Australian Government
Department of Agriculture, Water and the Environment

AUSTRALIAN Pork

The Supplementation of Pig Diets with Mineral Strontium

Final Report
APL Project No. 2015/014

June 2018

The University of Sydney
Principal Investigator: Jeff Downing
Faculty of Science
School of Life and Environmental Sciences
425 Werombi Road, Camden, NSW. 2570

Acknowledgements

This project is supported by funding from Australian Pork Limited and the Department of Agriculture.

The Experimental studies were conducted at facilities owned by The SunPork Group in Westbrook, Qld, Australia, and were managed by Robert Hewitt and technical staff under his guidance.

Executive Summary

The development of a healthy skeletal structure, along with optimum muscle growth in growing pigs is dependent on receiving a balanced diet composed of all essential nutrients. Strontium (Sr) is a trace mineral which across a range of species, has been reported to increase bone volume and density (Buehler et al., 2001; Marie, 2005). However, there is limited data on Sr supplementation in commercial livestock production, although a recent broiler chicken study showed improved liveweight gain and feed efficiency (Browning and Cowieson, 2014). There is the potential for Sr supplementation at low doses to improve the performance of growing pigs because Sr has been shown to significantly increase insulin-like-growth factor-1 (IGF-1) concentrations in goats (Li et al., 2008).

Further support for Sr to having a role in pig performance was provided by a small pilot trail conducted by our group in weaner/grower pigs. Strontium supplementation at 500 ppm of feed when fed to weaner pigs increased BWG and FCR over the 28 day weaner period. Over the total feeding period of 59 days BW was higher for pigs supplemented with Sr. These observations supported the interest in the current project.

The project consisted of two experiments with the following objectives:

1. Supplement pig diets with strontium and measure production performance as weight gain and feed efficiency.
2. Determine the effect of strontium supplementation on carcass characteristics.
3. Determine the effect of strontium supplementation on joint temperature as an indicator of inflammation and the likelihood of osteochondrosis.

The fundamental experimental design was similar for both experiments with treatments being the defining differences. The pigs were of a commercial genotype (breed) and allocated to treatment groups at the time of weaning, at an average age of 21 days. Pigs were reared in single sex pens consisting of 14 pigs per pen with 24 pens per experiment. Pigs were fed a commercial weaner, grower and finisher diet.

In experiment 1 three treatments were applied (8 replicate pens each; 4 males and 4 female). The control group were fed the basal diets throughout the study while a second treatment group received the basal diet plus supplemental (Sr) at 500 ppm in the weaner diet (day 1-28), then the supplemented grower (days 29-92) and supplemented finisher diet (days 93-121). A third group received the basal weaner diet and then Sr supplemental grower and finisher diets.

For experiment 2, four treatments were applied, each with 6 replicate pens (3 male and 3 female pens). The control group was fed the three (weaner, grower and finisher) basal diets throughout the study. The other treatments received the basal diets supplemented with 250, 500 or 750 ppm of Sr in weaner, grower and finisher diets. The pigs were fed the weaner diets over treatment days 1-28 and then transferred to the grower/finisher pens and fed the grower diets over treatment days 31-88 and then the finisher diets over treatment days 89-129.

During the weaner period (treatment days 1-28) measurements were taken weekly on a pen basis and then on a pen basis at the end of the grower (treatment days 92 and 88 for experiments 1 and 2, respectively) and finisher periods (treatment days 121 and 129 for experiments 1 and 2, respectively). Weekly feed disappearance was calculated from feed delivered minus any feed refusals. Feed conversion was calculated from body weight and feed data. At the completion of the treatment period the pigs were processed at a commercial abattoir. After evisceration the hot carcass weight (HSCW) was recorded and the P_2 fat depth measurement determined. At the end of the finisher period in experiment 1 a FLIR T620 Thermal Imaging Camera (FLIR Systems AB, Germany) was used to measure the minimum and maximum surface temperature of the left and right knee joint of each pig. Statistical analysis was conducted using the REML linear mixed model and ANOVA functions of Genstat® 18th edition.

In experiment 1, Sr supplementation in the weaner period (treatment days 1-28) supported higher average daily gain (ADG) and no effect on the daily feed intake but the improved growth supported a better feed efficiency (FCR). The supplementation starting at weaning resulted in higher BW and ADG that persisted until day 49 of treatment but at the end of the grower (day 90 of treatment) and end of the finisher phase (day 121 of treatment) there was no difference in BW or ADG. The supplementation from the start of the grower phase had no effect on any performance measure. Over the entire supplementation period the Sr supplementation had no effect on performance, carcass yield, P2 backfat measure or leg joint surface temperature.

Experiment 2, was essentially a dose response study where Sr was supplemented at 250, 500 or 750 ppm from weaning until processing. Contrary to the results in the weaner phase of experiment 1 (treatment days 1-28) the Sr supplementations had no effect on BW, ADG or ADFI at any week but there were small changes which were sufficient to have an influence on the FCR with it being improved when supplementation was at 500 and 750 ppm. During the grower/finisher phases (treatment days 31-129) the Sr supplementation had no effect on BW, ADG, ADFI and FCR. The overall result was that over the entire treatment period there were on performance improvements with SR supplementation at any concentration and at processing it followed that there was no effect on HSCW, dressing % or P2 backfat.

When pigs were supplemented with 500 ppm Sr in a commercial environment there were significant improvements in weaner growth performance and feed efficiency. During the weaner period pigs consumed approximately 10 kg of feed and so supplementation at 500 ppm a total of 5 mg of Sr per pig and would be a small economic cost. Strontium supplementation in the grower and finisher phase provided no economic benefit to performance.

Table of Contents

List of Tables

1. Background to Research

The development of a healthy skeletal structure, along with optimum muscle growth in growing pigs is dependent on receiving a balanced diet composed of all essential nutrients. Strontium (Sr) is a trace mineral which across a range of species, has been reported to increase bone volume and density (Ferraro et al., 1983; Marie et al., 1985; Matsumoto, 1988; Su et al., 1992; Grynpas et al., 1996; Marie, 1996; Buehler et al., 2001; Marie, 2005). However, there is limited data on Sr supplementation in commercial livestock production, although a recent broiler chicken study showed improved liveweight gain and feed efficiency (Browning and Cowieson, 2014).

In respect to human nutrition, Sr supplementation in the form of strontium ranelate, has been shown to significantly reduce bone fractures by up to 40% in osteoporotic patients (Meunier et al., 2004; Reginster et al., 2005), by increasing bone density and bone strength. There is the potential for Sr supplementation at low doses to improve the performance of growing pigs because Sr has been shown to significantly increase insulin-like-growth factor-1 (IGF-1) concentrations in three vertebrate species, humans (Gulhan et al., 2008), goats (Li et al., 2008) and rats (Ammann et al, 2004).

A pilot trail was conducted by our group in weaner/grower pigs. The purpose of the trial was to investigate the effect of feeding low concentrations of Sr on general performance parameters such as bodyweight (BW), average body weight gain (BWG), feed conversion efficiency (FCR) and leg joint health. A total of 60 (6 pens of 10 pigs each) weaner pigs (4 weeks of age) were randomly allocated to two treatment groups (3 pens per treatment). One group was given a Sr supplementation at 500 ppm of feed and the second a control treatment had no Sr supplementation. All pigs were individually ear tagged and weighed on days 7, 14, 21 and 28 of the weaner period. Feed intake, on a pen basis, was recorded on each weigh day. On day 29, all pigs were removed from the weaner pens and transferred to two large grower pens, each holding one of the treatments and the pigs continued to be fed their respective treatment diets for a further 31 days. The total feeding period was 59 days. The grower pigs were weighed on day 42 and 59 of treatment. On day 155 of age, being 80 days after the treatment started a photograph was taken of the left and right knee joint of each pig using a thermal imaging camera, from which was measured the minimum and maximum temperature of each joint.

There was no effect on BWG or FCR after the first 14 days of treatment during the weaner period (Table1.1), but BWG from day15-28 days of the weaner period was significantly higher for pigs fed the Sr supplemented diet ($P < 0.05$). The total BWG during the 28 day weaner period was higher for the Sr supplemented weaners ($P < 0.05$). Over days 15-28 of treatment the FCR tended to be lower for the Sr supplemented pigs ($P = 0.056$).

Table 1.1. The mean (± SEM) BWG# and FCR of pigs fed a control diet or control diet supplemented with Strontium (Sr) (500 mg/kg) for 28 days (day 29-56 of age) after being weaned at day 28 of age.*

	Weaner BWG per pig (0-14d) (kg)	Weaner BWG per pig (15-28d) (kg)	Weaner BWG per pig (0-28d) (kg)	Weaner FCR (0-14d)	Weaner FCR (15-28d)	Weaner FCR (0-28d)
Treatments						
Control	2.25 ± 0.15	4.34^{b} ± 0.26	6.46^{b} ± 0.35	2.08 ± 0.29	2.56^{x} ± 0.24	2.19 ± 0.15
Strontium	2.25 ± 0.16	5.33^{a} ± 0.27	7.60^{a} ± 0.37	2.33 ± 0.29	1.88^{y} ± 0.25	2.02 ± 0.15
P	NS	< 0.01	< 0.05	NS	0.056	NS

$^{a-b}$Means in columns without common superscript differ significantly (P < 0.05)
^{xy} Means in columns without common superscript tended to be different (P < 0.10)
#BWG = Body weight gain; *FCR = Feed conversion ratio

During the first phase of the grower period (days 28-42) BWG was not different between treatments (Table 1.2), however, over days 43-59 of treatment it tended to higher for the supplemented pigs (P = 0.057) , resulting in the final BW of the supplemented pigs to be higher (P < 0.05) at the end of the treatment period.

Table 1.2. The mean (± SEM) BWG of pigs fed a control diet or control diet supplemented with Sr (500 mg/kg) for 31 days (day 57- 88 days of age). Measurements were made on day 28, 42 and 59 of the treatment period. There was one group pen per treatment

Gender					
	Grower BW per pig at 42d (kg)	Grower BW per pig at 59d (kg)	Grower BWG per pig (28-42d) (kg)	Grower BWG per pig (43-59d) (kg)	Grower BWG per pig (28-59d) (kg)
Treatment					
Control	21.6 ± 0.59	30.8^{b} ± 0.75	7.2 ± 0.26	9.2^{x} ± 0.45	16.4 ± 0.53
Strontium	22.8 ± 0.63	33.2^{a} ± 0.80	6.9 ± 0.28	10.5^{y} ± 0.49	17.3 ± 0.57
P	NS	< 0.05	NS	0.057	NS

$^{a-b}$Means in columns without common superscript differ significantly^{xy} Means in columns without common superscript tended to be different (P < 0.10)

The effect of Sr supplementation on surface foreleg joint temperature is shown in Table 1.3. For the left t leg the maximum and average temperature was higher (P < 0.01) for the control pigs and this tended to be similar for the right leg but the differences were marginally non-significant (P = 0.059).

Table 1.3. The effects of Sr supplementation on the mean (± SEM) surface temperature (C°) of the left and right foreleg joint at 115 days of age (59 days of Sr supplementation) in grower pigs.

	Left foreleg Joint Minimum Temp (C°)	Left foreleg joint Maximum Temp (C°)	Left foreleg joint Average Temp (C°)	Right foreleg joint Minimum Temp (C°)	Right foreleg joint Maximum Temp (C°)	Right foreleg joint Average Temp (C°)
Treatment						
Control	24.3 ± 0.4	34.4 ± 0.4[a]	30.4 ± 0.4[a]	24.4 ± 0.4[x]	33.0 ± 0.5	29.9 ± 0.4
Strontium	23.5 ± 0.3	32.8 ± 0.4[b]	29.0 ± 0.3[b]	23.3 ± 0.4[y]	32.4 ± 0.4	29 ± 0.4
P	NS	< 0.01	< 0.01	0.059	0.054	0.062

[a-b]Means in columns without common superscript differ significantly

[xy] Means in columns without common superscript tended to be different ($P < 0.10$)

The pilot study was limited largely due to the low number of reps during the weaner phase and then only a single group pen in the grower phase. However, the data provided sufficient evidence that more comprehensive studies under commercial conditions were warranted. There is some evidence that joint inflammation leading to osteochondrosis could start during the weaner phase onwards. Therefore, this pilot study provided strong evidence to complete a more comprehensive study where strontium is supplemented from weaning to marketing taking into consideration the performance, carcass characteristics and joint inflammation in pigs. The results from this more comprehensive study are outlined in this report.

2. Objectives of the Research Project

i) Supplement pig diets with strontium and measure production performance as weight gain and feed efficiency.

ii) Determine the effect of strontium supplementation on carcass characteristics.

iii) Determine the effect of strontium supplementation on joint temperature as an indicator of inflammation and the likelihood of osteochondrosis.

3. Introductory Technical Information

Strontium (Sr) is a trace mineral and has been shown to improve bone volume and density (Ammann *et al*., 2004; Shahnazari *et al*., 2007; Li *et al*., 2008; Browning and Cowieson, 2014). However, Sr is not considered an essential nutrient but this is based on limited research (Pors Nielsen, 2004). Strontium and Ca are similar chemically and 99% of these minerals are located in bone. Strontium concentrations in livestock feed grains is low (3-20 mg/kg) with higher values found in inorganic mineral supplements such as limestone (329 mg/kg) (Browning and Cowieson, 2013).

Recent interest in Sr physiology has followed from the observation that Sr in the form of strontium ranelate, when provided at 2g Sr/day to osteoporotic human patients significantly reduced bone fractures (Meunier *et al*., 2004; Reginster *et al*., 2005). Supplementation with Sr is widely prescribed for the human osteoporotic condition. This positive effect of Sr on bone structure and subsequent strength has also been documented in monkeys (Biovin *et al*., 2009) and rats (Ammann *et al*., 2004).

Osteochondrosis (OCD) is defined as disturbance of endochondral ossification in joint cartilage and growth plates (Reiland, 1975). The OCD causes pain and is a welfare issue in growing pigs (Nakano and Aherne, 1993). It is a significant economic loss in commercial pig production (review: Hill, 1990; Yazdi *et al*., 2000). While the causes remain poorly defined, OCD is considered idiopathic and is more commonly seen in fast growing animals between 6-18 months of age (Jørgensen *et al*., 1995). It remains the most common cause of lameness in pigs (Reviews: Hill, 1990: Bohndorf, 1998). Common sites for OCD lesions include the medial condyles of the femur and humerus. Lundeheim (1987) reported that OCD was found in nearly 100% of young growing pigs to various degrees of severity.

There are genetic and phenotypic correlation between selection for growth rate and incidence of OCD lesions (Kadarmideen *et al*., 2004).While there is a genetic component to OCD other environmental factors are likely to influence the degree of gene expression. Biomedical stress could promote development of OCD (Ytrehus *et al*., 2004). It is proposed that the greater prevalence of OCD in free-ranging pigs compared to indoor housed pigs is related to the more extensive mobility outdoors (Potter, 1998; Etterlin, 2016).

Using six commercial breeds of pigs, differences in the rate of OCD was identified by Goedegebuure *et al*., (1980). A lower incidence was found in Yorkshire pigs compared with Landrace pigs (Grøndalen, 1974). The effect of sex is not consistent with some researchers identifying differences (Van der Wal *et al*., 1987; Goedegebuure *et al*., 1988) and other finding no sex effects on OCD rates (Grøddalen and Vangen, 1974). No clear evidence exists the OCD is a primary response to pathogenic organisms but secondary infection can exacerbate animals welfare. There is the possibility that the secondary consequences of disease may predispose the animals to OCD. Housing conditions that cause trauma can promote circumstances that increase potential for OCD.

Dietary calcium and phosphorous supplementation had no effect on the severity of OCD (Kornegay *et al*., 1990). Nakano et al., (1987) reviewed the nutritional effects on the severity of OCD and as a general conclusion found that there was no real evidence of nutritional preventative values of the nutrients investigated to date. Not all nutrients have been investigated so there remain potential benefits of unknown supplements including Sr on incidence of OCD. So a role for strontium in incidence of OCD needs consideration in pig nutrition.

There is some limited published research data on a role for strontium in the nutrition of production animals. In an earlier study, where Sr at 6000 ppm and 3000 ppm was fed to broilers had conflicting consequences (Weber at al., 1968). At 6000 ppm, growth and FCR was lower but at 3000 ppm there was no effect on performance. When aged laying hen diets were supplemented with 3,000 and 5,000 ppm Sr there was no effect on performance or eggshell thickness (Doberenz *et al*., 1969). However, Sr at 3000, 4500 and 6000 ppm had positive effects on bone density and strength in laying hens

(Shahnazari *et al.*, 2006). At 1200 and 2400 ppm Sr inclusion in the diet improved bone volume and architecture but not bone strength in broilers (Shahnazari *et al.* 2007).

In pigs strontium at 5,500 ppm in the diet was found to be toxic (Bartley and Reber, 1961). Using a more realistic inclusion rate of 50 ppm in four week old pigs, bone strength was increased 10-11% and mineral density by 6-8% (Pagano *et al.*, 2007). The intake of Sr on a body weight basis was determined to be 3 mg/kg/d. So the low dose of Sr had a positive effect on bone mineral content and breaking strength.

Insulin-like growth factor one (IGF-1) is known to be a local regulator of bone osteoblast and osteoclast function during bone formation (Seck *et al.*, 1998, Le Roith *et al.*, 2001) and cartilage growth (Canalis *et al.*, 1988, Canalis, 1993) and a predictor of overall bone mass density (Thomas *et al.*, 1998, Rucker *et al.*, 2004). Strontium ranelate at 2g per day with additional Ca (1,500 mg / day) and vitamin D (400 iu/day) to post-menopausal women for 6 months resulted in an 11.8% increase in serum IGF-1 (Gulhan *et al.*, 2008). A 15% increase in serum IGF-1 for male and 5% in female rats occurred after 104 weeks of supplementation with strontium ranelate (Ammann *et al.*, 2004). In goats, strontium at 40 mg/kg/day with 100mg /kg/day of Ca increased IGF-1 expression and bone formation (Li *et al.*, 2008).

There is strong interaction between IGF-1 and the hormonal form of vitamin D (1,25-$(OH)_2D_3$) acting to up-regulate each other, with 1,25-$(OH)_2D_3$ promoting IGF-1 receptor density (Ogata *et al.*, 2000), while and IGF-1 can elevate 1,25-(OH)2D_3 concentrations by stimulating the hydroxylation of 25(OH)D_3 to the active 1,25-$(OH)_2D_3$ hormone (Gomez, 2006, Wei *et al.*, 1998, Lawson *et al.*, 1979, Ahmad *et al.*, 2003).

The relationship between the vitamin D system and IGF-1 is further exemplified with the decline of both with increasing age in human studies. In middle-aged and elderly men, there was a significant relationship between serum IGF-1 and 25(OH)D_3 concentrations (Rucker *et al.*, 2004, Lawson *et al.*, 1979. Fatayerji *et al* (2000) found that strontium absorption was not related to 1,25-(OH)2D3 or 25(OH)D3 serum concentrations but positively correlated with IGF-1 (Fatayerji *et al.*, 2000).

The potential roles in bone functioning, OCD and connection with vitamin D and IGF-1 physiology suggest that there is a need to investigate the effects of supplemental Sr on general performance of commercial pigs.

4. Research Methodology

Based on the results of the pilot study two experiments were conducted in a commercial setting to evaluate the role of strontium supplementation in pig diets on performance and carcass yields.

4.1 Experimental designs

4.1.1 Experimental location and animal ethics

Both experiments were conducted at SunPork Group Farms in Westbrook, Qld., Australia. The use of animals complied with the requirements of the National Health and Medical Research Council of Australia, CSIRO and the Australian Agricultural Council entitled 'Australian code for the care and use of animals for scientific purposes, 8th edition.' National Health and Medical Research Council, Canberra, (2013) and was approved by the Animal Care and Ethics Committee of SunPork Farms.

4.2 Experimental Treatments

4.2.1 Experiment 1

In experiment 1, three treatments were applied, each with 8 replicate pens (4 male and 4 female pens). The control group were fed three (weaner, grower and finisher) basal diets throughout the study. A second treatment group (WS) received the basal diet plus supplemental strontium carbonate at 500 ppm in the weaner grower and finisher diets. The third group (GS) received the basal weaner diet and then transferred to supplemented strontium carbonate 500 ppm grower and finisher diets.
The pigs were fed the weaner diet for a total of 4 weeks (treatment days 1-28) and then remained in the weaner facility for a further 3 weeks (treatment days 29-49) and fed the grower diets. The extended period in the weaning facility was a commercial management decision. The pigs were then moved to the grower/finisher facility and feed the grower diet until day 92 of treatment when they were transferred to the finisher diet until day 121 of treatment.

4.2.2 Experiment 2

For experiment 2, four treatments were applied, each with 6 replicate pens (3 male and 3 female pens). The control group were fed the three (weaner, grower and finisher) basal diets throughout the study. The second, third and fourth treatments received the basal diets supplemented with 422 mg/kg (250 ppm Sr), 843 mg/kg (500 ppm Sr) and 1265 mg/kg (750 ppm Sr) of strontium carbonate. The pigs were fed the weaner diets over treatment days 1-28 and then transferred to the grower/finisher pens and fed the grower diets over treatment days 31-88 and then the finisher diets over treatment days 89-129.

4.3 Measurements

4.3.1 Experiment 1

The pigs were weighed on a pen basis at the start of the experiment and on a weekly basis over days 1-28 (days 29-49 of age) of the weaner period. The pigs remained in the weaner facility for treatment days 29-49 (days 50-70 of age) and were fed the grower diet and then weighed before being transferred to the grower/finisher facility and continued on the grower diet over days 50-92 of treatment (days 71-113 of age). The pigs were then fed the finisher diets over treatment days 93-121 (days 114-144 of age). Weekly feed intake was calculated from feed delivered minus any feed refusals. Feed conversion was calculated from body weight and feed data.

At the end of the finisher period a FLIR T620 Thermal Imaging Camera (FLIR Systems AB, Germany) was used to measure the minimum and maximum surface temperature of the left and right knee ankle joints of each pig. Thermal images were processed using FLIR Therma CAM Researcher Pro 2.10 software (FLIR Systems AB, Germany).

At the completion of the treatment period the pigs were processed at a commercial abattoir. After evisceration the hot standard carcass weight (HSCW) was recorded and the P2 fat depth measurement was determined. To fit in with commercial requirements of processing pigs at a market desirable weight the pigs were processed over a 2-3 week period after the final experimental weigh day.

4.3.2 Experiment 2

The pigs were weighed on a pen basis at the start of the experiment and on a weekly basis for the following four weeks of the weaner period. At the end of the 4 week weaner period and entry to the grower/finisher facility (day 31 of treatment) all pigs were weighed individually and then again at the end of the grower period (day 88 of treatment) and then at the end of the finisher period (day 129 of treatment). In the weaner period the weekly feed intake and FCR were calculated as described for experiment 1. During the grower/finisher period total feed intake and final body weight was recorded and from this FCR was calculated. At the completion of the finisher period the pigs were processed at a commercial abattoir. To fit in with commercial requirements of processing pigs at a market desirable weight the pigs were processed over a 2-3 week period after the final experimental weigh day. After evisceration HSCW was recorded and the P2 fat depth measurement determined.

4.4 Statistical analysis

4.4.1 Experiment 1

Data were stored in Microsoft Excel® and, unless stated otherwise, statistical analysis was conducted using the REML linear mixed model function of Genstat® 18th edition. The data were first tested for equality of variance using residual plots. When the equality of variance could be improved using a $\log_e$ transformation the data was transformed.

The measures for ADG, ADFI, FCR and BW were repeated measures on a pen basis. In the weaner period this was made on a weekly basis. During the grower/finisher period the analysis was made on a period of treatment basis. The analysis used the following REML linear mixed model function. The fixed model included the effects of treatment, sex and treatment day and the random model included the effects of replication and pen. Initially all two-way interactions between fixed effects were included in the model. Significance testing of fixed effects was conducted using Wald tests with a significance threshold of $P < 0.05$. Any non-significant interactions were removed from the model. The predicted means for all significant fixed effects were copied to Microsoft Excel® as well as the standard errors which were used to calculate the SEM. When significance was detected, the LSD, which is equal to two times the SED, was used to make pairwise comparisons of means. Microsoft Excel® was used to create graphical summaries of the back-transformed means.

For the final performance measures at day 121 of treatment, differences between the leg joint temperatures, HSCW weight and adjusted P2 were performed using the ANOVA function of Genstat® 18^{th} edition with treatment and sex included as the main effects. When effects were significant the individual comparisons were again made using LSD as described above.

4.4.2 Experiment 2

Over the 4 week weaning period measurements were made each week. Therefore, the analysis was similar to that described in experiment 1 for the weaner period. During the grower and finisher period bodyweight measurements were made on an individual pig basis while feed intake was determined on pen basis over the entire period. Therefore, over the grower/finisher period the bodyweight and ADG were analysed using REML linear mixed model function with the fixed model including the effects of treatment, sex and treatment day and the random model included the effects of replication and pen as described for experiment 1. The ADFI and FCR were analysed on a pen basis over the entire grower/finisher period by a two-way ANOVA with treatment and sex as the factors. Similarly, the effects of treatment and sex on HSCW and P2 were analysed by a two-way ANOVA. When effects were significant the individual comparisons were again made using LSD as described above.

5. Results

5.1 Experiment 1.

5.1.1 Performance during the weaner period (treatment days 1-28)

During the weaning period repeated measures were made on a pen basis every 7 days. During this period, the weaned pigs allocated to the control group and group to be fed Sr from the grower period were both fed the basal weaner diet.

5.1.1.1 Average daily gain (ADG)

Treatment (Table 2.1.) had a significant effect (P = 0.010) on ADG during the first 28 days of the feeding period with no interaction with day of treatment or sex. Pigs supplemented with Sr had a higher ADG (P < 0.05). Treatment day had a significant effect on ADG (P < 0.001), with it increasing significantly every additional treatment week (P < 0.05). Sex had no effect on ADG (P = 0.557) with males gaining 165 ± 5 g/d and females 169 ± 5 g/d.

Table 2.1. The mean (± SEM) ADG (g/d) for pigs fed a control diet (Control and GS) or diet supplemented with 500 ppm of strontium (WS) weaning until day 49 of age (days 1-28 of treatment).

	Day of Treatment (average age)				
Treatment	7 (28 d)	14 (35 d)	21 (42 d)	28 (49 d)	**Overall Treatment effect**
Control	53 ± 4	164 ± 12	228 ± 17	315 ± 24	158 ± 5^{b}
GS	52 ± 4	166 ± 13	233 ± 18	319 ± 25	159 ± 6^{b}
WS	64 ± 4	189 ± 15	255 ± 20	392 ± 31	187 ± 7^{a}
Overall day effect	$56 \pm 3_{A}$	$173 \pm 8_{B}$	$239 \pm 11_{C}$	$341 \pm 15_{D}$	

^{ab} Within columns values without similar superscripts are significantly different at P < 0.05.
$_{A\text{--}D}$ Within a row values without similar subscripts are significantly different at P < 0.05.

5.1.1.2 Average daily feed intake (ADFI)

Neither treatment (P = 0.609) nor sex (P = 0.239) had an effect on ADFI during the first 28 days of the feeding period (Table 2.2.). For males the mean (± SEM) intake was 305 ± 13 g/d and females was 323 ± 13 g/d. Treatment day had s significant effect on ADFI (P < 0.001) with the daily intake increasing every additional treatment week (P < 0.05).

Table 2.2. The mean (± SEM) ADFI (g/d) for pigs fed a control diet (Control and GS) or diet supplemented with 500 ppm of strontium (WS) from weaning until day 49 of age (28 days of treatment).

	Day of Treatment (average age)				
Treatment	7 (28 d)	14 (35 d)	21 (42 d)	28 (49 d)	**Overall Treatment effect**
Control	164 ± 9	277 ± 15	398 ± 22	516 ± 28	310 ± 15
WS	156 ± 9	268 ± 15	395 ± 22	519 ± 29	304 ± 15
GS	169 ± 9	288 ± 15	411 ± 23	572 ± 31	327 ± 16
Overall day effect	163 ± 6_A	277 ± 11_B	401 ± 16_C	535 ± 21_D	

$_{A\text{--}D}$ Within a row values without similar subscripts are significantly different at P < 0.05.

5.1.1.3 Feed Conversion Ratio (FCR)

Treatment had a significant effect (Table 2.3.) on the FCR (P = 0.006) but there was no interaction with day (P = 0.980) or with sex (P = 0.667). The Sr supplemented pigs had better FCR compared with the other treatment allocations (P < 0.05). Treatment day had a significant effect (P < 0.001) on FCR. In the first 7 days feed efficiency was lower than for the other weekly periods (P < 0.05). Sex had no effect on FCR (P = 0.352) with it being 1.90 ± 0.04 for the females and 1.85 ± 0.04 for the males.

Table 2.3. The mean (± SEM) FCR for pigs fed a control diet (Control and GS) or diet supplemented with 500 ppm of strontium (WS) from weaning until day 49 of age (28 days of treatment).

	Day of Treatment (average age)				
Treatment	7 (28 d)	14 (35 d)	21 (42 d)	28 (49 d)	**Overall Treatment effect**
Control	3.13 ± 0.20	1.69 ± 0.11	1.75 ± 0.11	1.64 ± 0.10	1.97 ± 0.04^a
WS	3.11 ± 0.21	1.60 ± 0.10	1.68 ± 0.11	1.62 ± 0.10	1.92 ± 0.05^a
GS	2.63 ± 0.17	1.52 ± 0.10	1.61 ± 0.10	1.45 ± 0.09	1.75 ± 0.04^b
Overall day effect	2.94 ± 0.11_A	1.60 ± 0.06_B	1.68 ± 0.06_B	1.57 ± 0.06_B	

^{ab} Within columns values without similar superscripts are significantly different at P < 0.05.
$_{\text{-D}}$ Within a row values without similar subscripts are significantly different at P < 0.05.

5.1.2 Performance during the different treatment periods

During the feeding period repeated measures were made on a pen basis at day 28, 49, 92 and 121days of treatment. This allowed evaluation of any potential effects on Sr on performance over different measurement periods.

5.1.2.1 Bodyweight (BW)

Day of treatment had significant effect on the BW ($P < 0.001$) but it depended on the treatment (Table 2.4) with the day x treatment interaction being significant ($P = 0.055$) and also depended on the pen sex (Table 4.4.) as the day x sex interaction was also significant ($P = 0.041$). There was no treatment x sex interaction ($P = 0.700$).

At weaning (day 0) all treatments had a similar mean BW. At days 28 and 49 the BW was higher for the WS treatment compared to the other treatments ($P < 0.05$). By day 92 the BW of treatment WS remained higher compared to control treatment ($P < 0.05$) but not the GS treatment. As expected the BW weight significantly increased ($P < 0.05$) at each weigh period (Table 2.5.). At day 92 males were heavier than females ($P < 0.05$) but there was no difference between sexes at any other weigh period.

Table 2.4. The mean (± SEM) BW (kg) for pig fed a control diet or diet supplemented with 500 ppm of strontium from weaning (at 21 days of age) until slaughter (WS) or from the start of the grower period (day 49 of treatment) until slaughter (GS).

	Day of Treatment (average age)				
Treatment	0 (22 d)	28 (49 d)	49 (70 d)	92 (113 d)	121 (144 d)
Control	$5.37 \pm 0.18_{A}$	$10.76 \pm 15_{B}^{b}$	$22.22 \pm 0.73_{C}^{b}$	$55.70 \pm 1.84_{D}^{b}$	$84.44 \pm 2.76_{E}$
GS	$5.58 \pm 0.18_{A}$	$10.90 \pm 15_{B}^{b}$	$22.73 \pm 0.75_{C}^{b}$	$57.00 \pm 1.84_{D}^{ab}$	$84.52 \pm 2.79_{E}$
WS	$5.48 \pm 0.19_{A}$	$11.79 \pm 15_{B}^{a}$	$23.94 \pm 0.79_{C}^{a}$	$58.15 \pm 1.88_{D}^{a}$	$86.31 \pm 2.84_{E}$

^{ab} Within columns values without similar superscripts are significantly different at $P < 0.05$.
$_{A\text{-}D}$ Within a row values without similar subscripts are significantly different at $P < 0.05$.

Table 2.5. The effect of sex on the mean (± SEM) BW (kg) for male or females pigs from weaning until the end of the finisher period.

	Day of Treatment (average age)				
Sex	0 (22 d)	28 (49 d)	49 (70 d)	92 (113 d)	121 (144 d)
Female	$5.39 \pm 0.17_A$	$11.12 \pm 0.34_B$	$23.22 \pm 0.72_C$	$57.97 \pm 1.80_D^a$	$84.94 \pm 2.63_E$
Male	$5.57 \pm 0.17_A$	$11.17 \pm 0.34_B$	$22.71 \pm 0.70_C$	$55.92 \pm 1.73_D^b$	$85.11 \pm 2.64_E$

^{ab} Within columns values without similar superscripts are significantly different at P < 0.05.
$_{A\text{-}D}$ Within a row values without similar suberscripts are significantly different at P < 0.05.

Average daily gain (ADG)

Treatment day had a highly significant effect on ADG but this depended on the treatments (Table 2.6.) as the day x treatment interaction was significant (P = 0.015) and also depended on the pen sex (Table 4.7.) as the day x sex interaction was also significant (P = 0.013). There was no treatment x sex interaction (P = 0.639). After 28 days of treatment pigs on the WS treatment had higher ADG than the other two treatments being fed the control diet (P < 0.05). On day 49 of treatment the GS and WS treatments both being supplemented with Sr had similar ADG but the gain for the WS remained higher than for of the control treatment (P < 0.05). No differences were recorded at day 92 and 121. As expected the ADG increased significantly at each of the weigh periods.

It was not until day 121 of treatment that there were any differences in ADG (Table 2.7) between the sexes when it was higher in males (P < 0.05).

Table 2.6. The mean (± SEM) ADG (g/d) for pigs fed a control diet or diet supplemented with 500 ppm of strontium from weaning (at 21 days of age) until slaughter (WS) or from the start of the grower period (day 70 of treatment) until slaughter (GS).

	Day of Treatment (average age)			
Treatment	28 (49 d)	49 (70 d)	92 (113 d)	121 (144 d)
Control	$187 \pm 5_A^b$	$521 \pm 15_B^b$	$798 \pm 22_C$	$987 \pm 27_D$
GS	$188 \pm 5_A^b$	$534 \pm 15_B^{ab}$	$810 \pm 23_C$	$949 \pm 26_D$
WS	$221 \pm 5_A^a$	$554 \pm 15_B^a$	$816 \pm 23_C$	$963 \pm 27_D$

^{ab} Within columns values without similar superscripts are significantly different at P < 0.05.
$_{A\text{-}D}$ Within a row values without similar subscripts are significantly different at P < 0.05.

Table 2.7. The effect of sex on the mean (± SEM) ADG (g/d) for male or females pig from weaning until slaughter.

	Day of Treatment (average age)			
Sex	28 (49 d)	49 (70 d)	92 (113 d)	121 (144 d)
Female	201 ± 4_A	549 ± 13_B	827 ± 19_C	930 ± 23_D^b
Male	196 ± 4_A	524 ± 13_B	790 ± 18_C	1008 ± 23_D^a

^{ab} Within columns values without similar superscripts are significantly different at P < 0.05.
$_{A\text{-}D}$ Within a row values without similar subscripts are significantly different at P < 0.05.

5.1.2.2 Average daily feed intake (ADFI)

Treatment day (Table 2.8.) had a significant effect on ADFI but there were significant interactions with treatment (P = 0.054) and sex (P = 0.026). As the pigs aged, their ADFI progressively increased (P < 0.05). Differences in ADFI were only noted on day 121 of treatment were is was higher in the control group compared to the Sr treatments (P < 0.05). Males had a lower ADFI on day 113 of treatment (Table 2.9.) but not on other periods.

Table 2.8. The mean (± SEM) ADFI (g/d) for pigs on a control diet or diets supplemented with 500 ppm of strontium from weaning (at 21 days of age) until slaughter (WS) or from the start of the grower period (day 70 of treatment) until slaughter (GS).

	Day of Treatment (average age)				
Treatment	28 (49 d)	49 (70 d)	92 (113 d)	121 (144 d)	**SEM**
Control	344_A	824_B	1640_C	2486_D^a	
GS	332_A	834_B	1621_C	2377_D^b	0.28
WS	360_A	858_B	1681_C	2403_D^b	
SEM			0.28		

^{ab} Within a column values without similar superscripts are significantly different at P < 0.05.
$_{A\text{-}D}$ Within a row values without similar subscripts are significantly different at P < 0.05.

Table 2.9. The effect of sex on the mean (± SEM) ADFI (g/d) for male or females pig from weaning until slaughter.

	Day of Treatment (average age)			
Sex	28 (49 d)	49 (70 d)	92 (113 d)	121 (144 d)
Female	353 ± 5_A	865 ± 13_B	1704 ± 21_C^a	2425 ± 23_D
Male	338 ± 5_A	818 ± 13_B	1591 ± 20_C^b	2419 ± 25_D

[ab] Within a column values without similar superscripts are significantly different at P < 0.05.
A-D Within a row values without similar subscripts are significantly different at P < 0.05.

5.1.2.3 Feed conversion ratio (FCR)

Treatment (P = 0.057) had a marginally non-significant effect on FCR but treatment day (P < 0.001) and sex (P = 0.04) had significant effects on FCR. On all days, the FCR was significantly different (P < 0.05) compared to other treatment days (Table 2.10). The FCR was lowest at day 49 and highest at day 121. Males had an FCR of 1.89 ± 0.01 which was lower than that of females at 1.96 ± 0.01 (P < 0.05).

Table 2.10. The mean (± SEM) FCR for pigs fed a control diet or diets supplemented with 500 ppm of strontium from weaning (at 21 days of age) until slaughter (WS) or from the start of the grower period (day 70 of treatment) until slaughter (GS).

	Day of Treatment (average age)			
Treatment	28 (49 d)	49 (70 d)	92 (113 d)	121 (144 d)
Control	1.82 ± 0.04_C^a	1.58 ± 0.03_D	2.05 ± 0.05_B	2.52 ± 0.06_A
GS	1.76 ± 0.04_C^a	1.57 ± 0.03_D	1.99 ± 0.04_B	2.50 ± 0.05_A
WS	1.62 ± 0.04_C^b	1.54 ± 0.03_D	2.05 ± 0.05_B	2.48 ± 0.05_A
Overall Average	1.73 ± 0.02^b	1.56 ± 0.02^a	2.03 ± 0.03^c	2.50 ± 0.03^d

[ab] Within a column values without similar superscripts are significantly different at P < 0.05.
A-D Within a row values without similar subscripts are significantly different at P < 0.05.

5.1.3 *Performance over the entire treatment period*

The performance measures for the entire treatment period are shown in Table 2.11. The treatments had no effect on final BW, the ADG, the ADFI or the FCR. Sex has a significant effect on ADFI with it higher for females (P < 0.05) and also a significant effect on FCR with males being more efficient than females (P < 0.05).

Table 2.11. The mean (± SEM) performance values for pigs fed for 121 days (days 21-144 of age a control diet or diets supplemented with 500 ppm of strontium from weaning (at 21 days of age) until slaughter (WS) or from the start of the grower period (day 49 of treatment) until slaughter (GS).

	Performance measure			
	BW (kg)	**ADG (g/d)**	**ADFI (g/d)**	**FCR**
Treatment				
Control	84.7 ± 1.5	654 ± 9	1387 ± 19	2.12 ± 0.02
GS	84.0 ± 1.4	657 ± 9	1345 ± 19	2.06 ± 0.02
Ws	86.5 ± 1.5	667 ± 10	1379 ± 19	2.06 ± 0.02
Sex				
Female	84.9± 1.2	657 ± 11	1398 ± 22[a]	2.13 ± 0.01[a]
Male	85.1 ± 1.2	656 ± 11	1343 ± 21[b]	2.04 ± 0.01[b]
P Values				
Treatment	0.453	0.425	0.306	0.134
Sex	0.917	0.992	0.022	0.006
T X S	0.387	0.447	0.253	0.397

[ab] Within a row values without similar superscripts are significantly different at P < 0.05.

5.1.3.1 Carcass traits

The pigs were slaughtered over days 139-167 of age with some pigs from each treatment group slaughtered on each processing day. The slaughter age had no effect on HSCW (P = 0.136) or P2 backfat (0.677) and was removed from any further analysis. The effects of treatment and sex on carcass traits are given in Table 2.12. Neither treatment (P = 0.540) nor sex (P = 0.445) had any effects on HSCW. Treatment had no effect (P = 0.284) on P2 backfat measure but the sex effect was significant (P < 0.001) with males having more backfat than the females (P < 0.05).

Table 2.12. The mean (± SEM) HSCW and P2 backfat for pigs fed for 121 days (days 21-144 of age a control diet or diets supplemented with 500 ppm of strontium from weaning (at 21 days of age) until slaughter (WS) or from the start of the grower period (day 49 of treatment) until slaughter (GS).

	Carcass Traits	
	HSCW (kg)	**P2 (mm)**
Treatment		
Control	81.3 ± 0.4	11.61 ± 0.24
GS	81.4 ± 0.5	11.11 ± 0.24
WS	82.0 ±0.5	11.15 ± 0.25
Sex		
Female	81.8 ± 0.4	10.76 ± 0.29^{b}
Male	81.4 ± 0.4	11.86 ± 029^{a}
P Values		
Treatment (T)	0.540	0.284
Sex (S)	0.445	< 0.001
T X S	0.141	0.447

5.1.3.2 Knee joint surface temperatures

The knee joint temperatures are shown in 2.13. The treatments had no effect on final knee joint temperatures. Sex has an effect on the average joint temperatures (P = 0.009) with it being higher in the males (P < 0.05).

Table 2.13. The mean (± SEM) knee joint surface temperatures for pigs fed for 121 days (days 21-144 of age a control diet or diets supplemented with 500 ppm of strontium from weaning (at 21 days of age) until slaughter (WS) or from the start of the grower period (day 49 of treatment) until slaughter (GS).

	Surface skin temperature (^{0}C)					
	Front right	**Front left**	**Rear right**	**Rear left**	**Front average**	**Rear average**
Treatment						
Control	35.33 ± 0.29	35.18 ± 0.21	35.61 ± 0.24	35.87 ± 0.17	35.30 ± 0.19	35.72 ± 0.16
GS	35.33 ± 0.29	35.47 ± 0.21	35.99 ± 0.24	36.04 ± 0.18	35.40 ± 0.02	36.03 ± 0.17
Ws	35.01 ± 0.30	35.08 ± 0.22	35.69 ± 0.25	35.85 ± 0.18	35.00 ± 0.02	35.77 ± 0.17
Sex						
Female	34.99 ± 0.24	34.88 ± 0.24	35.59 ± 0.20	35.65 ± 0.24	34.95 ± 0.23^{b}	35.62 ± 0.19^{b}
Male	35.47 ± 0.24	35.61 ± 0.22	35.93 ± 0.20	36.19 ± 0.19	35.55 ± 0.23^{a}	36.05 ± 0.19^{a}
P Values						
Treatment (T)	0.485	0.425	0.229	0.705	0.439	0.332
Sex (S)	0.043	0.0.003	0.089	0.008	0.010	0.023
T X D	0.233	0.221	0.224	0.443	0.213	0.361

[ab] Within a row values without similar superscripts are significantly different at P < 0.05.

5.2 Experiment 2.

5.2.1 Pig performance in the weaner period (treatment days 1-28)

5.2.1.1 Bodyweight (BW)

The effects of Sr supplementation on BW are given in Table 2.14. The treatment groups had a similar BW at weaning. Sr supplementation ($P = 0.902$) and sex ($P = 0.549$) had no effect on the BW at any sampling day during the 28 d weaning period. Sampling day (Table 2.15) had a significant effect on BW ($P < 0.001$) and this was independent of any interaction with treatment ($P = 0.554$) or with sex (0.120). At each progressive sampling day the BW was higher (all, $P < 0.05$).

Table 2.14. The mean (± SEM) BW (kg) for pigs fed a control diet or diets supplemented with 250, 500 or 750 ppm of strontium during the weaning period of 28 days.

	Day of Treatment (average age)					
	0 (21 d)	7 (28 d)	14 (35 d)	21 (42 d)	28 (49 d)	
Treatment						Overall Treatment effect
Control	5.69 ± 0.29	6.45 ± 0.32	7.87 ± 0.43	10.30 ± 0.55	13.25 ± 0.72	8.19 ± 0.40
250 ppm	5.72 ± 0.29	6.31 ± 0.32	8.30 ± 0.42	10.87 ± 0.50	14.11 ± 0.72	8.57 ± 0.42
500 ppm	5.77 ± 0.29	6.24 ± 0.32	8.32 ± 0.41	10.95 ± 0.54	14.15 ± 0.69	8.58 ± 0.42
750 ppm	5.69 ± 0.29	6.05 ± 0.31	7.87 ± 0.40	10.30 ± 0.53	13.25 ± 0.67	8.40 ± 0.41

Table 2.15. The mean (± SEM) BW (kg) for males and female pigs fed a control diet or diets supplemented with 250, 500 and 750 ppm of strontium during the weaning period of 28 days.

	Day of Treatment (average age)				
	0 (21 d)	7 (28 d)	14 (35 d)	21 (42 d)	28 (49 d)
Sex					
Female	$5.52 \pm 0.20_A^b$	$6.08 \pm 0.22_B$	$8.05 \pm 0.30_C$	$10.60 \pm 0.38_D$	$13.76 \pm 0.49_E$
Male	$5.98 \pm 0.21_A^a$	$6.35 \pm 0.22_B$	$8.24 \pm 0.30_C$	$10.74 \pm 0.39_D$	$13.76 \pm 0.49_E$

$_{A\text{--}D}$ For the main effects values within a row without similar subscripts are significantly different at $P < 0.05$.
^{ab} Within a row values without similar superscripts are significantly different at $P < 0.05$.

5.2.1.2 Average daily gain (ADG)

The effects of Sr supplementation and sex on ADG are given in Table 2.16. The treatment groups had a similar ADG at all sampling days (P = 0.251). Sex (P = 0.999) had no effects on the ADG at any sampling day during the 28 d weaning period. Sampling day had a significant effect on ADG (P < 0.001) with the ADG increasing on each progressive sampling day (all, P < 0.05).

When the data from the first sampling (day 7) is removed the effect of Sr supplementation (P = 0.265) and sex (P = 0.390) on ADG over days 7-28 of treatment were not significant.

Table 2.16. The mean (± SEM) ADG (g/d) for pigs fed a control diet or diets supplemented with 250, 500 or 750 ppm of strontium during the weaning period of 28 days. Overall effects were evaluated over days 1-28 and 8-28.

	Treatment day					
	7 (28 d)	14 (35 d)	21 (42 d)	28 (49 d)	**Overall effects Days 1-28**	**Overall effects Days 8-28**
Treatment						
Control	57 ± 7	259 ± 29	345 ± 39	419 ± 49	216 ± 13	335 ± 13
250 ppm	93 ± 11	283 ± 32	369 ± 42	463 ± 52	259 ± 15	364 ± 14
500 ppm	71 ± 9	295 ± 33	375 ± 43	452 ± 51	245 ± 15	368 ± 14
750 ppm	74 ± 9	267 ± 30	347 ± 39	430 ± 49	233 ± 14	341 ± 13
Sex						
Female	71 ± 9	295 ± 33	375 ± 43	452 ± 51	237 ± 11	358 ± 10
Male	74 ± 9	267 ± 30	347 ± 39	430 ± 49	238 ± 10	346 ± 9
Day						
	$73 \pm 5_D$	$275 \pm 16_C$	$359 \pm 20_B$	$441 \pm 25_A$		

$_{A\text{–}D}$ For the main effects values within a row without similar superscripts are significantly different at P < 0.05.

5.2.1.3 Average daily feed intake (ADFI)

The effects of Sr supplementation and sex on ADFI are given in Table 2.17. The treatment groups had a similar ADG at all sampling days (P = 0.456). Sex (P = 0.390) had no effects on the ADG at any sampling day during the 28 d weaning period. Sampling day had a significant effect on ADG (P < 0.001) with the ADG increasing on each progressive sampling day (all, P < 0.05).

When the data from the first sampling (day 7) is removed the effect of Sr supplementation (P = 0.456) and sex (P = 0.130) on ADG over days 7-28 of treatment were not significant.

Table 2.17. The mean (± SEM) ADFI (g/d) for pigs fed a control diet or diets supplemented with 250, 500 or 750 ppm of strontium during the weaning period of 28 days. Overall effects were evaluated over day 1-28 and 8-28.

	Treatment day					
	7 (28 d)	14 (35 d)	21 (42 d)	28 (49 d)	**Overall effects Days 1-28**	**Overall effects Days 8-28**
Treatment						
Control	129 ± 8	339 ± 22	533 ± 34	664 ± 43	352 ± 17	493 ± 19
250 ppm	163 ± 10	325 ± 24	597 ± 36	668 ± 44	393 ± 19	527 ± 21
500 ppm	138 ± 9	332 ± 21	512 ± 33	675 ± 43	355 ± 17	485 ± 19
750 ppm	143 ± 9	349 ± 22	523 ± 33	649 ± 42	361 ± 17	491 ± 19
Sex						
Female	153 ± 7	378 ± 17	563 ± 25	688 ± 31	387 ± 13	527 ± 14^{a}
Male	132 ± 6	321 ± 14	510 ± 23	645 ± 29	344 ± 12	473 ± 13^{b}
Day						
	142 ± 5$_{A}$	349 ± 11$_{B}$	536 ± 17$_{C}$	669 ± 21$_{D}$		

^{ab} For the main effects values within a column without similar superscripts are significantly different at P < 0.05.
$_{A\text{--}D}$ For the main effects values within a row without similar superscripts are significantly different at P < 0.05.

5.2.1.4 Feed conversion ratio (FCR)

Table 2.18. The mean (± SEM) FCR (g/d) for pigs fed a control diet or diets supplemented with 250, 500 or 750 ppm of strontium during the weaning period of 28 days. Overall effects were evaluated over day 1-28 and 8-28.

	Treatment day					
	7 (28 d)	14 (35 d)	21 (42 d)	28 (49 d)	**Overall effects Days 1-28**	**Overall effects Days 8-28**
Treatment						
Control	2.37 ± 0.15	1.31 ± 0.08	1.54 ± 0.09	1.58 ± 0.09	1.66 ± 0.05^{a}	1.58 ± 0.04^{a}
250 ppm	1.86 ± 0.12	1.32 ± 0.08	1.56 ± 0.09	1.86 ± 0.09	1.54 ± 0.04^{ab}	1.46 ± 0.04^{a}
500 ppm	1.72 ± 0.12	1.13 ± 0.07	1.36 ± 0.08	1.72 ± 0.09	1.40 ± 0.04^{c}	1.32 ± 0.04^{b}
750 ppm	1.60 ± 0.11	1.31 ± 0.08	1.50 ± 0.08	1.60 ± 0.09	1.48 ± 0.04^{bc}	1.44 ± 0.04^{a}
Sex						
Female	1.88 ± 0.09	1.34 ± 0.05	1.55 ± 0.06	1.53 ± 0.06	1.56 ± 0.03^{a}	1.56 ± 0.03^{a}
Male	1.85 ± 0.09	1.12 ± 0.05	1.43 ± 0.06	1.49 ± 0.06	1.47 ± 0.03^{b}	1.47 ± 0.03^{b}
Day						
	1.87 ± 0.06$_{C}$	1.26 ± 0.04$_{A}$	1.49 ± 0.04$_{B}$	1.50 ± 0.04$_{B}$		

^{ab} For the main effects values within a column without similar superscripts are significantly different at P < 0.05.
$_{A\text{--}D}$ For the main effects values within a row without similar superscripts are significantly different at P < 0.05.

The effects of Sr supplementation and sex on FCR are given in Table 2.18. The Sr supplementation had a significant effect on FCR (P = 0.005). The pigs supplemented with Sr at 500ppm in the diet had an improved FCR compared to all other treatments (P < 0.05). Also pigs supplemented with 750 ppm had better FCR than the pigs fed the control diet (P < 0.05).

Sex had a significant effect on the FCR (P = 0.031) with the males having a better FCR then the females (P < 0.05). Sampling day had a significant effect on FCR (P < 0.001) with the FCR recorded on day 7 being higher than other days (P < 0.05) and lower on day 14 (P < 0.05) compared to days 21 and 28 which were similar.

When the data from the first sampling (day 7) is removed the effect of sex (P = 0.010) on ADG over days 7-28 of treatment was significant. Again Males had a better FCR compared to the females (P < 0.05). The Sr supplementation had a significant effect on FCR (P = 0.031). The pig supplemented with Sr at 500ppm in the diet had an improved FCR compared to other treatments (P < 0.05).

5.2.2 The BW and ADG of pigs in the grower and finisher periods.

At the end of the weaner period (day 31 of treatment) and the end of the grower (day 88 of treatment) and finisher period (day 129 of treatment) individual rather than pen BW were recorded for all pigs. This data allowed repeated measures statistical analysis over these treatment periods.

5.2.2.1 Bodyweight (BW)

Table 2.19. The effect of treatment, treatment day and sex on the mean (± SEM) BW (kg) for pigs fed a control diet or diets supplemented with 250, 500 or 750 ppm of strontium from the start of the grower period (day 31 of treatment) until the end of the finisher period (day 129 of treatment). Analysis was performed on an individual pig rather than pen basis.

	Treatment period and day of treatment (pig age)			
	Weight Day 31 (age d 52)	Grower day 88 (age d109)	Finisher day 129 (age d 142)	
Treatment				**Overall treatment effect**
Control	15.0 ± 0.5	59.6 ± 2.0	95.1 ± 3.1	43.9 ± 1.3
250 ppm	15.7 ± 0.5	59.6 ± 2.0	94.3 ± 3.1	44.6 ± 1.3
500 ppm	15.7 ± 0.5	61.7 ± 2.0	98.2 ± 3.2	45.7 ± 1.4
750 ppm	15.1 ± 0.5	60.3 ± 1.9	94.5 ± 3.0	44.2 ± 1.3
Sex				**Overall sex effect**
Female	$15.4 \pm 0.6_C$	$60.5 \pm 2.5_B$	$92.4 \pm 3.7_A^b$	44.2 ± 0.9
Male	$15.3 \pm 0.7_C$	$60.2 \pm 2.5_B$	$98.9 \pm 4.0_A^a$	45.1 ± 0.9
Day				
	15.4 ± 0.3	60.3 ± 1.0	95.6 ± 1.5	

^{ab} For the main effects values within a column without similar superscripts are significantly different at P < 0.05.
$_{A\text{--}D}$ For the main effects values within a row without similar superscripts are significantly different at P < 0.05.

The effects of Sr supplementation, sex and treatment day on BW are given in Table 2.19. The Sr supplementation had no effect on BW (P = 0.826). Treatment day had a significant effect on BW but this depended on the sex and the interaction between these was significant (P < 0.001). The BW progressively increased at each sampling day (P < 0.05). Males and females had similar BW at treatment days 31 and 88 but males were heavier than females on day 129 (P < 0.05).

5.2.2.2 Average daily gain (ADG)

The effects of Sr supplementation and sex, and treatment day on ADG are given in Table 2.20. The Sr supplementation had no effect on ADG (P = 0.898). Treatment day has a significant effect on ADG but there was a significant interaction with sex (P < 0.001). Males and females had similar ADG at the end of the grower period but at the end of the finisher period males had higher ADG (P < 0.05).

Table 2.20. The effect of treatment, treatment day and sex on the mean (± SEM) ADG (g/kg) for pigs fed a control diet or diets supplemented with 250, 500 or 750 ppm of strontium from the start of the grower period (day 31 of treatment) until the end of the finisher period (day 129 of age). Analysis performed on an individual pig rather than pen basis.

	Average Daily Gain		
	Grower day 88 (day109)	Finisher day 129 (day 142)	**Overall treatment effect**
Treatment			
Control	745 ± 42	1048 ± 55	884 ± 45
250 ppm	724 ± 41	1031 ± 54	864 ± 45
500 ppm	765 ± 43	1083 ± 57	910 ± 47
750 ppm	761 ± 43	1022 ± 54	882 ± 46
Sex			
Female	$763 \pm 30_{A}$	$966 \pm 36_{B}^{a}$	859 ± 31
Male	$735 \pm 29_{A}$	$1142 \pm 42_{A}^{a}$	910 ± 33
Day			
	748 ± 21	1046 ±28	

[ab] For the main effects values within a column without similar superscripts are significantly different at P < 0.05.
$_{A\text{--}D}$ For the main effects values within a row without similar superscripts are significantly different at P < 0.05.

5.2.3 *Pig performance over the combined grower and finisher periods (Treatment days 31-129)*

The analysis was conducted on a pen basis. The effects of Sr supplementation and sex on the performance of the pigs over the grower and finisher periods (days 31-129 of treatment) are given in Table 2.21. The strontium supplementation had no effect on the final BW ranging between 94.8 and 98.5 kg. The Sr supplementation had no effect on the ADG (1086 t o 1157 g/d), the ADFI (2.32 to 2.55 kg/d) or on the FCR (2.10 to 2.25).

Males had a higher ADG then females (1236 ± 15 Vs 1012 ± 12 g/d) and this resulted in males having a higher ($P < 0.05$) BW (99.3 ± 1.8 Vs 92.7 ± 1.7 kg). The males had a higher ADFI ($P < 0.05$) than the females (2.57 ± 0.05 Vs 2.32 ± 0.05 kg/d) and together these differences supported males having a better ($P < 0.05$) FCR than the females (2.08 ± 0.05 Vs 2.29 ± 0.04).

Table 2.21. The mean (± SEM) BW, ADG, ADFI and FCR ADFI for pigs fed a control diet or diets supplemented with 250, 500 or 750 ppm of strontium from the end of the weaner period until the end of the finisher periods (days 31 – 129 of treatment). The analysis is based on a pen basis.

		Performance measure			
	Strontium (ppm)	BW (kg)	ADG (g/d)	ADFI (kg/d)	FCR
Treatment					
	0	95.5 ± 2.4	1126 ± 19	2.46 ± 0.7	2.19 ± 0.05
	250	94.8 ± 2.4	1106 ± 19	2.32 ± 0.7	2.10 ± 0.05
	500	98.5 ± 2.5	1157 ± 19	2.55 ± 0.7	2.20 ± 0.05
	750	95.1 ± 2.4	1086 ± 16	2.45 ± 0.7	2.25 ± 0.05
Sex					
Female	0	90.5 ± 3.2	1024 ± 25	2.28 ± 0.09	2.22 ± 0.07
	250	91.6 ± 3.3	1006 ± 24	2.22 ± 0.09	2.21 ± 0.07
	500	95.2 ± 3.4	1028 ± 25	2.44 ± 0.10	2.37 ± 0.08
	750	93.7 ± 3.4	1029 ± 29	2.35 ± 0.09	2.37 ± 0.08
	Overall	92.7 ± 1.7^{b}	1012 ± 12^{b}	2.32 ± 0.05^{b}	2.29 ± 0.04^{b}
Male	0	100.9 ± 3.6	1239 ± 30	2.67 ± 0.15	2.15 ± 0.07
	250	98.1 ± 3.5	1217 ± 29	2.43 ± 0.15	1.99 ± 0.06
	500	101.8 ± 3.7	1301 ± 32	2.66 ± 0.15	2.04 ± 0.07
	750	96.5 ± 3.5	1189 ± 29	2.54 ± 0.15	2.14 ± 0.07
	Overall	99.3 ± 1.8^{a}	1236 ± 15^{a}	2.57 ± 0.05^{a}	2.08 ± 0.05^{a}
P values					
	Treatment (T)	0.705	0.101	0.175	0.203
	Sex (S)	0.016	< 0.001	0.002	< 0.001
	T X S	0.750	0.702	0.733	0.377

^{ab} For the main effects values within a column without similar superscripts are significantly different at $P < 0.05$.

5.2.4 Pig Performance over the entire treatment period of 129 days

The effects of Sr supplementation and sex on the performance of the pigs over the entire treatment period of 129 days are given in table 2.22. The strontium supplementation had no effect on the final BW ranging between 94.8 and 98.5 kg. The Sr supplementation had no effect on the ADG (893 to 910 g/d), the ADFI (1.81 to 1.93 kg) or on the FCR (2.02 to 2.09).

Males had a higher ADG then females (949 ± 14 Vs 874 ± 13) and this resulted in males having a higher BW than females (99.3 ± 1.8 Vs 92.7 ± 1.7 kg). There was no difference in ADFI between males (1.88 ± 0.04 kg/d) and females (1.88 ± 0.04 kg/d) but the differences in ADG supported males having improved FCR (1.99 ± 0.02 Vs 2.12 ± 0.02).

Table 2.22. The mean (± SEM) BW, ADG, ADFI and FCR ADFI for pigs fed a control diet or diets supplemented with 250, 500 or 750 ppm of strontium from the end of the weaner period until the end of the finisher periods (days 1 – 129 of treatment). The analysis is based on a pen basis.

		Performance measure			
	Strontium (ppm)	BW (kg)	ADG (g/d)	ADFI (g/d)	FCR
Treatment					
	0	95.5 ± 2.4	910 ± 19	1.84 ± 0.05	2.02 ± 0.03
	250	94.8 ± 2.4	893 ± 19	1.81 ± 0.05	2.03 ± 0.03
	500	98.5 ± 2.5	936 ± 20	1.93 ± 0.05	2.03 ± 0.03
	750	95.1 ± 2.4	904 ± 19	1.89 ± 0.05	2.09 ± 0.03
Sex					
Female	0	90.5 ± 3.2	859 ± 25	1.78 ± 0.07	2.03 ± 0.04
	250	91.6 ± 3.3	860 ± 26	1.78 ± 0.07	2.07 ± 0.04
	500	95.2 ± 3.4	898 ± 27	1.94 ± 0.07	2.16 ± 0.04
	750	93.7 ± 3.4	850 ± 26	1.92 ± 0.07	2.18 ± 0.04
	Overall	92.7 ± 1.7[b]	874 ± 13[b]	1.85 ± 0.03	2.12 ± 0.02[b]
Male	0	100.9 ± 3.6	964 ± 28	1.91 ± 0.07	1.98 ± 0.04
	250	98.1 ± 3.5	929 ± 28	1.84 ± 0.07	1.99 ± 0.03
	500	101.8 ± 3.7	976 ± 29	1.93 ± 0.07	1.97 ± 0.03
	750	96.5 ± 3.5	929 ± 28	1.86 ± 0.07	2.01 ± 0.03
	Overall	99.3 ± 1.8[a]	949 ± 14[a]	1.88 ± 0.04	1.99 ± 0.02[a]
P values					
	Treatment (T)	0.705	0.466	0.372	0.244
	Sex (S)	0.016	< 0.001	0.554	< 0.001
	T X S	0.750	0.786	0.580	0.401

[ab] For the main effects values within a column without similar superscripts are significantly different at P < 0.05.

5.2.5 Processing Yields

The effect of Sr supplementation and sex on the processing carcass traits are given in Table 2.23. The slaughter weights (10.4-105 kg) were similar for all groups as were the HSCW (78-79 kg). And dressing % (75-76%) The Sr supplementation had no effect on the P2 backfat measure (10-11 mm).

The males had a higher slaughter weight (P < 0.05) than females (106.8 ± 0.7 Vs 103.0 ± 0.7 kg) but the females had a higher (P < 0.05) dressing percentage (77.1 ± 0.2 Vs 74.0 ± 0.2%) and these differences resulted similar HSCW for males (79.0 ± 0.6 kg) and females (79.5 ± 0.6 kg).

Table 2.23. The mean (± SEM) slaughter weight, HSCW, dressing percentage and P2 backfat measure for pigs fed a control diet or diets supplemented with 250, 500 or 750 ppm of strontium from weaning until slaughter th (days 31 – 129 of treatment). The analysis is based on a pen basis.

		Performance measure			
	Strontium (ppm)	Slaughter wt (kg)	HSCW (kg)	Dressing (%)	P2 backfat (mm)
Treatment					
	0	104.3 ± 0.58	79.0 ± 0.9	75.7 ± 0.3	10.5 ± 0.3
	250	105.0 ± 0.58	79.2 ± 0.9	75.4 ± 0.3	10.1 ± 0.3
	500	105.0 ± 0.59	79.9 ± 0.9	75.4 ± 0.3	10.5 ± 0.3
	750	104.2 ± 0.58	78.9 ± 0.9	75.7 ± 0.3	10.4 ± 0.3
Sex					
Female	0	102.1 ± 1.3	78.6 ± 1.2	77.0 ± 0.5	10.0 ± 0.4
	250	102.7 ± 1.3	79.5 ± 1.2	77.5 ± 0.5	10.1 ± 0.4
	500	103.9 ± 1.3	90.1 ± 1.2	77.1 ± 0.5	10.4 ± 0.4
	750	103.3 ± 1.3	79.6 ± 1.2	77.1 ± 0.5	10.5 ± 0.4
	Overall	103.0 ± 0.7[b]	79.5 ± 0.6	77.1 ± 0.2[a]	10.3 ± 0.2
Male	0	106.6 ± 1.3	79.3 ± 1.2	74.4 ± 0.5	11.0± 0.04
	250	107.4 ± 1.3	78.8 ± 1.2	73.4 ± 0.5	9.9 ± 0.03
	500	108.0 ± 1.3	79.8 ± 1.2	73.8 ± 0.5	10.7 ± 0.03
	750	105.1 ± 1.3	78.3 ± 1.2	74.5 ± 0.5	10.0 ± 0.03
	Overall	106.8 ± 0.7[a]	79.0 ± 0.6	74.0 ± 0.2[b]	10.5 ± 0.02
P values					
	Treatment (T)	0.529	0.826	0.875	0.642
	Sex (S)	< 0.001	0.636	< 0.001	0.419
	T X S	0.681	0.863	0.403	0.468

[ab] For the main effects values within a column without similar superscripts are significantly different at $P < 0.05$.

6. Discussion

An early in-house study at the University of Sydney using limited pig numbers suggested that dietary supplementation with Sr could support improvements in growth and feed efficiency and reduce inflammation in leg joints. The pigs were supplemented with 500 ppm of strontium from weaning for 59 days. The observations provided support for further evaluation using more extensive experiments under commercial conditions. This was the basis for the two experiments detailed in the current report.

In the first study, the effect of Sr supplementation at 500 ppm from the start of the weaning period until slaughter and sr supplementation from the start of the grower period until slaughter was evaluated. During the weaner period ADG was improved with the Sr supplementation which was not associated with an increase in ADFI resulting in an improved FCR. While the 3 treatments groups were weaned at the same weight, those supplemented with Sr at weaning had higher BW at the end of the weaner period and also during the grower period but was not different at the end of the finisher phase. When the Sr supplementation was started in the grower phase there was no effect on BW. The higher BW was in part supported by the higher ADG from weaning until at least day 49 of treatment. Starting the supplementation at weaning was able to improve overall feed efficiency compared to the control treatment.

There is limited data investigating any role for Sr in the nutrition of production animals. A high supplementation rate of 5500 ppm was reported to be toxic (Bartley and Reber, 1961). This observation was probably sufficient to limit further interest in investigating strontium's role. However, Pagano et al., (2007) used a more realistic physiological supplementation rate of 50 ppm but their interest focused on the effects Sr had on bone strength and density which were increased but no measures were made on performance characteristics.

The physiological processes whereby Sr improved pig growth rate in the weaner phase and feed efficiency is not clear. Insulin-like growth factor-1 (IGF-1) is a key regulator of muscle and bone development in the pig and other vertebrates namely (Duclos, 2005). Strontium ranelate given to osteoporotic post-menopausal women increased IGF-1 significantly by 12 % (Gulhan et al., 2008). Ammann et al., (2004) supplemented rats with Sr and increased IGF-1 concentrations by 15 % in the males and 4% in the females. In goats, serum IGF-1 increased in a dose-dependent manner following Sr supplementation (Li et al., (2008). Fatayerji et al., (2000) found that Sr absorption was positively correlated with IGF-1 and as the IGF-1 concentrations decrease with age there is poorer Sr absorption at the same time.

There is evidence that Sr acts to protect mitochondria by having a stabilising effect on the mitochondrial membranes and the support given depends on the Sr concentration within the extracellular fluid (Carafoli, 1965, Caplan and Carafoli, 1965). The mitochondria primary role is to provide energy as adenosine triphosphate (ATP) (Chance, 1965). Maintaining mitochondria stability could be acting to provide energy for anabolic processes.

While there some improvement in the grower phase the differences failed to support a significant increase in final BW at the end of the production period. Commercial considerations are always measured by the overall performance at the end of production and when performance was evaluated over the entire supplementation period there was no benefit. This transcended to their being no treatment effect on HSCW or on the P2 backfat measure.

In the pilot study (as discussed in the background), the Sr supplementation resulted in lower knee joint surface skin temperature and it was proposed that it may have been representative of reduced inflammation. Joint inflammation can potentially lead to leg weakness which is related to a range of clinical bone diseases such as arthritis and osteochondrosis. Osteochondrosis is regarded as the most important joint disease in pigs (Jørgensen et al., 1995) and the most common disease of cartilage growth in pigs (Dewey, 2006). Osteochondrosis occurs when joint cartilage fails to become bone in the distal condyle of the humerus (front elbow joint) and medial condyle of the femur (hind knee joint). It has been predicted that commercial growing pigs are afflicted with the condition to some degree (Nakano et al., 1987). Strontium has been proven to promote bone growth in vertebrates by two concurrent systems, firstly by the stimulation of bone osteoblast cells to produce bone and secondly by the inhibition of bone osteoclasts cells to reabsorb bone. (Marie et al., 1985, Canalis et al., 1996, Buehler et al., 2001, Marie et al., 2001, Le Roith et al., 2001). The ability of Sr to promote bone formation occurs possibly through IGF-1 regulation of bone formation (Delafontaine, 1995, Yakar et al., 2002).

The failure to record any effect of strontium on joint surface temperature in experiment 1 could mean that Sr is not involved or could mean that the incidence of subclinical osteochondrosis is low in this commercial herd. The incidence of leg problems is notable in the herd from which pigs were used in the University pilot study.

The main comment to make from experiment 2 is that there were minimal differences in the pig performance at any Sr supplementation rate. Contrary to the results in the weaner phase of experiment 1 (treatment days 1-28) the Sr supplementations had no effect on BW, ADG or ADFI at any week but there were small changes which were sufficient to have an influence on the FCR. The Sr supplementation at 500 and 750 ppm improved FCR compared to the control treatment. When the poor performance of weaner week 1 is removed the FCR was improved only by supplementing with 500 ppm. During the grower/finisher phases (treatment days 31-129) the Sr supplementation had no effect on BW, ADG, ADFI and FCR. The overall result was that over the entire treatment period there were no performance improvements with Sr supplementation at any concentration and at processing it followed that there was no effect on HSCW, dressing % or P2 backfat.

7. Implications & Recommendations

1. The preliminary pilot study suggested that Sr supplementation at 500 ppm improved performance of weaner pigs and provided evidence support to undertake more extensive studies under commercial conditions
2. When pigs were supplemented with 500 ppm Sr in a commercial environment there were significant improvements in weaner growth performance and feed efficiency. However, supplementation during the grower and finisher phase had no influence on pig performance or carcass yield at processing
3. In the dose response study the improvements in weaner performance were limited to improved feed efficiency at 550 ppm and again supplementation during the grower and finisher phase had no influence on pig performance or carcass yield at processing.
4. Strontium supplementation at 500 ppm would benefit pigs during the weaner period a time when the pigs are very susceptible to environmental and disease challenges. While it was not tested here the benefits could have likely been extended into the early part of the grower phase,
5. During the weaner period pigs consumed approximately 10 kg of feed and so supplementation at 500 ppm a total of 5 mg of Sr per pig would be a small economic cost.
6. Strontium supplementation in the grower and finisher phase provided no economic benefit.

.

8. Literature cited

Ahmad, A.M., Thomas, J., Clewes, A., Hopkins, M.T., Guzder, R., Ibrahim, H., Durham, B.H., Vora, J.P., and Fraser, W.D., (2003). Effects of growth hormone replacement on parathyroid hormone sensitivity and bone mineral metabolism. *The Journal of Clinical Endocrinology & Metabolism*, 88, p. 2860-2868.

Ammann, P., Shen, V., Robin, B., Mauras, Y., Bonjour, J.P,, and Rizzoli, R., (2004). Strontium ranelate improves bone resistance by increasing bone mass and improving. *Journal of Bone and Mineral Research,* 19, p**.** 2012-2020.

Bartley, J.C. and Reber, E., (1961). Toxic effects of stable strontium in young pigs. *The Journal of Nutrition* 75, p. 21-28.

Boivin, G., Deloffre, P., Perrat, B., Panczer, G., Boudeulle, M., Mauras Y., Allain, P., Tsouderos, Y., and Meunier, P.J., (2009). Strontium distribution and interactions with bone mineral in monkey iliac bone after strontium salt (S 12911) administration. *Journal of Bone and Mineral Research*, 11, p. 1302-11.

Bohndorf, K., (1998). Osteochondritis (osteochondrosis) dissecans: a review and new MRI classification *European radiology,* 8, p**.** 103-112.

Browning, L., and Cowieson, A., (2013). The concentration of strontium and other minerals in animal feed ingredients *Journal of Applied Animal Nutrition*, 2:e7

Browning, L., and Cowieson, A., (2014). Effect of vitamin D3 and strontium on performance, nutrient retention, and bone mineral composition in broiler chickens. Animal Production Science 54**,** p. 942-949.

Buehler, J., Chappuis, P., Saffar, J., Tsouderos, Y., and Vignery, A. (2001). Strontium ranelate inhibits bone resorption while maintaining bone formation in alveolar bone in monkeys (Macaca fascicularis). *Bone* 29, p. 176-179.

Canalis, E., (1993). Insulin like growth factors and the local regulation of bone formation. *Bone* 14, p. 273-276.

Canalis, E., Mccarthy, T., and Centrella, M., (1988). Growth factors and the regulation of bone remodelling. *Journal of Clinical Investigation* 81, p. 277-281.

Caplan, A. I., and Carafoli, E., (1965). The effect of Sr2+ on swelling and ATP-linked contraction of mitochondria. *Biochimica et biophysica act,* 104**,** p. 317-329.

Carafoli, E., (1965). Active accumulation of Sr2+ by rat-liver mitochondria II. Competition between Ca2+ and Sr2+. *Biochimica et Biophysica Acta (BBA)-General Subjects* 97**,** p. 99-106.

Chance, B., (1965). The energy-linked reaction of calcium with mitochondria. *Journal of Biological Chemistry* 240**,** p. 2729-2748.

Delafontaine, P., (1995). Insulin-like growth factor I and its binding proteins in the cardiovascular system. *Cardiovascular research* 30, p. 825-834.

Dewey, C., (2006). Diseases of the nervous and locomotor systems. *Diseases of swine* 9, p. 87-112.

Doberenz, A,. Weber, C., and Reid, B., (1969). Effect of high dietary strontium levels on bone and egg shell calcium and strontium. *Calcified Tissue International* 4, p. 180-184.

Duclos, M., (2005). Insulin-like growth factor-I (IGF-1) mRNA levels and chicken muscle growth. *Journal of physiology and pharmacology: an official journal of the Polish Physiological Society* 56**,** p. 25.

Etterlin, P.E. (2016)., Osteochondrosis in Pigs: A Study of the Effects of Free-range Housing in a Herd of Fattening Pigs. Thesis: Faculty of Veterinary Medicine and Animal Science. Swedish University of Agricultural Sciences. Uppsala Sweden. p. 51.

Fatayerji, D., Mawer, E., and Eastell, R. (2000)., The role of insulin-like growth factor I in age-related changes in calcium homeostasis in men. *Journal of Clinical Endocrinology and Metabolism* 85, p. 4657-4662.

Ferraro, E.F., Carr, R. and Zimmerman, K.A. (1983)., Comparison of the effects of strontium chloride and calcium chloride on alveolar bone. *Calcified Tissue International* 3, p. 258- 260.

Goedegebuure, S, A., Hani, H.J., van der Vark, P.C. and van der Wal, G. (1980)., Osteochondrosis on six breeds of slaughter pigs: 1. A morphological investigation of the status of osteochondrosis in relation to breed and level of feeding. *The Veterinary Quarterly* 2, p. 28-41.

Goedegebuure, S.A., Rothchild, M.F., Christian, L.L,. and Ross, R.F., (1988). Severity of osteochondrosis in three genetic lines of Duroc swine divergently selected for front-leg weakness. Livestock Production Science 19, p. 487-498.
Gomez, J.M., (2006). The Role of Insulin-like Growth Factor I Components in the Regulation of Vitamin D. Current Pharmaceutical Biotechnology 7, p. 125–132.

Grøndalen. T., and Vangen, O., (1974). Oesteochrodosis and arthrosis in pigs: A comparison of the incidence in three different lines of the Norwegian Landrace breed. Acta Veterinaria Scandinavica 15, p. 61-79.

Grøndalen, T., (1974). Oesteochrondosis and arthrosis in pigs: II. Incidence in breeding animals. Acta Veterinaria Scandinavica 15, p. 26-42.

Grynpas, M., Hamilton, E., Cheung, R., Tsouderos, Y., Deloffre, P., Hott, M. and Marie, P., (1996). Strontium increases vertebral bone volume in rats at a low dose that does not induce detectable mineralization defect. Bone 18, p. 253-259.

Gulhan, I., Bilgili, S., Gunaydin, R., Gulhan, S. and Posaci, C., (2008). The effect of strontium ranelate on serum insulin like growth factor-1 and leptin levels in osteoporotic postmenopausal women: a prospective study. *Archives of Gynecology and Obstetrics* 278, p. 437-441.

Hill, M.A., (1990). Causes of degenerative joint disease (osteoarthritis) and dyschondroplasis (osteochondrosis) in pigs. *Journal American Veterinary Medical Association* 197, p. 107-113.

Jørgensen, B., Arnbjerg, J., and Aaslyng, M., (1995). Pathological and radiological investigations on osteochondrosis in pigs, associated with leg weakness. *Journal of Veterinary Medicine Series A* 42, p. 489-504.

Kardarmideen, H.N., Schworer, D., Ilahi, H., Malek, M., and Hofer, A., (2004). Genetics of osteochondral disease and its relationship with meat quality and quantity, growth, and feed conversion traits in pigs. *Journal of Animal Science* 82, p. 3118-3127.

Kornegay, E.T., Combs, N.R., Viet, H.P. and Lindemann, M.D., (1990). Articular cartilage condition score of distal humerus and femur of swine as influenced by dietary Ca-P levels, sex and age, Canadian Journal of Animal Science 70. P. 255-258.

Lawson, D., Paul, A.A., Black, A.E., Cole, T., Mandal, A. and Davie, M., (1979). Relative contributions of diet and sunlight to vitamin D state in the elderly. British Medical Journal 2, p. 303-305.

Le Roith, D., Bondy, C., Yakar, S., Liu, J. L., Butler A., (2001). The somatomedin hypothesis: 2001. Endocrine Reviews 22, p. 53-74.

Li, Z,. Lu, W/W, Chiu, P.K., Lam, R.W., Xu, B., Cheung, K., Leong, J.C., and Luk, K.D., (2008). Strontium– calcium coadministration stimulates bone matrix osteogenic factor expression and new bone formation in a large animal model. *Journal of Orthopaedic Research* 27, p. 758-762.

Lundeheim, N., (1987). Genetic analysis of osteochondrosis and leg weakness in the Swedish pig progeny testing scheme. *Acta Agriculturae Scandinavica* 37, p.159-173.

Marie, P., (1996). Effects of strontium on bone tissue and bone cells. In: Therapeutic uses of trace elements: eds. Neve, P., Chappuis P., Lamand, M. Springer-Verlag. Boston. MA. p. 277-282.

Marie, P., Garba, M., Hott, M. and Miravet, L., (1985) Effect of low doses of stable strontium on bone metabolism in rats. *Mineral and Electrolyte Metabolism* 11, p. 5

Marie, P.J., (2005) Strontium as therapy for osteoporosis. *Current Opinion in Pharmacology* 5, p. 633-636.

Matsumoto, A. (1988). Effect of strontium chloride on bone resorption induced by prostaglandin E2 in cultured bone. *Archives of Toxicology* 62. p. 240-241.

Meunier P.J., Roux, C., Seeman, E., Ortolani, S., Badurski, J.E., and Spector, T.D., (2004). The effects of strontium ranelate on the risk of vertebral fracture in women with postmenopausal osteoporosis. *New England Journal of Medicine* 350, p. 459-68.

Nakano, T., and Aherne. F., (1993). Articular cartilage lesions in female breeding swine. *Canadian Journal of Animal Science* 73, p. 1005-1008.

Ogata, N., Chikazu, D., Kubota, N., Terauchi, Y., Tobe, K., Azuma, Y., Ohta, T., Kadowaki, T., Nakamura, K., Kawaguchi, H., (2000) Insulin receptor substrate-1 in osteoblast is indispensable for maintaining bone turnover. *Journal of Clinical Investigation* 105, p. 935-43.

Pagano, A.R., Yasuda, K., Roneker, K.R., Crenshaw, T.D., Lei, X.G., (2007). Supplemental Escherichia coli phytase and strontium enhance bone strength of young pigs fed a phosphorus-adequate diet. *The Journal of Nutrition* 137, p. 1795-1801.

Pors Nielsen, S.. (2004). The biological role of strontium. *Bone* 35, p. 583-588.

Potter, R. (1998). Clinical conditions of pigs in outdoor breeding herds. *In Practice* 20 p. 3-14.

Reginster, J.Y, Seeman, E., De Vernejoul, M., Adami, S., Compston, J., and Phenekos, C., (2005). Strontium ranelate reduces the risk of nonvertebral fractures in postmenopausal women with osteoporosis: Treatment of Peripheral Osteoporosis (TROPOS) study. *Journal of Clinical Endocrinology & Metabolism*, 90, p. 2816-2822.

Reiland, S., (1975). Osteochondrosis in the pig. A morphological and experimental investigation with special reference to leg weakness syndrome. Thesis. The Royal Veterinary College. Stockholm. p. 118.

Rucker, D., Ezzat, S., Diamandi, A., Khosravi, J., and Hanley, D.A., (2004). IGF-I and testosterone levels as predictors of bone mineral density in healthy, community-dwelling men. *Clinical Endocrinology* 60, p. 491-499.

Seck, T., Scheppach, B., Scharla, S., Diel, I., Blum, W.F., Bismar, H., Schmid, G,. Krempien, B., Ziegler. R., and Pfeilschifter, J., (1998). Concentration of Insulin-Like Growth Factor (IGF)-I and-II in Iliac Crest Bone Matrix from Pre-and Postmenopausal Women: Relationshipto Age, Menopause, Bone Turnover, Bone Volume, and Circulating IGFs 1. *The Journal of Clinical Endocrinology & Metabolism* 83, p. 2331-2337.

Shahnazari, M., Sharkey, N.A., Fosmire, G.J., and Leach, R.M., (2006) Effects of strontium on bone strength, density, volume, and microarchitecture in laying hens. *Journal of Bone and Mineral Research* 21, p. 1696-703.

Shahnazari, M., Lang, D., Fosmire, G, Sharkey, N., Mitchell, A., and Leach, R., (2007). Strontium administration in young chickens improves bone volume and architecture but does not enhance bone structural and material strength. *Calcified Tissue International* 80, p. 160-166.

Su, Y., Bonnet, J., Deloffre, P., Tsouderos, Y. and Baron, R., (1992). The strontium salt S12911 inhibits bone resorption in mouse calvaria and isolated rat osteoclasts cultures. *Bone and Mineral* 17, (abstract0 p. 188.

Thomas, M.K., Lloyd-Jones, D.M., Thadhani, R.I., Shaw, A.C., Deraska, D.J., Kitch, B.T., Vamvakas, E.C., Dick, I.M., Prince, R.L and Finkelstein, J.S., (1998). Hypovitaminosis D in medical inpatients. *New England Journal of Medicine* 338, p. 777-783.

Vad der Wal, P.G., Goedegebuure, S.A., Van der Valk, P.C., Engel, B. and Van Essan, G., (1987). Leg weakness and osteochondrosis in pigs; differences between the sexes of four breeds. *Livestock Production Science* 16, p. 65-74.

Weber, C., Doberenz, A., Wyckoff, R., and Reid, B., (1968). Strontium metabolism in chicks. *Poultry Science* 47, p. 1318-1323.

Wei, S., Tanaka, H., and Seino, Y., (1998). Local action of exogenous growth hormone and insulinlike growth factor-I on dihydroxyvitamin D production in LLC-PK1 cells. *European Journal of* Endocrinology 139, p. 454-460.

Yakar, S., Rosen, C. J., Beamer, W. G., Ackert-Bicknell, C. L., Wu, Y., Liu, J.-L., Ooi, G. T., Setser, J., Frystyk, J., and Boisclair, Y. R., (2002). Circulating levels of IGF-1 directly regulate bone growth and density. *Journal of Clinical Investigation* 110**,** p.771-782.

Yazdi, M.H., Lundeheim, N., Rydhmer, L., Ringmar-Cederberg, E. and Johansson, K., (2000). Survival of Swedish Landrace and Yorkshire sows in relation to osteochondrosis: a genetic study. *Animal Science* 71, p. 1-9.

Ytrehus, B., Ekman, S., Carlson, C.S., Teige, J., and Reinholt, F.P., (2004). Focal changes in blood supply during normal epiphyseal growth are central in the pathogenesis of osteochondrosis in pigs. *Bone* 35, p. 1294-1306