Phosphorus studies in pigs

1. Available phosphorus requirements of grower/finisher pigs

BY P. P. KETAREN*, E. S. BATTERHAM† AND E. WHITE

NSW Agriculture, Wollongbar Agricultural Institute, Wollongbar, NSW 2477, Australia

AND D. J. FARRELL

Department of Biochemistry, Microbiology and Nutrition, University of New England, Armidale, NSW 2351, Australia

AND B. K. MILTHORPE

Centre for Biomedical Engineering, University of New South Wales, Sydney, NSW 2033, Australia

(*Received 4 December 1991 – Accepted 7 September 1992*)

Two experiments were conducted to determine the available P requirements of grower and grower/finisher pigs and to define the conditions for conducting a growth assay for P availability. In the first experiment, diets with four levels of calculated available P (1–4 g/kg) and four Ca:available P ratios (1·7–2·9) were used to determine the available P requirements of grower pigs. The diets were formulated by substituting the required amounts of limestone and sodium tripolyphosphate for sugar in a soya-bean meal and sugar-based diet. In addition to measuring growth responses, a range of bones were examined to determine the most suitable criteria for assessing the response to available P. There was a small quadratic response of feed intake and growth rate of the pigs to level of available P, with maximum responses occurring to approximately 3 g available P/kg ($P < 0·05$). There were linear depressing effects of increasing Ca:available P ratios on carcass gain and feed conversion ratio ($P < 0·01$) but most of these effects occurred when the ratio exceeded 2·5:1. All bone variables examined increased linearly ($P < 0·05$) or curvilinearly ($P < 0·01$) with increasing available P concentration. In general, these variables were not affected by the Ca:available P ratio. The results of the growth responses and bone development indicate that the grower pig requires approximately 3 g available P/kg. However, for availability assays, where linearity of response is needed, the dietary concentration of available P should be a maximum of approximately 2 g/kg. In the second experiment four levels of calculated available P (1–4 g/kg) with a Ca:available P ratio of 2·5:1 were used to determine the available P requirements of grower/finisher pigs from 20 to 90 kg live weight. At 50 kg live weight the dietary available P concentration for half the pigs fed at 2, 3 and 4 g available P/kg was reduced to 1, 2 and 3 g/kg respectively. The pigs were fed *ad lib.* and growth performance, bone characteristics, P retention and ash concentration in the empty body were taken as response criteria to assess P adequacy. Among the variables tested, the ash concentration in the radius/ulna bone and P and ash concentrations in the empty body appeared to be more responsive than other variables to the changes in dietary P levels. Based on these variables, the P requirements for growth and bone development of growing pigs from 20 to 50 kg live weight was 3 g/kg and reduced to 2 g/kg for finisher pigs from 50 to 90 kg live weight.

Phosphorus: Growth response: Bone development: Pigs

Current recommendations for total P requirements for grower pigs vary from 4·8 to 7·9 (average of 6·1) g/kg and for finisher pigs from 4·0 to 5·9 (average 5·0) g/kg (Jongbloed,

* Present address: Balai Penelitian Ternak, Departemen Pertanian, PO Box 123, Bogor, Indonesia.
† For reprints.

1987). The Agricultural Research Council (1981) recommendations for total P for grower (6·3 g/kg) and finisher pigs (5·4 g/kg) are higher than the recent recommendations of the National Research Council (1988) for growers (5·0 g/kg total or 2·3 g available P/kg) and finisher pigs (4·0 g total and 1·5 g available P/kg). The National Research Council (1988) also recommended a Ca:total P ratio of between 1:1 and 1·5:1.

There are a number of possible reasons for this large variation in recommendations for total P: differences in the availability of P in the ingredients in the diets, differences in techniques for assessing P requirements (empirical or factorial), criteria used for assessing P response (growth or bone variables in empirical experiments), and possibly strain of pig.

With regard to availability, P in plant materials is much less available than P in animal materials or inorganic phosphates as a substantial proportion is organically bound in the form of phytate-P (Cromwell, 1980). The proportion of P available in feed ingredients for pigs varies from virtually 0 to 1, depending on source (Cromwell, 1989). Thus, the concentration of available P in a diet is considered to be a more precise measure for defining P requirements than total P. Also, variation in the availability of P in the diets used to determine P requirements may account for much of the variation in the total estimates. Additionally, the expression of Ca:available P ratio is preferable to Ca:total P ratio.

There are also a number of criteria used for assessing P requirements: weight gain, feed conversion ratio (FCR) and degree of bone mineralization (Agricultural Research Council, 1981). Bone mineralization has been reported to give a better indication of P requirements as approximately 75% of the total P in pigs is found in the skeletal tissues (Hays, 1976). In fact, P is withdrawn from the bones whenever the supply of P is insufficient to meet physiological needs, such as for growth (Underwood, 1966). The withdrawal of P does not occur equally readily from different parts of bones. The spongy bones, ribs, vertebrae and sternum, which are normally the lowest in ash content, are the first to be affected. The compact shafts of the long bones, such as humerus, femur, tibia and of the small bones of the extremities, are the last reserves to be used (Underwood, 1966). However, it is possible that the P concentration in the empty body may be the most accurate estimate of P requirements as it accounts for the P needed for skeletal and soft tissue development.

The availability of P in feed sources can be assessed using a slope–ratio assay (Cromwell, 1980). With this assay the response to graded levels of P in a test source is compared with the response to graded levels of a highly available source of P. There are a number of criteria that can be used to assess response including ash concentration and the strength of the bones (measured as bone bending moment). There is also a wide choice in the bones selected for the assay, for as mentioned previously, bones vary in their sensitivity to P deficiency. Ideally, those bones that are more sensitive to P deficiency should be more appropriate in slope–ratio assays. It is also essential to conduct the assay over the linear portion of the response curve of the grower pig to available P. The latter is hard to define as there is much uncertainty as to the available P requirements of grower/finisher pigs. It is also important to determine whether changes in the Ca:P ratio affect the pig's response to increasing P in the diet.

The present paper reports two experiments that were conducted to (1) determine the available P requirements of grower/finisher pigs and (2) define the conditions for conducting a slope–ratio assay to determine P availability. The objectives of the first experiment were: (1) to determine the nature of the response of the grower pig to increasing level of available P, (2) to determine the most appropriate criteria for assessing P requirements, (3) to determine whether the Ca:available P ratio affects growth, bone development and available P requirements, and (4) to determine the most appropriate criteria for assessing P availability in feed ingredients when using the slope–ratio assay in grower pigs. The objectives of the second experiment were: (1) to investigate additional criteria for assessing P availability for grower/finisher pigs particularly total P in the empty body, and (2) to determine the available P requirements for growth and bone development of grower/finisher pigs from 20 to 90 kg live weight.

EXPERIMENTAL

Expt 1. Available phosphorus requirements of grower pigs

Diets. Sugar (sucrose) and soya-bean meal were chosen for these studies. Sucrose is a P-free source of energy while soya-bean meal is a uniform source of protein, also low in available P. The soya-bean meal contained (g/kg) crude protein 456, crude fibre 59, diethyl ether extract 12, ash 60, Ca 2·8, P 6·7 (890 g dry matter/kg, air-dry basis). In addition, the availability of P in soya-bean meal has been estimated to be 0·25 (National Research Council, 1988). The basal diet was formulated to 15·7 MJ digestible energy (DE)/kg and 0·66 g available lysine/MJ DE (Standing Committee on Agriculture, 1987; Table 1). Additional amino acids were added to maintain the balance of amino acids, relative to lysine, as recommended by the Agricultural Research Council (1981).

Sixteen experimental diets with four different levels of calculated available P (1, 2, 3, 4 g/kg) and four Ca:available P ratios (1·7, 2·1, 2·5 and 2·9) were then formulated using the basal soya-bean meal–sucrose-based diet (Table 1). Additional oil was added where necessary to maintain the dietary DE concentration at 15·7 MJ/kg. The lowest and the highest dietary available P levels were about 50% below and 50% above the National Research Council (1988) recommendation for grower pigs. In terms of total P concentration, the highest P level was as the level recommended by the Agricultural Research Council (1981). Ca:available P ratios were within the range of National Research Council (1988) recommendations.

Animals and procedures. The sixteen diets were arranged in a 4 × 4 factorial design with three male and three female Large White pigs allotted per diet. The pigs were blocked according to 7-week weight, sex and position in the experimental facilities.

The pigs were allowed 1 week or more to adjust to pens and feeding systems. The dietary treatments were then introduced over a 3 d period, when the pigs reached 20 kg live weight. Feed was offered dry, *ad lib*., water was supplied by nipple drinkers. The pigs were slaughtered after reaching 50 kg live weight using an electric stunner. The carcass was washed clean and measurements of hot carcass weight, including head, tail and kidneys, and depth of backfat at the P_2 position (fat plus skin using a Danish optical intrascope 65 mm from the dorsal mid-line at the level of the posterior edge of the head of the last rib) were made. The carcass was kept overnight in a coolroom at 1° before splitting down the mid line. Eleven different bones (scapula, humerus, radius/ulna, first–fourth ribs, first–fourth vertebrae, sternum, coxae, femur, tibia/fibula, $metacarpal_4$ and $metatarsal_4$) were collected from the right side for determination of the weight, ash concentration and ash weight of the bones, and of bone bending moment. The bones were autoclaved at 120° for 6 min and were then cleaned of all flesh with a scalpel. The cleaned, fresh bones were weighed and cut approximately 25 mm long using a meat saw. They were then oven dried at 105° for about 18 h (until constant weight) and ground using a laboratory mill with a 3 mm screen.

Pig response was assessed in terms of daily feed intake, daily live-weight gain, FCR (feed intake/live-weight gain), killing-out proportion, carcass gain and FCR on a carcass basis, backfat thickness (P_2), fresh weight of bones, dry matter content of bones, dry weight of bones, ash concentration of bones, ash weight of bones, and bone bending moment.

For the calculation of carcass gain and FCR on a carcass basis, a factor of 0·744 was assumed for the estimated killing-out proportion of pigs at the commencement of the

Table 1. *Expts 1 and 2. Composition (g/kg, air-dry basis) of the basal diets*

	Expt 1	Expt 2
Components		
Soya-bean meal	435	435
Sucrose	541	538
Soya-bean oil	13	14
DL-Methionine	1·4	1·4
L-Valine	1·8	1·8
Vitamins and minerals*	5·0	5·0
Limestone	1·4	3·6
Sodium tripolyphosphate	1·1	0·9
Composition†		
Crude protein (N × 6·25)	198	192
Digestible energy (MJ/kg)	15·7	15·7
Lysine	11·7	11·7
Ca	1·7	2·5
Total P	3·2	3·3
Available P	1·0	1·0
Ca:available P ratio	1·7	2·5

* Contributed the following (mg/kg diet): Fe 60, Zn 100, Mn 30, Cu 5, I 2, Se 0·15, NaCl 2·8 g, retinol equivalent 960 μg, cholecalciferol 12 μg, α-tocopherol 20, thiamine 1·5, riboflavin 3, nicotinic acid 14, pantothenic acid 10, pyridoxine 2·5, cyanocobalamin 15 μg, pteroylmonoglutamic acid 2, choline 552, ascorbic acid 10, biotin 0·1.

† Calculated. For Expt 1 the soya-bean meal, limestone and sodium tripolyphosphate contained (g/kg): Ca 2·8, 380, 0; total P 6·7, 0, 250; estimated available P 1·67, 0 and 250 respectively. For Expt 2, the soya-bean meal, limestone and sodium tripolyphosphate contained (g/kg): Ca 2·6, 382, 0; total P 7·1, 0, 246, with estimated available P 1·78, 0 and 246 respectively.

experiment. This factor was determined previously using six pigs of approximately 20 kg liveweight.

Analytical methods. Bone bending moment of the $metacarpal_4$ and $metatarsal_4$ bones was measured using an Instron testing unit (model 4302). The bones were placed flatside down on two supports, 32 mm apart, and force applied perpendicular to the midshaft at constant speed of 20 mm/min, until it reached the maximum force needed to break the bones. Bone bending moment was then calculated based on an equation developed by Crenshaw *et al.* (1981*a*).

Bones were fat extracted, using acetone in a Soxhlet apparatus, before ashing at 650° for 16 h.

Statistical analyses. The results were analysed as a 4 × 4 factorial experiment and responses were then partitioned to test the linear and quadratic effects of available P levels and Ca:available P ratios. The percentage of the variance of the linear response to P compared with the sum of the variances of the linear response to P and error was calculated (expressed as V). This was used as a measure of the percentage of variation explained by the linear effect of available P, adjusting for all other variables.

Expt 2. Available phosphorus requirements of grower/finisher pigs

Diets. The basal diet was formulated to similar specifications as in Expt 1 (Table 1). A new batch of soya-bean meal was used and contained (g/kg) crude protein 441, crude fibre 46, diethyl ether extract 12, ash 58, Ca 2·6, P 7·1 (air-dry basis, 880 g dry matter/kg).

Four diets containing calculated available P concentrations of 1, 2, 3 and 4 g/kg with a Ca:available P ratio of 2·5:1·0 were then formulated. These levels were similar to those used in Expt 1 but only the one Ca:available P ratio was used. At 50 kg live weight, half the pigs fed on diets containing 2, 3 and 4 g available P/kg were given diets containing 1, 2 and 3 g available P/kg respectively.

Animals and procedures. Fifty-six Large White pigs were selected at approximately 7 weeks of age and allocated to the experimental facilities. The pigs were blocked according to 7-week weight, sex and position. Eight pigs were allocated to the diet containing 1 g/kg available P and 16 pigs were allocated each to the diets containing 2, 3 and 4 g available P/kg. All pigs were fed these diets from 20 to 50 kg live weight. At 50 kg live weight, half the pigs given the diets containing 2, 3 and 4 g available P/kg had their dietary P levels reduced by 1 g/kg to 1, 2 and 3 g available P/kg respectively. Experimental conditions were as for Expt 1.

The pigs were slaughtered after reaching 90 kg live weight using an electric stunner. The blood was collected and the viscera washed to remove undigested material. The blood and washed viscera were then combined and frozen. The carcasses (with hair) were washed clean with water, split longitudinally down the middle of the vertebrae and the left-hand side stored at $-15°$, then ground, mixed, sampled and freeze-dried before chemical analyses. The blood and viscera were processed in a similar manner.

Four different bones (radius/ulna, femur, $metacarpal_4$ and $metatarsal_4$) were collected from the right side for determination of the weight, ash concentration and ash weight of the bones and of bone bending moment. The bones were cleaned and processed as for Expt. 1.

In order to determine P and ash retention, four male and four female pigs were slaughtered at the commencement of the experiment (20 kg live weight) and the P and ash concentrations of the blood plus washed viscera and whole carcasses determined as described for pigs slaughtered at 90 kg live weight.

Pig response was assessed as for Expt 1 with the additional measurement of empty body weight:final live weight, gain/d and FCR on an empty-body-weight basis, ash and P concentrations in the empty body, ash and P retained, and P retained:available P intake. For calculations the following factors were used: 0·91 to convert initial live weight to estimated empty body weight; 4·68 g/kg P concentration for the pigs at the commencement of the experiment.

Analytical methods. The concentration of ash and the strength of the bones were determined as in Expt 1. The concentration of ash in the freeze-dried empty body samples was determined in a similar manner using 5 g samples. These ash samples were then digested with distilled 6 M-hydrochloric acid in a digestion block at 150°. P was then determined colorimetrically at 827 nm in a Shimadzu UV-240 spectrophotometer using a modification of ammonium molybdate–sulphuric acid reagent method (John, 1970).

Statistical analyses. The results were analysed by analysis of variance. Treatments were then partitioned to test the linear and quadratic effects of both constant and reduced dietary available P levels.

RESULTS

Expt 1. Available phosphorus requirements of grower pigs

Growth responses. All pigs remained healthy throughout the experiment and there were no leg abnormalities observed.

There was a curvilinear response to feed intake and for growth rate by the pigs to available P concentration ($P < 0·05$; Table 2). Maximum response was to approximately 3 g available P/kg in both cases. All other growth variables were unaffected by the available P concentration.

Table 2. *Expt 1. Effect of available phosphorus concentration and calcium: available phosphorus ratio in the diet on the performance of grower pigs*†

	Available P (g/kg) (P)				Ca: available P (R)				Statistical significance of effects of:						
										P		R			
	1	2	3	4	1·7	2·1	2·5	2·9	P × R	Lin	Quad	Lin	Quad	V	SEM (edf 83)
Feed intake (g/d)	2052	2106	2118	2031	2034	2101	2068	2103	NS	NS	*	NS	NS	0·1	34·6
Gain (g/d)	915	946	955	916	946	943	943	900	NS	NS	*	NS	NS	0·0	14·8
FCR	2·24	2·23	2·23	2·22	2·15	2·23	2·20	2·34	NS	NS	NS	**	NS	0·3	0·035
Killing-out proportion	0·78	0·78	0·77	0·78	0·78	0·78	0·78	0·77	NS	NS	NS	NS	NS	2·1	0·0003
Carcass gain (g/d)	739	762	758	733	761	757	760	714	NS	NS	*	**	NS	0·3	10·7
FCR (carcass basis)	2·78	2·78	2·81	2·77	2·67	2·78	2·73	2·95	NS	NS	NS	**	NS	0·0	0·004
Backfat (P_2; mm)	17·7	18·7	18·3	17·5	17·6	18·3	17·9	18·5	NS	NS	NS	NS	NS	0·2	0·51

FCR, feed conversion ratio; Lin, linear effects; Quad, quadratic effects; V, percentage variation explained by the linear effect of available P, adjusting for other variables; edf, error degrees of freedom; NS, $P > 0·05$.

* $P < 0·05$, ** $P < 0·01$.

† For details of diets and procedures, see Table 1 and pp. 251–252.

The increase in Ca:available P ratio depressed linearly both carcass gain and FCR ($P < 0{\cdot}01$).

Bone responses. The fresh weight of the bones increased in a linear manner with increasing dietary available P concentration ($P < 0{\cdot}05$ for metatarsal_4 and $P < 0{\cdot}01$ for the other bones; Table 3) but was unaffected by the Ca:available P ratio.

The dry matter of bones also increased in a linear ($P < 0{\cdot}01$) or, in most cases, in a curvilinear ($P < 0{\cdot}05$ for sternum and $P < 0{\cdot}01$ for other bones) manner to increasing dietary available P concentration (Table 4). In all cases maximum responses were to 4 g available P/kg.

It was not possible to collect the intact bones for the scapula, thoracic vertebrae, ribs, sternum and coxae, as these were damaged when the carcasses were split down the mid line. The dry weight of the other bones increased in a linear ($P < 0{\cdot}01$) manner to increasing dietary available P concentration (Table 5). The Ca:available P ratio had no effect on the dry weight of bones except for the femur which increased slightly ($P < 0{\cdot}05$) with increasing Ca:available P ratio.

The ash concentration of all bones increased curvilinearly ($P < 0{\cdot}01$) with the increase in available dietary P, except for the metatarsal_4 where the response was linear (Table 6). Ash concentration was unaffected by the Ca:available P ratio.

The weight of ash from all bones increased curvilinearly ($P < 0{\cdot}01$) with an increase in the dietary P level and was unaffected by the Ca:available P ratio of the diet (Table 7).

Bone bending moment of the metatarsal_4 bone increased linearly ($P < 0{\cdot}01$) and that of the metacarpal_4 curvilinearly ($P < 0{\cdot}05$) with the increase in dietary available P (Table 7). Both were unaffected by the Ca:available P ratio of the diet.

Relationship between linear response and dietary available phosphorus. In terms of the percentage of variation explained by the linear effect of available P in the diet, the response of growth variables was negligible (0·0–0·3 %, Table 2), low for the fresh weight of bones (8–21 %, Table 3) and higher for the dry matter of bones (23–59 %, Table 4), dry weight of bones (24–50 %, Table 5), ash concentration of bones (25–68 %, Table 6), ash weight of bones (51–73 %, Table 7) and bone bending moment (47–58 %, Table 7).

Expt 2. Available phosphorus requirements of grower/finisher pigs

Growth responses. All pigs remained healthy throughout the experiment and no leg abnormalities were observed. However, two of the pigs given the diet containing 1 g available P/kg from 20 to 90 kg live weight had gait difficulty by the end of the experiment.

Feed intake and live-weight gain were similar for pigs offered all diets during the 20–50 kg growth phase (Table 8). However, FCR was initially improved and then depressed with increase in dietary available P level ($P < 0{\cdot}05$).

During the 50–90 kg growth phase, feed intake of pigs given the constant dietary available P levels was similar ($P > 0{\cdot}05$), whereas both live-weight gain and FCR initially improved and then were depressed with increasing dietary available P level ($P < 0{\cdot}05$ and $P < 0{\cdot}01$ respectively). For those pigs given the diets containing reduced levels of available P (diets 5, 6 and 7) both feed intake and live-weight gain increased with increasing level of dietary available P ($P < 0{\cdot}05$).

During the 20–90 kg growth phase, feed intake of pigs given the constant dietary available P levels was similar ($P > 0{\cdot}05$), whereas both empty-body-weight gain and FCR on an empty-body-weight basis initially improved and then were depressed with increasing dietary available P level ($P < 0{\cdot}01$). For those pigs given the diets containing reduced levels of available P (diets 5, 6 and 7) both feed intake and live-weight gain increased with increasing level of dietary available P ($P < 0{\cdot}05$ and $P < 0{\cdot}01$ respectively). Empty body weight:live weight and back-fat thickness were not influenced by the dietary P level.

Table 3. *Expt 1. Effect of available phosphorus concentration and calcium: available phosphorus ratio in the diet on the fresh weight (g) of various bones of grower pigs*†

	Available P (g/kg) (P)				Ca:available P (R)				Statistical significance of effects of:						
										P		R			
Bones	1	2	3	4	1·7	2·1	2·5	2·9	P × R	Lin	Quad	Lin	Quad	V	SEM (edf 79)
Humerus	108	114	116	120	113	110	118	114	NS	**	NS	NS	NS	15	2·7
Radius/ulna	81	84	87	88	85	83	86	84	NS	**	NS	NS	NS	11	2·0
Femur	126	131	135	139	130	130	137	131	NS	**	NS	NS	NS	19	2·7
Tibia/fibula	88	91	95	98	92	91	95	91	NS	**	NS	NS	NS	21	2·1
Metatarsal$_4$	14·6	15·0	15·2	15·6	14·7	14·9	15·4	15·0	NS	*	NS	NS	NS	8	0·32

Lin, linear effects; Quad, quadratic effects; V, percentage variation explained by the linear effect of available P, adjusting for other variables; edf, error degrees of freedom; NS, $P > 0·05$.

* $P < 0·05$, ** $P < 0·01$.

† For details of diets and procedures, see Table 1 and pp. 251–252.

Table 4. *Expt 1. Effect of available phosphorus concentration and calcium: available phosphorus ratio in the diet on the dry weight: fresh weight (g/g) of various bones of grower pigs*†

	Available P (g/kg) (P)				Ca:available P (R)				Statistical significance of effects of:						
										P		R			SEM
Bones	1	2	3	4	1·7	2·1	2·5	2·9	P × R	Lin	Quad	Lin	Quad	V	(edf 79)
Scapula	0·49	0·54	0·56	0·57	0·54	0·55	0·52	0·54	*	**	**	NS	NS	55	0·008
Humerus	0·52	0·56	0·58	0·59	0·56	0·57	0·55	0·57	NS	**	NS	NS	NS	38	0·008
Radius/ulna	0·55	0·61	0·61	0·63	0·59	0·60	0·59	0·61	NS	**	**	NS	NS	45	0·008
Thoracic vertebrae	0·51	0·56	0·57	0·59	0·55	0·57	0·54	0·56	NS	**	**	NS	NS	59	0·006
Ribs	0·50	0·54	0·57	0·57	0·54	0·56	0·54	0·55	NS	**	**	NS	NS	49	0·007
Sternum	0·45	0·49	0·50	0·51	0·48	0·49	0·47	0·50	NS	**	*	NS	NS	23	0·011
Coxae	0·51	0·55	0·57	0·58	0·55	0·56	0·54	0·56	NS	**	**	NS	NS	55	0·007
Femur	0·51	0·56	0·57	0·58	0·55	0·55	0·55	0·57	*	**	**	NS	NS	33	0·009
Tibia/fibula	0·55	0·59	0·59	0·61	0·57	0·59	0·58	0·60	NS	**	NS	**	NS	41	0·007
Metatarsal$_4$	0·62	0·66	0·67	0·67	0·65	0·66	0·65	0·67	NS	**	**	NS	NS	34	0·007

Lin, linear effects; Quad, quadratic effects; V, percentage variation explained by the linear effect of available P, adjusting for other variables; edf, error degrees of freedom; NS, $P > 0{\cdot}05$.

* $P < 0{\cdot}05$, ** $P < 0{\cdot}01$.

† For details of diets and procedures, see Table 1 and pp. 251–252.

Table 5. *Expt 1. Effect of available phosphorus concentration and calcium: available phosphorus ratio in the diet on the dry weight (g) of various bones of grower pigs*†

	Available P (g/kg) (P)				Ca:available P (R)				Statistical significance of effects of:						
										P		R			
Bones	1	2	3	4	1·7	2·1	2·5	2·9	P×R	Lin	Quad	Lin	Quad	V	SEM (edf 83)
Humerus	56·1	63·7	66·1	70·6	63·4	62·8	64·9	65·4	NS	**	NS	NS	NS	42	1·33
Radius/ulna	43·9	50·1	52·4	54·9	50·2	49·8	49·9	51·4	NS	**	NS	NS	NS	40	1·10
Femur	62·9	72·2	75·4	79·1	70·7	70·9	74·1	73·9	NS	**	NS	*	NS	48	1·34
Tibia/fibula	47·0	52·4	55·4	59·4	52·3	52·9	54·3	54·6	NS	**	NS	NS	NS	50	1·10
$Metatarsal_4$	9·1	9·9	10·1	10·5	9·6	9·7	10·0	10·0	NS	**	NS	NS	NS	24	0·23

Lin, linear effects; Quad, quadratic effects; V, percentage variation explained by the linear effect of available P, adjusting for other variables; edf, error degrees of freedom; NS, $P > 0·05$.

* $P < 0·05$, ** $P < 0·01$.

† For details of diets and procedures, see Table 1 and pp. 251–252.

Table 6. *Expt 1. Effect of available phosphorus concentration and calcium : available phosphorus ratio in the diet on the concentration of ash (g/kg) of various bones of grower pigs*†

	Available P (g/kg) (P)				Ca : available P (R)				Statistical significance of effects of:						
										P		R			
Bones	1	2	3	4	1·7	2·1	2·5	2·9	P × R	Lin	Quad	Lin	Quad	V	SEM (edf 79)
Scapula	488	525	538	545	525	533	516	522	NS	**	**	NS	NS	57	4·7
Humerus	483	518	533	533	514	520	510	523	NS	**	**	NS	NS	49	4·9
Radius/ulna	486	528	536	545	524	529	519	523	NS	**	**	NS	NS	66	3·9
Thoracic vertebrae	487	523	534	540	523	529	515	517	NS	**	**	NS	NS	51	4·9
Ribs	476	514	532	538	516	523	503	516	NS	**	**	NS	NS	62	4·6
Sternum	390	420	444	446	421	428	413	437	NS	**	**	NS	NS	25	9·7
Coxae	456	501	522	526	504	510	487	504	NS	**	**	NS	NS	68	4·5
Femur	455	493	519	521	496	504	486	501	NS	**	**	NS	NS	65	4·7
Tibia/fibula	475	513	525	529	510	518	501	515	NS	**	**	NS	NS	57	4·4
$Metatarsal_4$	499	510	525	519	520	514	509	510	NS	**	NS	NS	NS	50	6·8

Lin, linear effects; Quad, quadratic effects; V, percentage variation explained by the linear effect of available P, adjusting for other variables; edf, error degrees of freedom; NS, $P > 0·05$.

** $P < 0·01$.

† For details of diets and procedures, see Table 1 and pp. 251–252.

Table 7. *Expt 1. Effect of available phosphorus concentration and calcium: available phosphorus ratio in the diet on the weight of ash (g) and bone-bending moment (kg-cm) of various bones of grower pigs*†

	Available P (g/kg) (P)				Ca:available P (R)				Statistical significance of effects of:						
										P		R			
Bones	1	2	3	4	1·7	2·1	2·5	2·9	P × R	Lin	Quad	Lin	Quad	V	SEM (edf 79)
Wt of ash															
Humerus	21·9	26·7	29·2	31·2	27·2	27·1	27·1	27·3	**	**	**	NS	NS	70	0·58
Radius/ulna	17·1	21·6	23·2	24·7	21·5	21·9	21·3	21·4	NS	**	**	NS	NS	70	0·47
Femur	22·8	28·8	31·6	33·4	29·3	29·5	29·0	28·5	**	**	**	NS	NS	68	0·69
Tibia/fibula	17·7	21·8	23·9	25·8	22·0	22·4	21·8	22·3	**	**	**	NS	NS	73	0·47
$Metatarsal_4$	2·9	3·4	3·7	3·8	3·3	3·5	3·4	3·5	NS	**	**	NS	NS	51	0·09
Bone bending moment															
$Metacarpal_4$	28·6	37·2	42·5	45·0	36·5	37·5	40·5	38·8	NS	**	*	NS	NS	47	1·42
$Metatarsal_4$	24·0	33·6	37·7	43·2	33·0	35·0	35·8	34·8	NS	**	NS	NS	NS	58	1·28

Lin, linear effects; Quad, quadratic effects; V, percentage variation explained by the linear effect of available P, adjusting for other variables; edf, error degrees of freedom; NS, $P > 0·05$.

* $P < 0·05$, ** $P < 0·01$.

† For details of diets and procedures, see Table 1 and pp. 251–252.

Table 8. *Expt 2. Effect of available phosphorus level in the diet on the performance of grower/finisher pigs*†

	Available P (g/kg)							Statistical significance of effects of:					
	Constant level (C)‡				Reduced level (R)§			C		R			
	1	2	3	4	2–1	3–2	4–3						SEM
Diet no.…	1	2	3	4	5	6	7	Lin	Quad	Lin	Quad	C‖ *v.* R	(edf 36)
20–50 kg live wt													
Feed intake (g/d)	2266	2384	2288	2463	—	—	—	NS	NS	—	—		74·6
Live-wt gain (g/d)	864	933	897	915	—	—	—	NS	NS	—	—		24·8
FCR	2·62	2·56	2·55	2·70	—	—	—	NS	*	—	—		0·049
50–90 kg live wt													
Feed intake (g/d)	1954	2045	1995	2030	1906	1968	2118	NS	NS	*	NS	NS	63·9
Live-wt gain (g/d)	854	944	935	863	850	894	980	NS	*	*	NS	NS	34·9
FCR	2·30	2·18	2·14	2·36	2·27	2·22	2·17	NS	**	NS	NS	NS	0·056
20–90 kg live wt													
Feed intake (g/d)	2089	2219	2158	2207	2061	2070	2272	NS	NS	*	NS	NS	65·7
Live-wt gain (g/d)	855	958	925	872	859	885	961	NS	**	**	NS	NS	26·2
FCR	2·44	2·32	2·34	2·53	2·42	2·35	2·37	NS	**	NS	NS	NS	0·041
Empty-body-wt: live wt (kg/kg)	0·95	0·94	0·95	0·95	0·94	0·94	0·94	NS	NS	NS	NS	NS	0·004
Empty-body-wt gain (g/d)	825	913	885	836	818	843	915	NS	**	**	NS	NS	24·6
FCR (empty-body-wt basis)	2·53	2·43	2·44	2·64	2·54	2·46	2·49	NS	**	NS	NS	NS	0·042
Backfat (P_2; mm)	22·8	20·1	20·9	21·9	19·0	20·3	22·8	NS	NS	NS	NS	NS	1·32

FCR, feed conversion ratio; Lin, linear effects; Quad, quadratic effects; edf, error degrees of freedom; NS, $P > 0·05$.

* $P < 0·05$, ** $P < 0·01$.

† For details of diets and procedures, see Table 1 and pp. 252–253.

‡ The dietary P level was kept constant from 20 to 90 kg live weight.

§ The dietary P level was reduced 1 g/kg when the pigs reached 50 kg live weight.

‖ Excluding diet 1.

Table 9. *Expt 2. Effect of available phosphorus level in the diet on the fresh weight (g), dry weight (g) and dry weight: fresh weight (g/g) of various bones*†

	Available P (g/kg)							Statistical significance of effects of:					
	Constant level (C)‡				Reduced level (R)§			C		R			
	1	2	3	4	2–1	3–2	4–3						SEM
Diet no....	1	2	3	4	5	6	7	Lin	Quad	Lin	Quad	C‖ *v.* R	(edf 36)
Fresh wt													
Radius/ulna	140	147	157	148	147	146	157	NS	NS	NS	NS	NS	4·64
Femur	213	226	236	223	220	226	234	NS	*	NS	NS	NS	5·2
$Metatarsal_4$	22	24	24	23	23	24	23	NS	NS	NS	NS	NS	0·9
Dry wt: fresh weight													
Radius/ulna	0·64	0·68	0·68	0·70	0·67	0·69	0·69	**	NS	*	NS	NS	0·008
Femur	0·61	0·64	0·67	0·72	0·69	0·67	0·70	**	NS	NS	NS	NS	0·018
$Metatarsal_4$	0·72	0·74	0·75	0·76	0·74	0·75	0·76	**	NS	*	NS	NS	0·008
Dry wt													
Radius/ulna	90	101	106	104	98	100	109	**	*	*	NS	NS	3·3
Femur	130	146	157	160	152	152	164	**	NS	NS	NS	NS	5·2
$Metatarsal_4$	16·0	17·9	18·0	17·3	16·8	18·0	17·7	NS	*	NS	NS	NS	0·61

Lin, linear effects; Quad, quadratic effects; edf, error degrees of freedom; NS, $P > 0·05$.
* $P < 0·05$, ** $P < 0·01$.
† For details of diets and procedures, see Table 1 and pp. 252–253.
‡ The dietary P level was kept constant from 20 to 90 kg live weight.
§ The dietary P level was reduced 1 g/kg when the pigs reached 50 kg live weight.
‖ Excluding diet 1.

Table 10. *Expt 2. Effect of available phosphorus level in the diet on ash concentration (g/kg) and bone bending moment (kg-cm) of various bones*†

	Available P (g/kg)							Statistical significance of effects of:					
	Constant level (C)‡				Reduced level (R)§			C		R			
	1	2	3	4	2–1	3–2	4–3						SEM
Diet no....	1	2	3	4	5	6	7	Lin	Quad	Lin	Quad	C‖ *v.* R	(edf 36)
Ash concentration¶													
Radius/ulna	510	549	560	569	526	556	567	**	**	**	NS	NS	4·9
Femur	491	540	560	552	508	530	558	**	**	**	NS	**	6·0
$Metatarsal_4$	528	543	527	541	507	518	528	NS	NS	NS	NS	NS	11·8
Bone bending moment													
$Metacarpal_4$	62·9	81·1	81·2	98·7	63·5	82·9	97·5	**	NS	**	NS	*	3·18
$Metatarsal_4$	53·1	80·6	86·3	90·8	54·4	80·4	86·6	**	NS	**	NS	*	5·67

Lin, linear effects; Quad, quadratic effects; edf, error degrees of freedom; NS, $P > 0·05$.
* $P < 0·05$, ** $P < 0·01$.
† For details of diets and procedures, see Table 1 and pp. 252–253.
‡ The dietary P level was kept constant from 20 to 90 kg live weight.
§ The dietary P level was reduced 1 g/kg when the pigs reached 50 kg live weight.
‖ Excluding diet 1.
¶ Based on fat-free dried bones.

Table 11. *Expt 2. Effect of available phosphorus in the diet on P concentration (g/kg, dry-matter basis), P retained (g), P retained:available P intake (g/g), ash concentration (g/kg, dry matter basis) and ash retained (g) in the empty body*†

	Available P (g/kg)							Statistical significance of effects of:					
	Constant level (C)‡				Reduced level (R)§			C		R			
	1	2	3	4	2–1	3–2	4–3						SEM
Diet no....	1	2	3	4	5	6	7	Lin	Quad	Lin	Quad	C‖ *v*. R	(edf 34)
P concentration	6·81	7·90	8·68	8·41	7·29	8·47	8·82	**	**	**	NS	NS	0·232
P retained	164	214	248	246	178	221	260	**	**	**	NS	**	8·3
P retained: available P intake	1·01	0·66	0·51	0·35	0·74	0·56	0·45	**	**	**	NS	**	0·023
Ash concentration	38·4	45·5	49·7	48·5	41·8	48·1	50·8	**	**	**	NS	NS	1·18
Ash retained	1431	1743	1916	1913	1512	1736	1973	**	**	**	NS	**	31·4

Lin, linear effects; Quad, quadratic effects; edf, error degrees of freedom; NS, $P > 0{\cdot}05$.
** $P < 0{\cdot}01$.
† For details of diets and procedures, see Table 1 and pp. 252–253.
‡ The dietary P level was kept constant from 20 to 90 kg live weight.
§ The dietary P level was reduced 1 g/kg when the pigs reached 50 kg live weight.
‖ Excluding diet 1.

There was no significant difference between dietary constant P level and reduced P level on any performance variables measured.

Bone responses. The fresh weight of the bones was not affected by dietary available P level except for the femur bone which responded curvilinearly ($P < 0{\cdot}05$) to P level for those pigs given diets with constant P levels (Table 9).

The proportion of dry matter in the bones in nearly all cases increased linearly with increasing dietary available P concentrations ($P < 0{\cdot}05$, $P < 0{\cdot}01$).

The dry weight of the bones increased linearly ($P < 0{\cdot}01$) or curvilinearly ($P < 0{\cdot}05$) with increasing dietary available P for those pigs fed on the constant-P diets whereas only the radius/ulna bones increased linearly with increasing dietary available P for those pigs fed on the reduced dietary available P levels (diets 5, 6 and 7; $P < 0{\cdot}05$).

The concentration of ash in the bones of the radius/ulna and femur increased curvilinearly ($P < 0{\cdot}01$) with increasing dietary available P level for those pigs fed on constant levels of available P (diets 2–4; Table 10), and linearly ($P < 0{\cdot}01$) in those pigs fed on reduced available P levels ($P < 0{\cdot}01$). The concentration of ash in the metatarsal$_4$ bone was unaffected by dietary available P level ($P > 0{\cdot}05$).

The strength of bones as measured by bone bending moment of both metacarpal$_4$ and metatarsal$_4$ bones increased linearly ($P < 0{\cdot}01$) with an increase in the dietary constant and reduced available P level. The bone bending moment of these bones of pigs receiving the dietary constant P level was significantly ($P < 0{\cdot}05$) higher than that in the dietary reduced P level.

Empty-body composition. The concentration of P and P retained in the empty body both increased curvilinearly ($P < 0{\cdot}01$) with an increase in dietary constant P levels and linearly ($P < 0{\cdot}01$) in those pigs fed on reduced P levels (Table 11). Maximum P concentration was obtained when the pigs received a constant-P diet containing approximately 3 g/kg. However, there was no significant difference between means of P concentration of pigs receiving the constant and reduced dietary P levels whereas those pigs fed on reduced levels of available P (diets 5, 6 and 7) had lower P retentions than the pigs fed on constant available P diets ($P < 0{\cdot}01$; diets 2–4).

P retained as a proportion of P intake decreased curvilinearly ($P < 0{\cdot}01$) in pigs receiving a constant dietary P and linearly ($P < 0{\cdot}01$) for those pigs receiving reduced P levels. Mean P retained : P intake was greater in the pigs receiving the reduced dietary P levels than those receiving the constant dietary P levels.

In general, both the concentration and weight of ash in the empty body responded in a similar manner to P concentration and P retention.

DISCUSSION

Expt 1. Available phosphorus requirements of grower pigs

The different responses of the various criteria used to assess P response indicate the problem of defining available P requirements of grower pigs. The growth variables (feed intake and growth rate) indicated curvilinear responses to available P up to approximately 3 g/kg and then growth responses were depressed. These effects were, however, only small. In contrast, the majority of bone variables examined indicated substantial initial increases to available P concentration and the responses were curvilinear up to the maximum concentration examined (4 g available P/kg). Thus, recommendations for available P requirements are a compromise between growth responses and adequate bone development. In this case the majority of response to most bone variables had been achieved by 3 g available P/kg and this level would seem to be a suitable recommendation for grower pigs.

It is surprising, however, that there was no evidence of leg abnormalities in the pigs given the lowest level of dietary available P (1 g/kg), and growth response was only slightly less than that achieved by the higher-available-P diets. This indicates that the growth variables are largely insensitive to the available P concentration in the diet. The bone variables, however, indicated poor bone development, both with regard to ash concentration, total bone mass and bone strength for the pigs fed at the lowest available P level (1 g/kg). However, the results of Expt 2 indicated that this level of production was sustainable within the finisher phase.

The depressing effect of increasing the Ca:available P ratio on growth rate and increased FCR (Table 2) indicate that the grower pig is not tolerant of high Ca:available P ratios. However, increasing the ratio had no effect on bone development. Although the depressing effects of increasing the ratio on growth responses were linear, the majority of the depressing effect only occurred when the ratio increased from 2·5:1 to 2·9:1. Thus, a Ca:available P ratio of between 1·7:1 and 2·5:1 seems suitable.

The recommendation of 3 g available P/kg is slightly higher than the recommendations (2·3 g/kg) of the National Research Council (1988). However, the recommended range of Ca:available P of 1·7:1–2·5:1 is similar to the National Research Council (1988) recommendations of 1·0:1–1·5:1 for Ca:total P. There appear to be no other reports on the available P requirements of grower pigs.

The dry matter of the bones responded in a similar pattern to the bone ash concentration. These responses indicate that water in the bone matrix was being continually replaced by crystals of bone mineral until maximum mineralization was achieved (McLean & Urist, 1968). With a further increase in the dietary P level up to 4 g/kg, the bone dry weight, bone ash weight and the bone bending moment, particularly in the metatarsal$_4$ bone, continued to increase while the bone ash concentration remained unaffected. This indicates that P requirement for maximum bone bending is at least 4 g/kg in the diet. Crenshaw *et al.* (1981*a*) also indicated that bone bending moment was increased while the bone ash concentration remained constant and this was associated with an increase in the total amount of bone. The increase was attributed to the increase in the inside diameter of fully calcified bone rather than the increase in the outside diameter.

All types of bones in all criteria measured responded significantly to the change in dietary P level. Crenshaw *et al.* (1981*b*) also reported that femur, humerus, metacarpal$_4$, metatarsal$_4$, ribs and thoracic vertebrae bones tended to respond to the change in dietary P when fed to pigs from 1 to 3 or 5 months old. However, among the bones tested in our experiment it appeared that the ash concentrations of radius/ulna, coxae and femur bones are more responsive than any other bones as they had higher percentage variation. This was not in agreement with the findings of Underwood (1966) who reported that bones were the last to be depleted when P was insufficient in the diet.

The results indicate that when assessing the availability of P with slope–ratio assays, growth responses are unlikely to be suitable criteria of response. In all cases, the responses were not linear and the relationship between available P concentration and growth responses was slight (0·0–0·3, Table 2). In contrast, a number of the bone variables appeared suitable criteria of response.

In particular, the weight of ash and bone bending moment (Table 7), and ash concentration (Table 6) all had reasonably high degrees of variability related to the linear effect of dietary available P (50–70%). In addition, there were no effects of Ca:available P ratio on these variables. This is important as it is not possible to equalize Ca:available P ratios in slope–ratio assays as the availability of P in the test source is unknown.

There were, however, linear and curvilinear responses in the previously mentioned bone variables to increasing dietary available P concentration. This indicates, for a slope–ratio assay to be based on the linear portion of the response, the diets need to be formulated to a maximum of approximately 2 g available P/kg.

Overall, these results indicate that the available P requirement of grower pigs for growth rate and acceptable bone development is approximately 3 g/kg diet, with Ca:available P ratios of between 1·7 and 2·5. For assessing available P requirements, ash concentration, ash weight and bone bending moment of a number of bones are suitable criteria. These bone criteria appear suitable also for slope–ratio assays provided the diets are formulated to approximately 2 g available P/kg.

Expt 2. Available phosphorus requirements of grower/finisher pigs

As in Expt 1, the responses in live-weight and empty-body-weight gain appeared fairly insensitive to dietary available P level and there were no clear patterns in the responses obtained. For example, maximum growth rate appeared to be achieved with those pigs fed on approximately 2 g available P/kg from 20 to 90 kg and 4–3 g available P for those pigs fed on the reduced available P diets.

The linear and curvilinear responses in the concentration and retention of P in the empty body indicates that maximum P concentration and retention were achieved with those pigs fed on 3 g available P/kg from 20 to 90 kg and 4–3 g available P/kg for those pigs fed on the reduced P concentration in the finisher phase. If these variables were taken as the index of response then the requirements for available P for grower/finisher pigs would be either 3 g/kg or 4–3 g/kg if reduced levels are fed in the finisher phase.

However, if bone breaking strength of the $metacarpal_4$ and $metatarsal_4$ were taken as the variables of response then the available P requirements of grower/finisher pigs would be at least 4 g/kg and possibly higher, as the pigs were responding in a linear manner to increase in available dietary P concentration.

Thus, as for grower pigs, recommendations for requirements of available P for grower/finisher pigs appear to be a compromise between growth responses and adequate bone development. It would seem that dietary available P concentrations of 3 g/kg during the grower phase followed by 2 g/kg in the finisher phase resulted in high levels of P concentrations in the empty body and adequate bone development, and would appear suitable as a recommendation for available P requirements.

However, in determining available P requirements, determining P concentration in the empty body is expensive; quicker and less expensive techniques are required. Ash concentration and ash weight are quicker techniques than P determinations but they still require total empty body measurements. It would seem that the ash concentrations in the radius/ulna and femur bones could be used to predict P requirements for bone development as they gave similar responses to P and ash concentrations in the empty bodies.

Although maximum bone strength does not appear to be the most suitable criterion for assessing P requirements, the technique is useful for indicating bone strength and levels of 80 kg-cm for $metacarpal_4$ and $metatarsal_4$ bones appear adequate for skeletal development and function of pigs weighing 90 kg live weight.

Generally, the fresh weight of bones was not affected by either dietary constant or reduced available P levels. On the other hand, the increase in the dietary available P level increased linearly the dry weight:fresh weight ratio of all bones except the femur in the reduced dietary P levels. These responses may again be explained by water in the bone matrix being continually replaced by crystals of bone mineral until maximum mineralization was achieved (McLean & Urist, 1968). In the present experiment it was also found that ash concentration in the radius/ulna and femur bones increased with the increase in dietary available P, which indicates the increase in bone mineralization.

The highest utilization of available P was found in pigs receiving the lowest dietary

P (1 g/kg) where all the available P intake was retained. This indicates that the available P was completely utilized when the pigs were supplied with only a very-low-P diet. As at this dietary P level the bone development of pigs was impaired, the available P intake may have been primarily utilized for the growth of soft tissue. As the available P intake of the pigs increased, bone development improved but available P utilization decreased. Jongbloed (1987) also reported that the absorption and retention of P decreased with the increase in dietary P level. He offered two possible reasons for this: (1) P intake exceeding the P requirement, or (2) P intake exceeding the absorption capacity of the pig. If this is the case then the linear and curvilinear decreases in utilization in the present experiment indicate that absorption efficiency is reduced with increase in available P intake.

Overall, the results indicate that P requirement for growth and bone development of growing pigs is 3 g P/kg from 20 to 50 kg and 2 g P/kg for finisher pigs from 50 to 90 kg growth phase. Among variables tested in the present experiment the ash concentration in the radius/ulna bone and the P and ash concentration in the empty body appeared to be more responsive than the other variables to the change in the dietary P level. Therefore, the estimate for P requirements of grower/finisher pigs in the present study were based on these criteria of responses.

The authors are grateful to Ms E. B. Dettmann for statistical analyses. Financial support from the Australian International Development Assistance Bureau and the Pig Research and Development Corporation is gratefully acknowledged.

REFERENCES

Agricultural Research Council (1981). *The Nutrient Requirements of Pigs*. Slough: Commonwealth Agricultural Bureaux.

Crenshaw, T. D., Peo, E. R. Jr, Lewis, A. J. & Moser, B. D. (1981*a*). Bone strength as a trait for assessing mineralization in swine: a critical review of techniques involved. *Journal of Animal Science* **53**, 827–835.

Crenshaw, T. D., Peo, E. R. Jr, Lewis, A. J., Moser, B. D. & Olson, D. (1981*b*). Influence of age, sex and calcium and phosphorus levels on the mechanical properties of various bones in swine. *Journal of Animal Science* **52**, 1319–1329.

Cromwell, G. L. (1980). Biological availability of phosphorus for pigs. *Feedstuffs* **52**, 38–42.

Cromwell, G. L. (1989). Requirements, biological availability of calcium, phosphorus for swine evaluated. *Feedstuffs* **60**, 16–25.

Hays, V. W. (1976). *Phosphorus in Swine Nutrition*. Des Moines, Iowa: National Feed Ingredients Association.

John, M. K. (1970). Colorimetric determination of phosphorus in soil and plant materials with ascorbic acid. *Soil Science* **109**, 214–220.

Jongbloed, A. W. (1987). Phosphorus in the feeding of pigs. PhD Thesis, Drukkerij de Boer, Lelystad.

McLean, F. C. & Urist, M. R. (1968). *Bone: Fundamentals of the Physiology of Skeletal Tissue*, 3rd ed. Chicago: University of Chicago Press.

National Research Council (1988). *Nutrient Requirements of Swine*. Washington, DC: National Academy Press.

Standing Committee on Agriculture (1987). *Feeding Standards for Australian Livestock. Pigs*. East Melbourne: CSIRO Press.

Underwood, E. J. (1966). *The Mineral Nutrition of Livestock*. Aberdeen: The Central Press (Aberdeen) Ltd.

Printed in Great Britain