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A high dietary iodine increases thyroid iodine stores and iodine concentration in blood serum but has little effect on muscle iodine content in pigs

F. Schöne [a,*], Christina Zimmermann [a], G. Quanz [b], G. Richter [a], M. Leiterer [a]

[a] *Agricultural Institute of Thuringia, Naumburger Straße 98, D-07743 Jena, Germany*
[b] *Hessian Service Center for Agriculture, Horticulture and Nature Conservation – Farm, Animal Research Station Neu-Ulrichstein, D-35315 Homberg, Germany*

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Abstract

There is still iodine deficiency in many populations, which justifies efforts to increase this trace element in food such as milk, eggs and meat by fortifying compound animal feeds with extra iodine. The iodine requirement of growing pigs is in the order of 100–200 μg/kg feed (as a supplement) and the effects of this dosage range or higher on pork iodine concentration should be determined including the action of relevant iodine antagonists in feed, e.g., rapeseed. In three experiments on a total of 208 pigs [Pietrain × (Landrace × Large White)] the iodine concentration of meat (m. longissimus) – 71 samples –, blood serum – 100 samples – and of the thyroid – 100 samples – was analysed by intracoupled plasma-MS. In Experiment 1, 4 × 10 pigs received diets without or with rapeseed cake (0 and 3.2 mmol glucosinolates/kg diet) either with 125 or with 250 μg iodine/kg. In Experiment 2, the three groups with 46 pigs each were fed high iodine diets (1200 μg supplementary iodine/kg) without or with 100 or 150 g solvent extracted rapeseed meal/kg diet (0; 0.8 and 1.2 mmol glucosinolates/kg). In Experiment 3, 3 × 10 pigs received either 600 μg iodine/kg feed (1) or the 5-fold dosage (600 + 2400 μg iodine/kg diet) administered 7 days (2) or 18 days (3) before slaughtering. The group means of pork iodine content were in the relatively small range from 3 to 16 μg/kg, which contrasted to the enormously varying dosage range from 125 to 3000 μg iodine/kg diet. There was a certain iodine dosage effect in Experiment 3 when – in comparison to the control – a 3-fold higher meat iodine concentration resulted from a 5-fold higher diet iodine concentration. In Experiment 1 with the low iodine offer, rapeseed cake with glucosinolates decreased the serum iodine level whereas in Experiment 2 this did not happen due to higher iodine fed and lower glucosinolates exposure. The thyroid iodine reflected the dietary iodine better than blood serum iodine and the serum better than muscle. However, in Experiment 2, 1200 μg iodine/kg diet produced only half the serum iodine concentration than half as much dietary iodine in Experiment 3 (600 μg iodine/kg diet), which may result from rapid elimination of blood iodine and a higher urinary excretion by longer duration of feed withdrawal before blood sampling. The muscle of pigs has to be classified as a low iodine food. Thus, there are no possibilities to concentrate this trace element reproducibly in amounts relevant for human nutrition in pork.

Keywords: Iodine; Pork; Thyroid; Blood serum; Animal feed

1. Introduction

There is still iodine deficiency in the German population justifying the use of iodized common salt in food processing and the household on the one hand and on the other hand the efforts to increase concentrations of this trace element in milk, eggs and meat by fortifying compound animal feeds with extra iodine (Kaufmann & Rambeck, 1998; Rambeck, Kaufmann, Feng, Hollwich, & Arnold, 1997; Richter, 1995). In the past the iodine status of pigs was investigated with regard to iodine deficiency (Smith, 1915) often exacerbated by antithyroid compounds, e.g., glucosinolates of rapeseed feeds and hypothyroidism, as

* Corresponding author. Tel.: +49 3641 463615; fax: +49 3641 463630.
E-mail address: f.schoene@jena.tll.de (F. Schöne).

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deficiency illness, was prevented by iodine addition to the diet (Devilat & Skoknic, 1971). Target of food iodine is the thyroid which has the ability to concentrate and store the trace element and synthesize thyroid hormones. The iodine status of growing pigs, taking account of food iodine supply and/or permissible antithyroid compounds, has been characterized by determining thyroid hormone concentration of blood serum (Mc Kinnon & Bowland, 1977; Spiegel, Bestetti, Rossi, & Blum, 1993), the thyroid iodine content (Schöne et al., 1990) and the iodine concentration of sows' serum and milk (Laurberg et al., 2002; Schöne, Leiterer, Hartung, Jahreis, & Tischendorf, 2001). There were some efforts to determine the iodine content of meat but the methods used up to the 1990s seemed to be less sensitive and specific. However, in the last decade the assay of iodine has improved (Fecher, Goldmann, & Nagengast, 1998; Leiterer, Truckenbrodt, & Franke, 2001) to allow the detection of the trace element in low iodine matrices.

The objective of present investigations was to analyze the muscle iodine content of pigs fed diets with defined amounts of iodine. Additionally, indicators of animal's iodine status, i.e., thyroid and serum iodine concentration, were established for the given food iodine supply. The iodine requirement of growing pigs is of the order of 100–200 μg/kg feed and this range and higher diet levels on pork iodine concentration were investigated. Since glucosinolates affect the iodine status, the role of these secondary plant metabolites was investigated by the inclusion of rapeseed feeds in the diets.

2. Materials and methods

The samples originated from 3 experiments with a total of 208 pigs [Pietrain × (Landrace × Large White)]: Experiment 1 with 4 × 10 male-castrated pigs, Experiment 2 with 3 × 46 pigs – one half of them female and one half male castrated, Experiment 3 with 3 × 10 male-castrated pigs. The performance and further results have been published (Richter, Bargholz, Leiterer, & Lüdke, 2002; Schöne, Tischendorf, Leiterer, Hartung, & Bargholz, 2001; Weiß, Quanz, & Schöne, 2004).

In Experiments 1 and 2, the number of samples for the iodine determination was restricted: Experiment 1 – the iodine concentration in meat (m. longissimus) in each second sample (5 per group); Experiment 2 – 10 serum and 10 thyroid samples and 7 muscle samples per group.

2.1. Diets and procedure in the experiments

In Experiment 1 (Table 1), the four groups of 10 pigs each received two diets – one diet without, one diet with 150 g rapeseed press cake/kg diet (0 or 3.2 mmol glucosinolates/kg diet), which were supplemented either with 125 (groups 1 and 3) or with 250 μg iodine/kg (groups 2 and 4). In Experiment 2, the three groups with 46 pigs each were fed high iodine diets (1.2 mg supplementary iodine/kg) without or with 100 or 150 g solvent extracted rapeseed meal/kg diet (0; 0.8 and 1.2 mmol glucosinolates/kg). In Experiment 3, 3 × 10 pigs received either 600 μg iodine/kg feed (1) or an additional dosage of 2400 μg iodine/kg diet one week (2) or 18 days (3) before slaughter.

The glucosinolate concentration of rapeseed press cake used in the diet of Experiment 1 (Table 1) was 21.2 mmol/kg; that of rapeseed meal (Experiment 2) 10 mmol/kg (basis air dry matter). In Experiment 1, the lower iodine dosage tested was similar to the 140 μg iodine per kg diet recommended by the National Research Council NRC (1998). Basal diets had iodine concentrations below the detection limit of <20 μg/kg. Iodine was provided as KI bound to casein which was found to be highly stable. In the diets added iodine dosages were confirmed analytically.

The design and protocols of the animal experiments were approved by the Official Commission for Animal Experimentation (permission of Thuringian Ministry of Health and Welfare, dated 18 March 1991). In Experiments 1 and 3, pigs were held in individual pens in the Thuringian animal nutrition research unit Remderoda. Experiment 2 took place in the climatized pig barn with pens for 2 pigs each at the Hessian farm-animal-research station Neu-Ulrichstein (Weiß et al., 2004).

The pigs were weighed at the beginning, once fortnightly and at the end of experiment, determined by the recommended body-weight. Feed mixtures were offered ad libitum and feed intake was recorded as difference between the daily weight of the feed offered and refused. Pigs were slaughtered after 12 (Experiments 1 and 3) or 24 h (Experiment 2) feed withdrawal in the abattoir in Jena, Germany. Classification of leanness was done by backfat and m. longissimus measurement at the 13th/14th rib region with a Fat-O-Meater (PG 200, Giralda-Opto-Elektronik, Aichach, Germany).

The thyroids were removed at slaughter, weighed and frozen in polyethylene bags at −20 °C. Blood was sampled from the anterior vena cava on the penultimate day after a 12 h fasting period. Blood samples were transferred to glass tubes, centrifuged after 2 h for 15 min at 1600 and the serum was frozen at −20 °C until analysed.

The meat sample of 150–200 g was cut from the pork chop (left carcass half) m. longissimus, which had been transported to the meat laboratory after retaining and chilling the carcass overnight. The sampling position was standardized at transition from the breast to the lumbar region (last rib). The weighed samples consisting of pure muscle without attached fat or connective tissue were cut in cubes, freezed at −20 °C, freeze-dried and finely ground.

2.2. Analyses

In the experiments, the dry matter, crude protein, ether extract, crude fibre and ash content was determined in feed ingredients as well as diets (Bassler & Buchholz, 1993). Glucosinolates of rape feeds were determined by HPLC with sinigrin as internal standard (European Community, 1990). The iodine content of diets and lyophilized meat samples was analysed using intracoupled plasma-mass

Table 1
Diets in the three experiments with a total of 208 pigs

Diets (mmol/kg diet)	Experiment 1[a] with 40 pigs				Experiment 2[b] with 138 pigs			Experiment 3[c] with 30 pigs
	Without rapeseed cake		With rapeseed cake		Without rapeseed meal	With rapeseed meal		Without rapeseed feeds
	<0.1		3.2		<0.1	0.8	1.2	<0.1
Supplementary iodine (μg/kg diet)	125	250	125	250	1200	1200	1200	600 (control) + extra iodine in two groups[d]
Ingredients per kg diet								
Rapeseed press cake (g)			150					
Rapeseed meal, solvent extracted (g)						100	150	
Soya-bean meal (g)	145		55		190	117	80	175
Peas (g)								100
Plant oil (g)	5		5		10	22	26	30
Wheat (g)	410		380		490	500	500	445
Barley (g)	410		380		283	234	217	217
Mineral and vitamin premix (g)	30		30		27	27	27	33
Analysed composition per kg diet [880 g dry matter]								
Crude protein (g)	169		165		163	170	166	153
Ether extract (g)	27		48		38	44	50	39
Lysine (g)	8.6		8.9		9.4	9.7	9.5	9.2
Metabolisable energy (MJ)[e]	13.0		12.9		13.4	13.5	13.4	13.5

[a] Supplementation per kg diet: lysine 1.5 g, Ca 4 g, P 1.3 g, Na 1.1 g, Fe 50 mg, Cu 20 mg, Zn 60 mg, Mn 20 mg, Se 0.15 mg, iodine see above, retinol equivalents (as coated retinyl ester preparation) 1.35 mg, cholecalciferol 14 μg, alpha-tocopherol (as alpha-tocopheryl acetate preparation) 15 mg, cobalamin 15 μg.

[b] Supplementation per kg diet: lysine 1.4–2.2 g, Ca 3.9 g, P 0.5 g, Na 1.6 g, Fe 185 mg, Cu 21 mg, Zn 130 mg, Mn 130 mg, Se 570 μg, see above, retinol equivalents (as coated retinyl ester preparation) 3.3 mg, cholecalciferol 30 μg, alpha-tocopherol (as alpha-tocopheryl acetate preparation) 100 mg, vitamin K_3 0.6 mg, thiamin 1.2 mg, riboflavin 3.7 mg, pyridoxine 2.4 mg, niacin 18 mg, Ca-pantothenate 7 mg, cobalamin 25 μg, 50 mg choline chlorid.

[c] Supplementation per kg diet: lysine 2.3 g, methionine 0.7, Ca 7.49 g, P 1.5 g, Na 1.5 g, Mg 0.15 g, Fe 120 mg, Cu 21 mg, Zn 150 mg, Mn 90 mg, Se 300 μg, iodine see above, retinol equivalents (as coated retinyl ester preparation) 4.5 mg, cholecalciferol 38 μg, alpha-tocopherol (as alpha-tocopheryl acetate preparation) 15 mg, pyridoxine 3 mg, niacin 9 mg, Ca-pantothenate 4.5 mg, cobalamin 30 μg.

[d] +2400 μg/kg diet during 7 days (group 2) or 18 days (group 3) before slaughtering.

[e] Calculation according to analysed crude nutrients and the digestibilities and coefficients of DLG-Feed tables (Deutsche Landwirtschaftsgesellschaft, 1991).

spectrometry (ICP-MS, ELAN 6000, Perkin–Elmer) after matrix disintegration and solution with tetramethylammoniumhydroxide, TMAH (Fecher et al., 1998; Leiterer et al., 2001).

One millilitre TMAH (TAMA Chemicals, Kawasaki Lab., Osaka, Japan) was added to 500 mg finely ground solid sample and 5 ml distilled deionized water in a 50 ml polypropylene tube with a gas tight closure. After disintegration for 3 h at 90 °C and cooling to room temperature 19 ml distilled deionized water were added and centrifuged for 15 min at 4000. To determine the iodine concentrations in the samples the method of standard addition calibration was used. Sample (4 × 1 ml) was spiked with three different amounts of iodine as KI (ultrapure, Johnson Matthey ALFA products, Karlsruhe, Germany): 5, 10 and 20 μg iodine/l, made up with distilled deionized water to 5 and 1 ml tellurium (200 μg/l, Merck, Darmstadt, Deutschland) added. The fourth not spiked sample was measured after the highest calibration sample signalling the software the start of analysis.

The method had a recovery of 95–109%, a detection limit of 2.2 μg iodine/kg lyophilized meat and a determination limit of 6.63 μg iodine/kg lyophilized meat = 0.55 and 1.65 μg/kg fresh matter. Results were confirmed using the certified standard BCR N 151 (Community Bureau of Reference, Brussels, Belgium). In the case of serum, freshly prepared KI standards were added to the liquid samples and these were directly injected into the plasma of ICP. Tellurium (Spex, Grasbrunn, Germany), 100 μg/l, was used as internal standard. Further details of the serum iodine measurement and determination of thyroid iodine have been described (Schöne, Tischendorf, et al., 2001).

2.3. Statistical methods

Statistical analyses were performed with the Statistical Analysis System software package (SAS 6.11, SAS Institute Heidelberg, Germany) using variance analysis and Students' Newman–Keuls test to compare the group means at P 0.05 level. Results in the tables are given as arithmetic means ± SD.

3. Results

3.1. Performance and carcass lean

In Experiment 1, the different iodine dosages did not affect the fattening and slaughtering performance whereas

the rapeseed cake depressed the feed intake (not shown) and gain significantly (Table 2). In Experiment 2, rapeseed-meal feeding did not confirm the negative effect probably due to a lower glucosinolate content – 1.5 mmol/kg diet with 150 g rapeseed meal/kg versus Experiment 1 with 3.2 mmol/kg diet via 150 g rapeseed cake/kg. In Experiment 3, the short-term application of extra iodine did not affect performance.

Indeed, the carcass lean of the exclusive barrow groups in Experiments 1 and 3 was lower than in Experiment 2 with the mixed groups of females and barrows. The relatively big difference between the similarly heavy finishers of Experiments 2 and 3 seems to be an expression of the different Thuringian and Hessian breeding programmes.

3.2. Thyroid weight and iodine in thyroid, blood serum and meat

In Experiment 1, the high glucosinolate content of the rapeseed-press-cake diet increased significantly the thyroid weight and the higher iodine dosage could at least partially compensate for thyroid enlargement (Table 3). In Experiment 2, the diet without rape feed or the diets with the rapeseed meal low in glucosinolate content did not affect the thyroid weight, neither in Experiment 3, did the short-term differing iodine dosage.

The thyroid iodine indicated the iodine supply as well as the occurrence of rape feed and glucosinolates, respectively. In Experiment 1 administering iodine close to the recommended dose, less than 1000 μg iodine/g thyroid were detected. In Experiment 3 giving 5-fold the requirement more than 1000 μg iodine/g thyroid (>10 mg in the total gland) was observed and in Experiment 2 administering almost 9-fold the requirement approximately 3000 μg iodine/g thyroid (about 30 mg in the total gland) was found. The glucosinolates via rapeseed meal (Experiment 2) and the rapeseed cake (Experiment 1) led to a significantly lower thyroid iodine concentration compared to the diets free of rape feeds with the same iodine dosage.

Regarding the total iodine content of thyroid gland the glucosinolate effect was not so much pronounced and therefore the glucosinolate mediated thyroid iodine concentration decrease partially seems to be a simple dilution due to the gland enlargement.

In case of the low iodine offered in Experiment 1 rapeseed cake and higher dietary glucosinolate content decreased the serum iodine level whereas this did not happen in Experiment 2 with a higher iodine offer and the lower glucosinolate level of the rapeseed meal diet. The serum iodine reflected the dietary iodine. However, in Experiment 2, 1200 μg iodine/kg diet caused only half the serum iodine concentration that it did in Experiment 3 with half the dosage: 600 μg iodine/kg diet. There seemed to be some adaptation phenomena of the serum iodine and some further effects, e.g., the duration of feed withdrawal before blood sampling which was longer in Experiment 2 (24 h) due a longer transportation duration from Neu-Ulrichstein/Hessen to the slaughterhouse in Jena/Thuringia than in Experiment 3 (12 h) with a short distance between Thuringian Experiment station and slaughterhouse.

The pork iodine content (Table 4) did not vary in the magnitude that was expected from the enormous dietary dosage range of 125–3000 μg iodine/kg diet in the three experiments. In Experiment 1, the diet with rapeseed press cake (3.2 mmol glucosinolates/kg diet) led to significantly higher meat iodine concentration than the diet without glucosinolates. In combination with the rapeseed press cake the higher iodine dosage of 250 μg/kg caused an increase in the meat iodine content and the effects of both

Table 2
Body weight (BW), daily weight gain, feed:gain ratio and carcass weight and lean in the experiments (arithmetic means ± SD)

Experiment – group	Iodine dosage (μg/kg diet)	Body weight		Daily weight gain (g/day)	Feed:gain[A]	Carcass weight (kg/100 kg BW)	Lean weight[B] (g/kg carcass)
		Initial (kg)	Final (kg)				
Experiment 1 – rapeseed cake (10 pigs/group, duration ca. 15 weeks)							
1 – Without	125	24.4 ± 2.3	103.9 ± 3.7	765[ab] ± 40	3.14 ± 0.18	80.1 ± 1.5	528 ± 36
2 – Without	250	23.9 ± 1.0	103.6 ± 3.0	794[a] ± 58	3.03 ± 0.19	80.9 ± 1.6	536 ± 34
3 – 150 g/kg diet	125	24.2 ± 2.5	104.2 ± 3.9	726[ab] ± 103	3.13 ± 0.36	79.7 ± 1.4	523 ± 28
4 – 150 g/kg diet	250	23.6 ± 2.3	103.1 ± 4.2	709[b] ± 62	3.19 ± 0.25	79.9 ± 2.2	516 ± 42
Experiment 2 – rapeseed meal (46 pigs/group, duration ca. 13 weeks)							
1 – Without	1200	40.3 ± 4.8	116.6 ± 3.5	797 ± 90	2.84 ± 0.28	77.5 ± 2.6	559 ± 35
2 – 100 g/kg diet	1200	41.4 ± 4.8	116.6 ± 3.4	821 ± 89	2.80 ± 0.27	77.3 ± 3.6	568 ± 34
3 – 150 g/kg diet	1200	41.0 ± 4.7	117.1 ± 3.3	813 ± 94	2.70 ± 0.27	76.7 ± 3.1	572 ± 34
Experiment 3 – extra iodine (10 pigs/group, duration ca. 14 weeks)							
1 – Total fattening	600	23.1 ± 5.0	119.2 ± 6.4	987 ± 55	2.73 ± 0.18	77.8 ± 4.5	526 ± 20
2 – 7 Days[C]	600 + Extra 2400	23.1 ± 4.9	118.3 ± 7.6	968 ± 72	2.70 ± 0.10	77.4 ± 5.8	516 ± 34
3 – 18 Days[C]	600 + Extra 2400	23.2 ± 4.0	118.4 ± 4.9	978 ± 45	2.74 ± 0.15	77.1 ± 2.9	516 ± 29

[ab] Mean values with unlike superscript letters within Experiment 1 were significantly different ($P < 0.05$, Newman–Keuls test).
[A] kg feed per kg gain.
[B] Choirometer classification.
[C] Before slaughtering.

Table 3
Thyroid weight relative to body weight (BW) and iodine (I) concentration of thyroid and blood serum (10 samples/group, arithmetic mean ± SD)

Experiment – group	Iodine dosage (μg/kg diet)	Thyroid weight (g/100 kg BW)	Thyroid (μg iodine/g)	Thyroid (total mg/gland)	Serum (μg iodine/l)
Experiment 1 – rapeseed cake					
1 – Without	125	$7.04^{c} \pm 1.29$	$594^{b} \pm 292$	$4.1^{b} \pm 1.8$	$38^{ab} \pm 4$
2 – Without	250	$7.90^{c} \pm 2.01$	$968^{a} \pm 418$	$7.4^{a} \pm 3.6$	$48^{a} \pm 5$
3 – 150 g/kg diet	125	$18.81^{a} \pm 4.95$	$87^{d} \pm 51$	$1.6^{c} \pm 0.8$	$24^{b} \pm 4$
4 – 150 g/kg diet	250	$12.95^{b} \pm 3.28$	$337^{c} \pm 124$	$4.7^{b} \pm 2.7$	$42^{ab} \pm 4$
Experiment 2 – rapeseed meal					
1 – Without	1200	9.05 ± 2.49	$2826^{a} \pm 306$	$30.0^{B} \pm 9.3$	66 ± 8
2 – 100 g/kg diet	1200	9.37 ± 1.17	$2306^{b} \pm 299$	$24.8^{B} \pm 4.1$	63 ± 10
3 – 150 g/kg diet	1200	8.63 ± 3.42	$2229^{b} \pm 438$	$22.1^{B} \pm 8.9$	64 ± 7
Experiment 3 – extra iodine					
1 – Control	600	10.27 ± 2.47	$1363^{b} \pm 192$	$16.2^{b} \pm 5.9$	$118^{b} \pm 25$
2 – 7 Days[A]	600 + Extra 2400	8.57 ± 1.69	$1750^{ab} \pm 59$	$17.6^{b} \pm 4.7$	$549^{a} \pm 160$
3 – 18 Days[A]	600 + Extra 2400	10.10 ± 3.13	$2154^{a} \pm 324$	$26.0^{a} \pm 3.1$	$510^{a} \pm 251$

[abcd] Mean values with unlike superscript letters within Experiment 1, Experiment 2 or Experiment 3 were significantly different ($P < 0.05$, Newman–Keuls test).
[A] Before slaughtering.
[B] Tendency in ANOVA, $P = 0.07$.

Table 4
Iodine concentration of m. longissimus, μg iodine/kg (arithmetic mean ± SD, SD and minimum–maximum-range)

Experiment – group	Iodine dosage (μg/kg diet)	Number of samples	Meat (mean ± SD)	Minimum–maximum
Experiment 1 – rapeseed cake				
1 – Without	125	5	$3.4^{b} \pm 2.3$	<1.6–6.1
2 – Without	250	5	$4.1^{b} \pm 3.2$	<1.6–8.8
3 – 150 g/kg diet	125	5	$7.2^{b} \pm 2.7$	4.3–11.1
4 – 150 g/kg diet	250	5	$15.8^{a} \pm 3.9$	12.0–22.2
Experiment 2 – rapeseed meal				
1 – Without	1200	7	3.5 ± 1.7	2.1–6.9
2 – 100 g/kg diet	1200	7	3.3 ± 1.3	2.0–5.8
3 – 150 g/kg diet	1200	7	2.8 ± 0.7	1.9–3.8
Experiment 3 – extra iodine				
1 – Control	600	10	$4.5^{b} \pm 2.1$	2.5–9.6
2 – 7 Days[A]	600 + Extra 2400	10	$14.6^{a} \pm 5.3$	3.3–21.6
3 – 18 Days[A]	600 + Extra 2400	10	$10.6^{a} \pm 5.2$	3.5–21.7

[ab] Mean values with unlike superscript letters within Experiment 1 or Experiment 3 were significantly different ($P < 0.05$, Newman–Keuls test).
[A] Before slaughtering.

the factors (glucosinolates, iodine) were significant in the two way analysis of variance.

Contrary to Experiment 1 in Experiment 2 with the immensely higher iodine dosage no effect of the rapeseed meal diets with their low glucosinolate contents (group 2: 0.8 mmol/kg diet, group 3: 1.5 mmol/kg diet) could be determined as compared with the control diet without rape feed.

In Experiment 3 testing a short-term higher iodine administration before slaughtering both the regimes – the 3000 μg iodine/kg diet for one week or for almost 3 weeks – increased the meat iodine concentration significantly. A concentration of 12.6 μg iodine/kg meat as average between both the groups with the extra iodine addition represents a meat concentration three times that of the control group and this resulted from dietary iodine concentration differences of 5-fold (3000 μg/kg diet versus 600 μg/kg diet).

4. Discussion

Excepting the diets with high rape content of 150 g/kg of Experiment 1 and Experiment 2 the experimental diets were typical for pigs. The rape cake as well as the rapeseed meal originated from double zero seed which is standard now in the EU. The lower glucosinolate content of meal than of cake is due to the glucosinolate decomposition by steam-heat treatment used to remove the solvent, the preferential method for oil extraction (Schöne, Tischendorf, et al., 2001).

As mentioned, in this study the tested feed iodine dosages met the requirement (Experiment 1) or they exceeded it (Experiments 2 and 3). Therefore, an iodine dosage effect on the fattening performance or on the carcass data could not be expected. In former experiments, totally lacking iodine addition to feed strong goitre was present, and in the simultaneously presence of iodine antagonists, e.g.,

glucosinolates (Schöne et al., 1990), an additional growth retardation occurred.

One objective of the experiments, namely to increase the concentration of iodine in meat by feeding measures and thus an improvement of the nutritional quality of pork for consumers could not be achieved. There are physiological constraints in the mammalian organism against a (too) high meat iodine content. The unequal distribution of iodine in the organism, its thyroid storage, mobilization and excretion has to be considered.

4.1. Iodine in the pig – role of dietary iodine and glucosinolates

Considering the results only in those groups of pigs receiving glucosinolate free diets, thyroid iodine was in a range from above 500 to almost 3000 μg/g which covered the broad range of the results of former experiments (Schöne, 1999) with exception of extreme iodine deficiency and goitre, respectively. Clearly, the organ reflected the supply, however, an almost five to 10-fold difference in dietary iodine in Experiment 2 compared to Experiment 1 resulted in three to 5-fold differences in thyroid iodine which indicates a diminishing iodine utilization with increasing iodine supply. Too much iodine blocks the trace element's deposition and hormone production of thyroid (Markou, Georgopoulos, Kyriazopoulou, & Vagenakis, 2001). There is an upper limit of 10 mg iodine/kg pig feed according to German feed legislation (Weinreich, Krüsken, & Radewahn, 1997). In a former pig experiment (Schöne, 1999) this maximum iodine addition doubled the thyroid weight and the cited current upper iodine limit of pig feed should be further diminished.

Thyroid represents not only the store but also the control centre of the iodine and thyroid hormone household. The organ accumulates iodine in two steps: (1) Iodide from intestinal absorption and from thyroid hormone degradation is trapped and transported by sodium iodide symporter which was detected not only in thyroid epithelium, but also in other tissues, e.g., in the mammary gland (Spitzweg, Joba, Eisenmenger, & Heufelder, 1998). (2) The thyroid peroxydase (TPO) also located in the epithelial cells oxidizes iodine$^-$ to elemental iodine, which iodinates tyrosyl residues and hormone precursors of thyroglobulin. Thyroglobulin located in the follicles, represents the true iodine store. The iodoprotein may carry the trace element to an extremely varying degree depending on the dietary iodine level, and also on the amount of iodine antagonists occurring in food. The glucosinolates are degraded and metabolized to isothiocyanates, oxazolidinethions and further compounds, which are oxidized and detoxified by TPO (Kohler, Taurog, & Dunford, 1988). Due to glucosinolates in the diet the TPO activity does not seem sufficient to oxidize so much iodide and – as was shown in Experiments 1 and 2 – in rape fed pigs the thyroid iodine stores were lower than in the pigs fed glucosinolate free diets.

Blood and muscles contain only traces of iodine compared to thyroid (Fig. 1). The ratios of iodine concentrations of the serum to the thyroid amount to 1:10,000 and those of the meat to the gland even to 1:100,000. Therefore, the weight differences between the three tissues may not compensate for the enormous concentration differences.

A serum iodine level of 24–66 μg/l in Experiments 1 and 2 was in a reference range of 20–80 μg iodine/l which was derived from former pig experiments (Schöne, 1999). In this range one half and more of serum iodine are

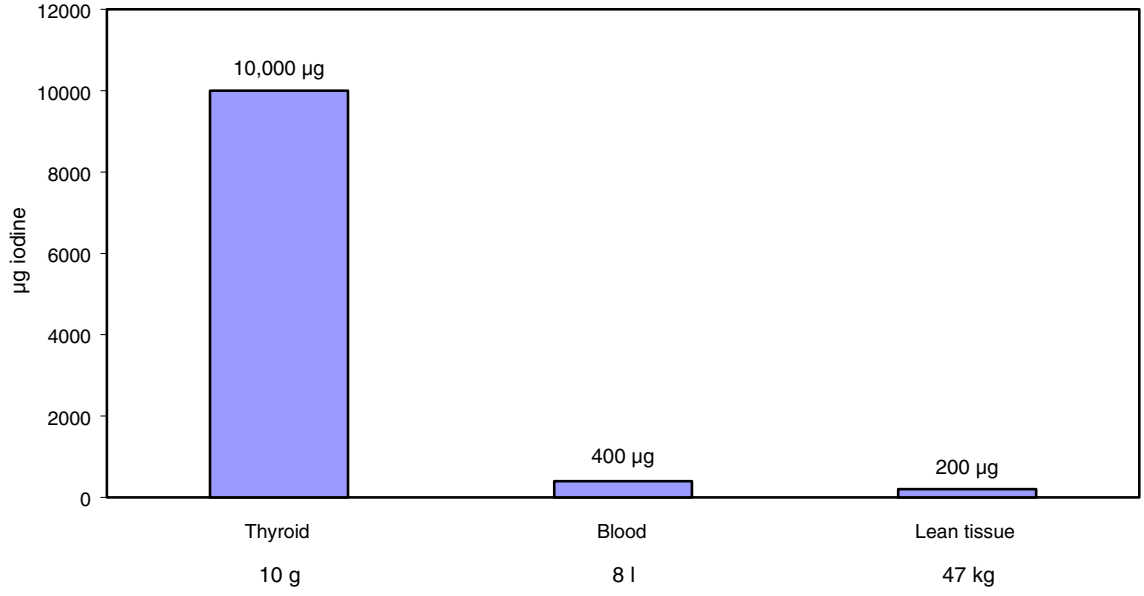

Fig. 1. Estimations of a total content of iodine in main parts of a slaughtered pig of 112 kg body weight and 88 kg carcass weight (as calculated from the group means of present experiments, Table 2). The calculation of thyroid weight was done with exception of groups 3 and 4 in Experiment 1 (Table 3). The blood weight of farm animals amounts to 70 ml/kg body weight. In the blood an equilibrium between the iodine of serum and that of erythrocytes was suggested.

represented by the iodine of thyroid hormones, particularly thyroxine (T4). The total serum iodine minus the iodine of the T4 and triiodothyronine (T3) is represented by iodide, i.e., the non-hormone percentage of serum iodine. In Experiment 3 supplying additionally 2400 μg iodine/kg feed a mean serum iodine of >500 μg/l indicated iodine overdosage whereby >90% of serum iodine were represented by the non-hormone-part, i.e., iodide. Only a defined and limited amount of this ionic iodine might be handled by thyroid-sodium-iodide symporter – TPO system and the excessive iodide would be excreted via kidneys and urine. The renal elimination of iodide is a rapid process and in Experiment 2 the urine samples taken from urinary bladder after slaughtering showed very high iodine concentrations (240 ± 214 μg/l, $n = 30$).

The glucosinolates diminished, as hypothesized, the iodide-oxidizing capacity of TPO, which was shown by the lower iodine stores of the thyroid (Table 3) and in lower serum T4 concentration (Schöne, Tischendorf, et al., 2001). Rapeseed or glucosinolates induced decreased TPO activity and a diminished thyroid iodine input as well as T4 output would result in more non-hormone iodine, i.e., ionic iodine, in the serum (Schöne, Tischendorf, et al., 2001) and more iodine in the meat as shown in Experiment 1. Regarding the thyroid mass (8–10 g per 100 kg pig weight), the blood volume (60–80 ml/kg body weight) and the muscle mass (540 g lean/kg carcass) and a so far questionable iodine content of fat tissue, inner organs, nervous tissue and skeleton, the "moderately filled" thyroid (1000 μg iodine/g) may represent more than four fifths of the total iodine in the organism (Fig. 1). In case of high thyroid concentrations (1500–2000 μg/g) the thyroid iodine share is above nine-tenths of total organism's iodine or the extra-thyroid iodine pool does not seem to exceed one-tenth. Relatively more iodine outside the thyroid would be found only in case of lower iodine stores of <500 μg iodine/g thyroid.

The detected muscle iodine concentration in the range of 4–10 μg/kg agreed with the data of three muscle samples determined by neutron activation analysis (Dermelj et al., 1996), however, they represent only one-twentieth to one-tenth of the further investigations' results (Rambeck et al., 1997; Swanson et al., 1990) and of the nutrient tables' data (Scherz & Senser, 2000). Probably the high muscle iodine concentrations reported in the literature result from insensitive and non-specific iodine detection mainly by the Sandel–Kolthoff reaction.

4.2. Consequences for a strategy against iodine deficiency

Contrasting with the presented failure to concentrate the trace element in pork by iodine fortification of diets, the iodine concentration of milk and eggs (Kaufmann & Rambeck, 1998; Richter, 1995) was convincingly increased by high iodine diets in hens' and cows' feeding. According to a further report (Schöne, Leiterer, Kirchheim, Franke Kathrin, & Richter, 2002), in beef and lamb similarly low iodine concentrations were detected as well as in pork with no or minor effects of the diet iodine administered.

Today in Germany milk and fresh milk (products) could contribute in a magnitude of one-fourth to one-third (Bader, Möller, Leiterer, Franke, & Jahreis, 2005; Zimmermann, Leiterer, Engler, Jahreis, & Schöne, 2005) of the 130 μg mean total iodine intake/adult/day estimated in adults in the nation-wide survey on iodine in Germany in the year 1996 (Gärtner, Manz, & Großklaus, 2001). This total iodine intake amount is still insufficient in comparison to the recommended 200 μg iodine/adult/day (D-A-CH, 2000). At least one half of the estimated iodine intake comes from iodized salt either from direct individual salting or from that what is used in the bakeries (ca. 30 μg I/adult and day) and by the meat processors (ca. 20 μg iodine/adult and day). Seafish, the "classical" iodine source, represents less than 5% of present German iodine intake.

The cited shares of iodine intake from the several food groups base – irrespective daily food consumption levels – on estimated percentages of the iodized salt administered from total salt usage which amounts to two-thirds in the bakeries and to one-third in the German meat processing plants (Großklaus, 1999).

It can be concluded that moderate and high iodine dosages of pig diets did not affect the fattening performance and the carcass. The dietary iodine was reflected almost exclusively by the thyroid iodine stores and to a certain degree by the iodine serum concentration. The meat of pigs has to be classified as a low iodine food. There are no possibilities to concentrate this trace element reproduceably and relevant for human nutrition in pork because overdoses of iodine seem to be rapidly eliminated as iodide via urine. A strategy to improve the iodine supply in human nutrition will be based both on the iodized salt's use in food processing and on the concentration of iodine in milk and eggs that can be attained by feeding measures with an upper iodine level which is harmless with regard to the health of the animals.

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