are the mean of experimental diets from Exp. 1 and Exp. 2.

[b]Vitamin and mineral premix provided per kilogram of complete diet: Cu from copper sulfate, 15 mg; Fe from ferrous sulfate monohydrate, 24 mg; Mn from manganese oxide, 31 mg; Zn from zinc oxide, 80 mg; I from potassium iodate, 0.3 mg; Se from sodium selenite, 0.2 mg; retinyl acetate, 0.7 mg; cholecalciferol, 12.7 µg; DL-alpha-tocopheryl acetate, 40 mg; Vitamin K, 4 mg; vitamin B12, 15 µg; riboflavin, 2 mg; nicotinic acid, 12 mg; pantothenic acid, 10 mg; vitamin B1, 2 mg; vitamin B6, 3 mg and celite 2,000 mg.

[c]The diet contained 500 phytase units (FYT) per kg feed from RONOZYME HiPhos (DSM, Belfast, UK).

[d]Calculated values.

[e]SID lysine = Standardized ileal digestible lysine.

Records, Sampling, and Analysis

Individual pig weights were recorded on d0, 32, and 62 of Exp. 1, and on d0, 40, and 76 of Exp. 2 and pen-group weights were also recorded on d19, and 57 in Exp. 2. Feed disappearance for each pen was recorded daily and calculated for the periods between each pig weighing in each experiment. Average daily gain (ADG), average daily feed intake (ADFI), and FE were calculated for each period and for the entire experiment. FE was calculated as ADG/ADFI.

Liquid feed samples (~250 g) were collected on d42 from all 36 pens and stored at −20°C prior to chemical analysis. Samples of the whole diet in dry form (~250 g) were collected on d42 of Exp. 1 and stored at −20°C for ATTD determination. Freshly voided fecal samples (~250 g/day) were collected from the floor of the pen or as they were being voided by the pig from all 36 pens (9 pens/treatment) on d43 and 44 of Exp. 1, and stored at −20°C for ATTD determination. The feces collected represented a pooled sample from a minimum of three pigs/pen group on each day. Liquid feed samples for chemical analysis and fecal samples for ATTD determination were oven dried at 55°C for 72 h.

Slaughter

At slaughter, pigs were stunned using CO_2 and killed by exsanguination in a commercial slaughterhouse after 62 or 76 days of receiving the experimental diets in experiments 1 and 2, respectively. Pigs were fasted for ~12 h prior to slaughter.

The following measurements were taken: hot carcass weight was recorded 45 min after stunning, and back-fat thickness and muscle depth, measured at 6 cm from the edge of the split back at the level of the 3rd and 4th last rib were determined using a Hennessy Grading Probe (Hennessy and Chong, Auckland, New Zealand). Carcass weight was estimated by multiplying the weight of the hot eviscerated carcass, (minus tongue, bristles, hooves, genital organs, flare fat, kidneys, and diaphragm) 45 min after slaughter by 0.98 (European Communities (Pig Carcase (Grading)) (Amendment) Regulations, 1994). Lean meat content was estimated according to the following formula: Estimated lean meat content (%) = 60.3 − 0.847x + 0.147y where x is the fat depth (mm); y is the muscle depth (mm) (Department of Agriculture and Food and Rural Development, 2001). Dressing percentage was calculated from final live-weight (LW) and cold carcass weight.

Feed Analysis and ATTD Determination

Samples were analyzed for nitrogen (N), DM, ash, gross energy (GE), neutral detergent fiber (NDF), ether extract (EE), amino acids (AA), and AIA. Feed and fecal samples were ground in a Christy Norris mill through a 2 mm screen. Fecal samples from the two collection days (d43 and 44 of Exp. 1) were pooled into one sample per pen prior to analysis (n = 9/treatment). Liquid feed samples for proximate and AA analysis were pooled into one sample per treatment prior to analysis. DM (AOAC.934.01), ash (AOAC.942.05) and EE concentration (AOAC.920.39) were determined according to methods of the Association of Official Analytical Chemists (AOAC, 2005). The N content was determined using the LECO FP 528 instrument (Leco Instruments UK Ltd., Cheshire, UK) (AOAC.990.0). Crude protein (CP) was calculated as N × 6.25. The NDF content was determined according to the method of Van Soest et al. (1991) using an Ankom 220 Fibre Analyser (Ankom Technology, Macedon, New York, USA). The concentration of AIA in dry diets was determined according to the method of McCarthy et al. (1977) in order to measure the CATTD of nutrients using the AIA technique. GE was determined using an adiabatic bomb calorimeter (Parr Instruments, Moline, IL USA). AA determination was carried out using cation exchange HPLC as previously described by McDermott et al. (2016) (AOAC 994.12).

Verification of Water-to-Feed Ratios and Liquid Feed Quantity Delivered

Verification of water-to-feed ratios was carried out on d34 (n = 4 pens/treatment) and d55 (n = 5 pens/treatment) of Exp. 1 and d22 (n = 4 pens/treatment) and d75 (n = 3 pens/treatment) of Exp. 2 to verify that the liquid feeding system was mixing water and feed in accurate ratios. The entire feed delivery for each pen during feed-out was collected by diverting liquid feed from the main feed line, below the trough solenoid, into a clean, dry collection box. The feed collected was continuously agitated using a mechanical agitator and a representative sample (~250 g) taken during agitation to avoid any settling out of the feed. The sample was weighed before oven drying at 65°C for 72 h. Samples were removed from the oven, cooled in a desiccator for 1 h, and weighed. The moisture content of the liquid feed was calculated by difference (weight of liquid sample − weight of dried sample) and was used to determine the water-to-feed ratio of each sample on a DM basis.

The liquid feed system was also checked during Exp. 1 to ensure that the total mixed feed volume of liquid feed delivered to troughs was as recorded by the feeding computer. This process took place on d21 and 49 of Exp. 1. For this, the entire feed delivery for a pen was collected by diverting the feed from the main feed line as above. Three pen feed volumes per treatment were collected and weighed and compared with the volume displayed for feed-out on the computer. The difference in the actual feed delivery volume was calculated as a deviation percentage from the correct feed volume displayed on the computer.

Statistical Analysis

Data were analyzed using the MIXED procedure of SAS 9.4 (SAS Institute, Inc., Cary, NC, US) after checking for normality. For growth parameters (ADFI, ADG, FE, and LW); dietary treatment, sex, day of the experiment, and their associated interactions were included in the model as fixed effects. For carcass growth parameters (carcass ADG and carcass FE), dietary treatment, sex, and their associated interaction were included in the model as fixed effects. Initial LW was used as a covariate when significant in the model and day as a repeated variable in the model and pen was the experimental unit for growth and carcass growth parameters. For carcass trait parameters; dietary treatment and sex and their associated interaction were included in the model as fixed effects with pen as the experimental unit. Carcass cold weight was included as a co-variate in the analysis of dressing percentage, muscle and fat depth and lean meat percentage. Initial LW was included as a co-variate for the analysis of cold weight. For ATTD data, dietary treatment was included in the model as a fixed effect with pen as the experimental unit. The normality of scaled residuals was investigated using the UNIVARIATE procedure of SAS. Results are presented as LS means ± SEM. Differences were considered significant at $P < 0.05$ and as tendencies at $0.05 < P < 0.10$. When interactions are described, if $P > 0.05$, then no interaction existed.

RESULTS

Pig Deaths and Removals

Six pigs were removed during Exp. 1; two due to lameness, three due to hernias or ruptures and one was found dead following a suspected heart attack. Three pigs were removed from the 2.4:1 treatment, one pig removed from the 3.0:1 treatment, one pig removed from the 3.5:1 treatment and one pig removed from the 4.1:1 treatment. One pig from the 2.4:1 treatment in Exp. 1 was also fully condemned at slaughter. No pigs were removed from treatment during Exp. 2 and all 216 pigs were slaughtered.

Verification of Water-to-Feed Ratios and Quantity of Liquid Feed Delivered to Troughs

The water-to-feed ratio verification results are reported in Table 2. Results to verify the quantity of liquid feed delivered to the troughs during Exp. 1 showed that all treatment delivery volumes were within −3.41% and +4.46% of the planned delivery volume. The mean ratios determined were slightly higher than the target values for the planned ratios in Exp. 2.

Effect of Water-to-Feed Ratio on the Growth and Carcass Traits of Growing-Finishing Pigs in Experiment 1

Treatment × sex interactions are shown in Table S1. There was a treatment × sex interaction for ADG in the period d33–62 in which males fed the 4.1:1 treatment grew faster than females fed 4.1:1. There were treatment × sex interactions for FE in the periods from d1–32 ($P < 0.01$) and from d33–62 ($P < 0.01$). For d1–32, male pigs fed the 3.5:1 treatment were more efficient than females fed 2.4:1 (data not shown). From d33–62, male pigs fed the 3.5:1 treatment were more efficient than female pigs fed 2.4:1 or 3.0:1. There was also an interaction for dressing percentage: Female pigs had a higher dressing percentage than male pigs at all water-to-feed ratios except for 4.1:1, where males and females had a similar dressing percentage.

The effect of treatment on feed intake, growth, FE and carcass characteristics in Exp. 1 is shown in Table 3. Overall, pigs fed at a water-to-feed ratio of 3.5:1 had a lower ADFI than those fed at 2.4:1 and 3.0:1 ($P < 0.05$), whereas those fed at 4.1:1 had a similar ADFI to all other treatments. This was also reflected in the period from d33–62. In the period from d1–32, pigs fed at 3.5:1 had a lower ADFI than those fed at 3.0:1 ($P < 0.01$), whereas those fed at 2.4:1 and 4.1:1 had a similar ADFI to all other treatments. There were no treatment differences observed for ADG or carcass ADG for any period of the experiment. For the overall experimental period, FE of pigs fed at 3.5:1 was better than for pigs fed at 2.4:1 and 3.0:1 ($P < 0.05$) whereas pigs fed at 4.1:1 had an FE that was similar to that of pigs on all other treatments and the same results were observed for carcass FE. For the d1–32 period, the FE of pigs fed at 3.5:1 was better than for pigs fed at 2.4:1 ($P < 0.05$), whereas pigs fed at 3.0:1 and 4.1:1 had a similar FE to all other treatments. For the period from d33–62, the FE of pigs fed at 3.5:1 was better than for those fed at and 3.0:1, but similar to those fed at 4.1:1 and 2.4:1 ($P < 0.05$).

At d0, pigs on the 3.0:1 treatment were heavier than pigs on 4.1:1 ($P < 0.05$), whereas all other treatments had a similar weight. At slaughter, pigs fed

Table 2. Verification of water-to-feed ratios as fed during two experiments comparing commercially used water-to-feed ratios for growing-finishing pigs

	Water-to-feed ratio (DM Basis)			
	2.4:1	3.0:1	3.5:1	4.1:1
Exp. 1, d34[a]	2.5:1	3.1:1	3.5:1	4.2:1
Exp. 1, d55[b]	2.5:1	3.2:1	3.6:1	4.2:1
Exp. 1 mean	2.5:1	3.1:1	3.5:1	4.2:1
Exp. 2, d22[a]	2.5:1	3.6:1	3.9:1	4.4:1
Exp. 2, d75[c]	2.5:1	3.2:1	3.6:1	4.3:1
Exp. 2 mean	2.5:1	3.4:1	3.8:1	4.3:1

[a]Mean value of samples from four troughs/treatment.

[b]Mean value of samples from five troughs/treatment.

[c]Mean value of samples from three troughs/treatment.

4.1:1 had a significantly lower dressing percentage than those fed the other 3 treatments ($P < 0.01$). There were no treatment differences for carcass cold weight, muscle depth, fat depth or lean meat percentage ($P > 0.05$).

Effect of Water-to-Feed Ratio on the Growth, and Carcass Traits of Growing-Finishing Pigs in Experiment 2

The treatment × sex interactions from Exp. 2 are shown in Table S3. There was a treatment × sex interaction for LW at d57. Female pig weight was not affected by water-to-feed ratio, whereas males fed at 4.1:1 were lighter than those fed at 2.4:1 ($P < 0.05$). There were treatment × sex interactions for ADG from d41–57 and d58–76 and for dressing percentage at slaughter (data not shown). In the period from d41–57, the growth of females was not affected by water-to-feed ratio, whereas the growth of males was reduced when fed at 4.1:1 compared with being fed at 2.4:1 ($P < 0.001$). In the d58–76 period, males fed the 2.4:1 ratio had a faster growth than females fed 2.4:1 and 4.1:1 ($P < 0.001$). There was also a tendency for an interaction for carcass ADG where female growth rate was not affected by water-to-feed ratio but male pigs fed 2.4:1 grew faster than male pigs fed 4.1:1 ($P = 0.09$). There was an interaction for FE in the d1–19 period. The FE of females was not affected by water-to-feed ratio, whereas male pigs fed at 3.5:1 had a better FE than those fed at 3.0:1 ($P < 0.05$). The effect of treatment on the ADFI, ADG, FE, and carcass characteristics of growing-finishing pigs in Exp. 2 is shown in Table 4. Overall, there was a tendency for feed intake to be reduced when pigs were fed at

Table 3. The effect of four commercially used water-to-feed ratios on the growth parameters and carcass traits of growing-finishing pigs (Exp. 1)[a]

	Water-to-feed ratio (DM[b])					*P*-value		
	2.4:1	3.0:1	3.5:1	4.1:1	SEM	Treatment	Sex	Treatment × sex
LW[c], kg								
d0	40.8	41.4	40.6	39.8				
d32	66.6	67.0	66.2	66.4	0.73	0.88	0.17	0.75
d62	102.6	100.7	103.1	101.7	1.21	0.52	0.01	0.46
ADFI[c], g/day								
d1–32	2,167[a,b]	2,182[a]	2,000[b]	2,032[a,b]	44.5	0.01	0.57	0.02
d33–62	3,147[a]	3,159[a]	2,877[b]	2,959[a,b]	78.8	0.03	0.99	0.06
Overall	2,657[a]	2,670[a]	2,439[b]	2,495[a,b]	57.0	0.01	0.81	0.14
ADG[c], g/day								
d1–32	980	994	973	978	22.3	0.92	0.20	0.80
d33–62	1,220	1,223	1,220	1,229	22.3	0.99	0.001	0.01
Overall	1,100	1,108	1,096	1,103	18.1	0.97	0.01	0.90
FE[c], g/g								
d1–32	0.452[a]	0.454[a,b]	0.484[b]	0.481[a,b]	0.0081	0.01	0.01	0.01
d33–62	0.390[a,b]	0.386[a]	0.422[b]	0.416[a,b]	0.0100	0.03	0.001	0.01
Overall	0.421[a]	0.420[a]	0.453[b]	0.448[a,b]	0.0081	0.01	0.001	0.12
Carcass								
Carcass ADG[d], g/day	907	915	905	896	14.6	0.83	0.03	0.81
Carcass FE[e], g/g	0.345[a]	0.346[a]	0.371[b]	0.365[a,b]	0.0063	0.01	0.03	0.16
Cold-weight, kg	78.7	77.2	79.0	77.1	0.95	0.37	0.11	0.32
Dressing percentage, %	76.7[a]	76.6[a]	76.7[a]	75.8[b]	0.17	0.01	0.001	0.05
Muscle, mm	47.5	46.2	47.0	45.7	0.60	0.17	0.001	0.40
Fat, mm	12.4	12.7	12.3	12.1	0.38	0.68	0.02	0.79
Lean meat, %	56.8	56.3	56.8	56.8	0.35	0.71	0.01	0.73

[a]Least square means and pooled standard errors of the mean. All treatments had nine pen replicates per treatment, each with six pigs per pen.

[b]DM = Dry matter; Water-to-feed ratios presented on a DM basis.

[c]LW = live-weight; ADFI = Average daily feed intake; ADG = Average daily gain; FE = Feed efficiency.

[d]Carcass ADG: From live-weight at start of experiment to slaughter = ([carcass weight in kg − LW on day 1 × 0.65] × 1,000)/number of days on treatment (Lawlor and Lynch, 2005).

[e]Carcass FE: From start of experiment to slaughter = carcass ADG (g)/total ADFI (g).

[a,b,c] Within each row, values that do not share a common superscript are significantly different ($P < 0.05$).

[A,B,C] Within each row, values that do not share a common superscript tend to be different ($0.05 < P < 0.10$).

4.1:1 compared with 2.4:1 ($P = 0.06$), whereas the ADFI of pigs fed at 3.0:1 and 3.5:1 were similar to both. For the periods from d1–19 and 41–57, pigs fed at 4.1:1 had a lower ADFI than those fed at 2.4:1 ($P < 0.05$), whereas those fed at 3.0:1 and 3.5:1 had a similar ADFI to all other treatments.

In the period d41–57 and overall, ADG was reduced when pigs were fed at 4.1:1 compared with 2.4:1 ($P < 0.05$), whereas pigs fed at 3.0:1 and 3.5:1 had similar ADG to both. The same result was also noted for carcass ADG ($P < 0.05$). There were no overall treatment differences observed for FE ($P > 0.05$). In the period d1–19, pigs fed at 3.5:1 had a better FE than pigs fed at 3.0:1 ($P < 0.05$), whereas those fed at 2.4:1 and 4.1:1 had a similar FE to all other treatments.

On d19, pigs fed at 3.5:1 were heavier than pigs fed at 4.1:1 ($P < 0.01$), whereas those fed at 2.4:1 and 3.0:1 had similar weights to pigs fed all other treatments. On d57, pigs fed at 2.4:1 were heavier than pigs fed at 4.1:1 ($P = 0.05$) whereas those fed at 3.0:1 and 3.5:1 had similar weights to pigs fed all other treatments. At slaughter (d76), pigs fed at 2.4:1 were heavier than pigs fed at 4.1:1 ($P = 0.05$), whereas those fed at 3.0:1 and 3.5:1 had similar weights to pigs fed all other treatments. At slaughter, pigs fed at 2.4:1 had heavier carcasses than those fed at 4.1:1 ($P < 0.01$), whereas those fed at 3.0:1 and 3.5:1 had similar carcass weights to all other treatments. There were no treatment differences observed for dressing percentage, muscle depth, fat depth and lean meat percentage between treatments ($P > 0.05$).

Effect of Water-to-Feed Ratio on ATTD

The results from the determination of the ATTD are shown in Table S5. There were no treatment effects observed for DM, organic matter, N, GE, or ash digestibilities.

Effect of Water-to-Feed Ratio on GE, Crude Protein, Ash, and AA Content in the Diet

Results of proximate and AA analysis of dry feed and feed from troughs during Exp. 1 are shown in Table S6. There were no obvious differences in crude protein, GE, or ash between treatments in troughs. The lysine content of the dry diet was 12.4 g/kg DM. The lysine content of the trough samples from the 4.1:1 treatment was lower than those from other treatments at 8.6 g/kg DM compared with 10.6, 10.0, and 10.7 g/kg DM in the 2.4:1, 3.0:1, 3.5:1, and 4.1:1 treatments, respectively.

DISCUSSION

This study compared four commercially used water-to-feed ratios (O' Meara et al., 2019) using a state of the art short trough ad libitum liquid feeding system. Such a study is fundamental to identify the appropriate water-to-feed ratio for optimal growth and FE of liquid-fed growing-finishing pigs. The results here can be easily implemented on-farm to improve FE and, in turn, farm profitability.

Verification of Water-to-Feed Ratios

The liquid feed system employed in the current study forces air through the feed pipes at high pressure, thereby ensuring that minimal feed residue remains in pipes between feeds. This, combined with the weighing by load cells in the mixing tanks ensured that accurate volumes of correctly proportioned liquid feed were delivered to feed troughs for accurate comparison of water-to-feed ratios. Earlier studies have shown that older liquid feeding systems have not always provided equal distribution of DM and minerals to all troughs on a feed line (Braun and De Lange, 2004a; O'Reilly and Lynch, 1992). This unequal distribution is less of a concern with new liquid feeding technology, as shown in the current experiment. Liquid feed was agitated in the mixing tank for 5 min prior to feed-out; however, as access to feed was provided on an ad libitum basis, feed residue remained in the trough between feeding events. Therefore, there was an opportunity for spontaneous fermentation to occur in the troughs prior to feed ingestion.

Effect of Water-to-Feed Ratio on Overall Growing-Finishing Pig Performance

Growth rate was not affected by water-to-feed ratio in Exp. 1; however, the growth rate of pigs fed at the highest ratio (4.1:1) in Exp. 2 was reduced and carcass weight was lighter than in pigs fed at the lowest ratio (2.4:1). This result for ADG mirrors feed intake observations. When growing-finishing pigs are provided with a very dilute diet, such as the 4.1:1 diet, physical intake capacity appears to limit DM intake and consequently growth rate. An early liquid feeding study by Braude and Rowell (1967) showed that liquid feeding at water-to-feed ratios > 4.1:1 DM does not provide production advantages

Table 4. The effect of four commercially used water-to-feed ratios on the growth and carcass parameters of growing-finishing pigs (Exp. 2)[a]

	Water-to-feed ratio (DM[b])					*P*-value		
	2.4:1	3.0:1	3.5:1	4.1:1	SEM	Treatment	Sex	Treatment × sex
LW[c], kg								
d0	31.9	32.2	31.9	31.1				
d19	45.1[a,b]	44.5[a,b]	45.3[a]	44.0[b]	0.32	0.01	0.44	0.02
d40	69.2	68.0	68.7	67.1	0.71	0.15	0.37	0.39
d57	92.6[a]	90.5[a,b]	91.4[a,b]	89.0[b]	0.94	0.05	0.03	0.03
d76	121.6[a]	119.5[a,b]	119.9[a,b]	117.4[b]	0.99	0.05	0.001	0.32
ADFI[c], g/day								
d1–19	1,923[a]	1,866[a,b]	1,818[a,b]	1,747[b]	51.5	0.04	0.84	0.12
d20–40	2,557	2,468	2,439	2,382	67.4	0.24	0.78	0.62
d41–57	3,176[a]	3,077[a,b]	3,015[a,b]	2,943[b]	65.4	0.05	0.41	0.20
d58–76	3,794	3,719	3,603	3,540	98.8	0.24	0.31	0.39
Overall	2,863[A]	2,782[A,B]	2,719[A,B]	2,653[B]	62.4	0.06	0.54	0.57
ADG[c], g/day								
d1–19	905	870	914	852	18.9	0.07	0.29	0.25
d20–40	1,148	1,118	1,111	1,097	20.8	0.35	0.03	0.22
d41–57	1,368[a]	1,327[a,b]	1,336[a,b]	1,285[b]	18.2	0.02	0.001	0.001
d58–76	1,512	1,510	1,481	1,473	33.2	0.78	0.001	0.001
Overall	1,233[a]	1,206[a,b]	1,211[a,b]	1,177[b]	12.7	0.02	0.001	0.21
FE[c], g/g								
d1–19	0.468[a,b]	0.465[a]	0.500[b]	0.487[a,b]	0.0100	0.03	0.92	0.02
d20–40	0.450	0.454	0.457	0.463	0.0082	0.58	0.10	0.24
d41–57	0.435	0.433	0.446	0.441	0.0101	0.75	0.10	0.16
d58–76	0.402	0.409	0.416	0.422	0.0103	0.47	0.01	0.08
Overall	0.439	0.440	0.455	0.453	0.0083	0.26	0.08	0.15
Carcass								
Carcass ADG[d], g/day	932[a]	905[a,b]	908[a,b]	882[b]	8.7	0.01	0.001	0.09
Carcass FE[e], g/g	0.330	0.329	0.339	0.338	0.0065	0.50	0.16	0.17
Cold-weight, kg	89.1[a]	87.0[a,b]	87.3[a,b]	85.4[b]	0.66	0.01	0.001	0.09
Dressing percentage, %	73.2	72.8	72.8	72.7	0.25	0.46	0.01	0.34
Muscle, mm	47.5	47.0	46.5	47.4	0.47	0.46	0.001	0.69
Fat, mm	15.0	14.6	14.9	14.2	0.32	0.32	0.001	0.90
Lean meat, %	54.6	54.9	54.5	55.2	0.26	0.25	0.001	0.80

[a]Least square means and pooled standard errors of the mean. All treatments had nine pen replicates per treatment each with six pigs per pen.

[b]DM = Dry matter; Water-to-feed ratios presented on a DM basis.

[c]LW = Live-weight; ADFI = Average daily feed intake; ADG = Average daily gain; FE = Feed efficiency.

[d]Carcass ADG: From live-weight at start of experiment to slaughter = ([carcass weight in kg − LW on day 1 × 0.65] × 1,000)/number of days on treatment (Lawlor and Lynch, 2005).

[e]Carcass FE: From start of experiment to slaughter = carcass ADG (g)/total ADFI (g).

[a,b,c] Within each row, values that do not share a common superscript are significantly different ($P < 0.5$).

[A,B,C] Within each row, values that do not share a common superscript tend to be different ($0.05 < P < 0.10$).

in growing-finishing pigs, where improved growth rates and FE were reported on a 2.9:1 DM water-to-feed ratio compared with 4.6:1 DM. It should be noted, however, that no supplementary water was provided to liquid-fed pigs in the study by Braude and Rowell (1967) and that pigs were only fed twice daily.

Both experiments in the current study found that FE deteriorated, albeit numerically in Exp. 2, when the water-to-feed ratio was reduced below 3.5:1. For both periods of Exp. 1, pigs fed at 3.5:1 had a better FE than pigs fed at 2.4:1, whereas the only significance in Exp. 2 was from d0–19 where pigs fed at 3.5:1 were more feed efficient than those fed at 3.0:1. Although every effort was made to minimise feed wastage through trough design and use of a rubber mat under and around the troughs, it is likely that feed wastage was responsible for the poorer FE, particularly in Exp. 1, at the lower water-to-feed ratios (2.4:1 and 3.0:1). Pigs fed these treatments had a higher ADFI but similar growth rate to those fed at 3.5:1 and 4.1:1. At a lower water-to-feed ratio, where wastage of liquid feed occurred, a greater proportion of DM was lost per kg of liquid feed wasted. This increased wastage means that wastage by pigs fed at a lower water-to-feed ratio will decrease their actual feed intake more than those that waste feed at a higher ratio. The feed troughs in the current study were at floor level and this may have also negatively affected feed wastage, making it easy for pigs to remove feed on their feet and faces at feeding. In Exp. 2, management of the feeding system was improved by closer monitoring of feed disappearance which helped to improve FE while still ensuring ad libitum feeding. It is possible that different results may be achieved using a long-trough, restricted liquid feeding system. Hurst et al. (2008) reported improved FE when liquid feed was restricted-fed compared to ad libitum and suggests that the difference was mainly due to feed wastage.

It was previously shown that the optimal ratio of water-to-feed for liquid feeding increases with pig age (Sol Llop, 2016). However, results from the individual periods of both experiments in the current study suggest that this is not the case for the growing-finishing period. In Exp. 1, a water-to-feed ratio of 3.5:1 was optimum throughout the entire experiment based on FE, because increasing the water-to-feed ratio to 4.1:1 reduced dressing percentage, most likely due to increased gut fill and weight. In Exp. 2, increasing water-to-feed ratio above 3.5:1 caused a reduction in ADG and carcass weight compared to pigs fed at 2.4:1.

Sol Llop (2016) used regression analysis to conclude that ADG is maximized at 1.6:1 DM and 2.0:1 DM water-to-feed from 46.7 to 64.0 kg and 64.0 to 85.4 kg LW, respectively. They also concluded that FE is best at 1.5:1 DM and 1.8:1 DM water-to-feed from 46.7 to 64.0 kg and 64.0 to 85.4 kg, respectively. Contrary to our study, they found no treatment differences in ADFI which may be as a result of the semi-restricted feeding management implemented. They only compared ratios ranging from 0.7:1 to 3.0:1 DM for the first period (46.7–64.0 kg) and from 1.5:1 to 3.9:1 for the second period (64.0–85.4 kg); therefore, the recommended ratios do not directly compare with the commercially used treatments employed in the current study. A constant water supply was available in both studies. It should be noted that diets were hand-mixed and fed twice daily in the latter experiment. With the feeding equipment currently available, feeding a water-to-feed ratio as low as 0.7:1 DM, or in fact below 2.4:1 DM, is simply not practical. Furthermore, pigs in the current study had ad libitum access to feed; however, it is likely that pigs in the study by Sol Llop (2016) were feed-restricted, at least to some extent, since pigs in their study were only fed twice daily. Overall, our results suggest that a water-to-feed ratio of 3.5:1 is optimum based on FE and dressing percentage throughout the growing-finishing phase.

Effect of Water-to-Feed Ratio on Carcass Traits at Slaughter

In Exp. 1, pigs fed at 4.1:1 had a significantly lower dressing percentage than pigs fed the other three treatments. Although this was not found in Exp. 2, LW at slaughter and carcass weight were reduced on the 4.1:1 treatment. These results show that increasing the water-to-feed ratio to 4.1:1 has negative consequences on carcass characteristics at slaughter. It is hypothesized that the reduced dressing percentage was due to increased intestinal weight in response to the larger volumes of liquid feed ingested at each feeding, despite the suggestion by Geary et al. (1996) that adding water to diets does not influence gut size in the same way that fibrous components do. While FE was not negatively affected at the highest ratio in the current experiment, carcass characteristics were clearly affected, suggesting that 3.5:1 DM water-to-feed is optimum. In the study by Sol Llop (2016), pigs only received the highest ratio of 3.9:1 for 26 days prior to slaughter, which may not have been long enough to affect dressing percentage.

Effect of Water-to-Feed Ratio on Feed Composition, ATTD, Water Intake, and Slurry Production

Despite limited dietary AA analysis, it would appear that a certain amount of lysine was lost in the liquid feed, with the greatest losses occurring with the 4.1:1 treatment. There was a ~15% loss of lysine when the trough samples from 2.4:1, 3.0:1 and 3.5:1 were compared with the dry diet, but >30% loss was found for the 4.1:1 sample. Pedersen et al. (2002) reported almost complete loss of synthetic lysine in liquid feed that remained in pipelines during an 8-hour period. Therefore, it is highly likely that the lysine lost in the current experiment was the added crystalline lysine. The increased feed volume delivered to troughs on this high water-to-feed ratio, (4.1:1), may have resulted in a bigger quantity of feed sitting in the trough for a longer period of time, providing more opportunity for spontaneous fermentation, and therefore AA degradation, compared with the other ratios.

There were no treatment effects on nutrient digestibility in the current study, which is in agreement with previous work (Pedersen and Stein, 2010; Sol Llop, 2016). The fact that there were no differences in ATTD further supports our hypothesis that wastage of more concentrated liquid feed was responsible for the poorer FE values when water-to-feed ratios below 3.5:1 were fed, particularly in Exp. 1. In contrast, Barber et al. (1991) found that a water-to-feed ratio increase from 1.9:1 to 3.7:1 DM significantly improved DM digestibility in a linear fashion. However, it is likely that the increased DM digestibility reported by Barber et al. (1991) was more in response to meeting the animals' requirements for water than the water-to-feed ratio *per se*, as pigs did not receive supplementary water.

It is important to note that there are legal obligations to supply supplementary water to pigs (Council Directive 2008). In the current study, water intake for each treatment may have been higher than indicated by the water-to-feed ratio but water usage from the supplementary drinking bowls was not measured. Therefore, it is difficult to compare the results of the current study to those in the literature, as many older studies did not supply supplementary water when investigating liquid feeding (Barber et al., 1963, 1991; Braude and Rowell, 1967). Results from weaner work shows that pigs will consume more supplementary water when liquid feed is fed at low water-to-feed ratios (Geary et al., 1996; Gill et al., 1987). It is likely that, had we been able to record voluntary water intake, pigs on the lower water-to-feed ratio would have had higher voluntary water intakes, but all pigs would have used supplementary water, regardless of water-to-feed ratio.

Although not measured in the current study, slurry storage and disposal costs increase using liquid feeding compared to dry feeding (Stotfold Research Centre, 2005). Previous work has shown that increased slurry volumes are produced by pigs on high compared to low water-to-feed ratios (Kornegay and Vander Noot, 1968). It is interesting that growth rate on the lowest water-to-feed ratio was similar to all other treatments in Exp. 1 and better than the highest ratio in Exp. 2. If management of liquid feeding at lower water-to-feed ratios could be improved to minimise wastage, an improvement in FE could be achieved, reducing slurry volumes produced.

In conclusion, results from the current study, in which water-to-feed ratios were shown to have been accurately delivered to troughs at feeding, show that growing-finishing pigs, on a sensor-fed short-trough liquid feeding system, are most feed efficient, and have high growth rates and good dressing percentage when liquid feed is provided at a water-to-feed ratio of 3.5:1. Increasing the ratio to 4.1:1 reduced growth rate and negatively affected carcass characteristics, while reducing it below 3.5:1 negatively affected FE. However, decreasing the water-to-feed ratio to 2.4:1 improved growth; therefore, if management at 2.4:1 can be improved to reduce feed wastage, FE could be further improved and higher growth rates achieved.

ACKNOWLEDGMENTS

The authors thank Teagasc for funding this research. Fiona O' Meara was in receipt of a Teagasc Walsh Scholarship for the duration of her PhD. The authors also thank Tomas Ryan, David Clarke, Henry Allen, John Heffernan, Pat Magnier, John Walsh, and Dan O'Donovan of the Pig Development Department (Teagasc, Co. Cork, Ireland).

Conflict of interest statement. The authors declare no conflict of interest.

LITERATURE CITED

AOAC. 2005. Association of Official Analytical Chemists 2005. Official methods of analysis. 18th edition. Gaithersburg (MD): Association of Official Analytical Chemists International.

Barber, R., R. Braude, and K. Mitchell. 1963. Further studies on the water requirements of the growing pig. Anim Sci. 5:277–282 doi:10.1017/S0003356100021802

Barber, J., P. Brooks, and J. Carpenter. 1991. The effects of water to food ratio on the digestibility, digestible energy and nitrogen retention of a grower ration. Anim Prod. 52:601 doi:10.1017/S0308229600020869

Braude, R., and J. Rowell. 1967. Comparison of dry and wet feeding of growing pigs. J. Agric. Sci. 68:325–330 doi:10.1017/S0021859600012818

Braun, K., and C. De Lange. 2004a. Co-products used in swine liquid feeding: aspects of food safety and nutritional value. In: Proc. Eastern Nutrition Conference, Ottawa. p 205–222.

Braun, K., and K. de Lange. 2004b. Liquid swine feed ingredients: Nutritional quality and contaminants. In: Proc. Eastern Nutrition Conference, Ottawa. p 11–12.

Council Directive. 2008. Council Directive 2008/120/EC of 18 December 2008 laying down minimum standards for the protection of pigs.

Cumby, T. 1986. Design requirements of liquid feeding systems for pigs: a review. J Agr Eng Res. 34:153–172. doi:10.1016/S0021-8634(86)80015-4

Department of Agriculture and Food and Rural Development. 2001. European Communities (Pig Carcass (Grading)) Regulations. Dublin: Statutory Instrument no. 413.

English, P. R., V. Flower, S. Baxter, and B. Smith. 1988. The growing and finishing pig: improving efficiency. Chichester (UK): Farming Press Books.

European Communities (Pig Carcase (Grading)) (Amendment) Regulations, 1994.

Geary, T. M., P. H. Brooks, D. T. Morgan, A. Campbell, and P. J. Russell. 1996. Performance of weaner pigs fedad libitumwith liquid feed at different dry matter concentrations. J Sci Food Agr. 72:17–24. doi:10.1002/(SICI)1097-0010(199609)72:1<17::AID-JSFA598>3.0.CO;2–3

Gill, B., P. Brooks, and J. Carpenter. 1987. Voluntary water use by growing pigs offered liquid foods of differing water to meal ratios. In: Smith, A. T. Smith and T. L. J. Lawrence, editors. Pig housing and the environment: occasional publication. Vol. 11. Edinburgh (UK): British Society of Animal Production; p. 131–133.

Hurst, D., L. Clarke, and I. J. Lean. 2008. Effect of liquid feeding at different water-to-feed ratios on the growth performance of growing-finishing pigs. Animal. 2:1297–1302. doi:10.1017/S175173110800253X.

l'Anson, K., M. Choct, and P. H. Brooks. 2012. The influence of particle size and processing method for wheat-based diets, offered in dry or liquid form, on growth performance and diet digestibility in male weaner pigs. Anim Prod Sci. 52:899–904. doi:10.1071/AN12082

Kornegay, E., and G. Vander Noot. 1968. Performance, digestibility of diet constituents and N-retention of swine fed diets with added water. J Anim Sci. 27:1307–1312. doi:10.2527/jas1968.2751307x

Lawlor, P. G., and P. B. Lynch. 2005. Effect of sow feed intake during gestation on the growth performance of progeny to slaughter. Archives of Animal Breeding. 48(Special Issue):48–55

McCarthy, J., J. Bowland, and F. Aherne. 1977. Influence of method upon the determination of apparent digestibility in the pig. Can J Anim Sci. 57:131–135. doi:10.4141/cjas77-015

McDermott, A. et al. 2016. Prediction of individual milk proteins including free amino acids in bovine milk using mid-infrared spectroscopy and their correlations with milk processing characteristics. J Dairy Sci. 99:3171–3182. doi:10.3168/jds.2015–9747

O'Meara, F. 2020. Strategies to improve the microbial quality of liquid feed and optimise growth of liquid-fed grow-finisher pigs. PhD thesis, Waterford Institute of Technology.

O'Reilly, J., and P. Lynch. 1992. Uniformity of composition of mix dispensed from computerised wet feed systems for pigs. In: Irish Grassland and Animal Production Association 18th Annual Research Meeting

Pedersen, A., N. Canibe, I. Hansen and Aaslying, M. 2002. Fermented Liquid Feed for Finishers—Pelleted Feed, vol. 1. Report No. 567. The National Committee for Pig Production, Copenhagen, Denmark.

Pedersen, C., and H. H. Stein. 2010. Effects of liquid and fermented liquid feeding on energy, dry matter, protein and phosphorus digestibility by growing pigs. Livest Sci. 134:59–61. doi:10.1016/j.livsci.2010.06.097

Pond, W. G., and J. H. Maner. 1984. Swine production and nutrition. Westport (CT): AVI Publishing Co., Inc.

Russell, P. J., T. M. Geary, P. H. Brooks, and A. Campbell. 1996. Performance, water use and effluent output of weaner pigs fedad libitumwith either dry pellets or liquid feed and the role of microbial activity in the liquid feed. J Sci Food Agr. 72:8–16 doi:10.1002/(SICI)1097-0010(199609)72:1<8::AID-JSFA646>3.0.CO;2-K

Sol Llop, C. 2016. Utilización de subproductos agroindustriales en alimentación líquida para cerdos de engorde. PhD thesis, Universitat Autonoma de Barcelona.

Stotfold Research Centre. 2005. The British Pig Industry's Centre of Excellence. Finishing pigs: System of research production trial 1. Report.

Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J Dairy Sci. 74:3583–3597. doi:10.3168/jds.S0022-0302(91)78551-2

Yang, T., B. Howard, and W. Macfarlane. 1981. Effects of food on drinking behaviour of growing pigs. Appl. Anim. Ethol. 7:259–270. doi:10.1016/0304-3762(81)90082-1