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Original article

I. A bibliographic database for quantitative analysis of phosphorus flow in ruminants

David BRAVO[a,b]*, Daniel SAUVANT[a], Catherine BOGAERT[b], François MESCHY[a]

[a] UMR INRA-INAPG, Physiologie de la Nutrition et Alimentation, 16 rue Claude Bernard, 75231 Paris Cedex 05, France
[b] UNION IN VIVO Ets INZO° Chierry BP 19, 02402 Château-Thierry Cedex, France

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Abstract — The present study describes a quantitative analysis of phosphorus metabolism in ruminants. The database compiles 100 sources either published (95) or unpublished (5) involving studies on true or apparent phosphorus balances carried out before 1999. The database reports 652 distinct experimental conditions (lines) described with experimental variables (column) involving a total of 2 982 animals: 414 lambs (33 references), 1 078 sheep (37 references), 64 pregnant ewes (3 references), 212 lactating ewes (5 references), 528 calves (20 references), 4 maintenance cows (1 reference), 519 lactating cows (6 references), 42 kids (1 reference) and 121 lactating goats (3 references). The reliability of the database was tested using some general relationships.

metabolism / phosphorus / quantitative aspect / ruminant

1. INTRODUCTION

Phosphorus is currently one of the most polluting nutrients because of high animal husbandry concentrations in restricted areas [1]. Lowering pollution is the current challenge to preserve the environment and the consumer's perception of Agriculture. Dietary manipulations in monogastrics [2] have been extensively investigated. Very few of these studies have been performed in ruminants even though they may contribute up to 0.70 of phosphorus from animal faeces and urine [1]. Important points remain concerning the phosphorus metabolism of ruminants. Which value of true phosphorus absorption coefficient is more appropriate: 0.55 [3] or 0.70 [4]? What influences dietary phosphorus availability? Should these factors be taken into account? How should phosphorus excretion, particularly endogenous faecal phosphorus, be determined? The answers to these and other questions will undoubtedly improve our way of optimising phosphorus feeding.

Many studies on phosphorus in ruminants were carried out and published in the 1970s and 1980s. Today, these reports

* Corresponding author: dbravo@inzo-net.com

represent a potential database for statistical analysis. The present authors reviewed the literature in order to compile the publications dealing with true or apparent phosphorus absorption and quantify the main effects on phosphorus metabolism in ruminants. Three articles report this work. The aim of the present paper was to describe the structure and content of the database as well as the methods applied to compile it. The two companion articles analyse the quantitative relationships of the digestive flux of phosphorus (article 2) and phosphorus excretion (article 3).

2. MATERIALS AND METHODS

This technique of quantitative reviewing has been widely used in human health care [5] and veterinary science [6]. Digestive flux studies [7] and dietary investigations [8] have previously been performed in our laboratory using this method.

2.1. Publications selected

A quantitative analysis of published and unpublished studies is a quantitative and, if possible, exhaustive review of trials with a common experimental aim [9]. The CAB abstracts were screened using the key words "phosphorus", "ruminants", "digestibility" and "metabolism" for original articles published before May 1999. In the database we only retained trials in which the digestibility of phosphorus or the phosphorus flux were determined in one of the three major species of domestic ruminants. The measurements using radio-isotopic techniques and those using other techniques were respectively designated "true" and "apparent" phosphorus digestibility studies.

In the appendix reference list, each selected publication is followed by a number in brackets ([B12] for instance) coding for the variable publication (PUB). Some of the reference sources reported one or more experiments (or trials), in which various treatments were used. Each line of the database represents the application of one treatment to a single group or animal.

2.2. Variables

Each experimental line is completed for the reference (PUB) and trial (TRIAL), for the quantitative and qualitative data on animals and diets, and for different phosphorus flux. The aim of the trials was also recorded and encoded in eleven levels in the proportions indicated in brackets: the consequences of varying phosphorus intake (0.32), phosphorus requirements (0.12), phosphorus digestibility and availability (0.13), inorganic phosphates (0.08), phosphorus metabolism and faecal endogenous phosphorus (0.06), distribution between faecal and urine phosphorus excretion (0.04), poultry litter as a source of phosphorus for sheep (0.03), influence of vitamin D3 on phosphorus metabolism (0.02), phosphorus metabolism in grazing animals (0.02), phosphorus metabolism in milk-fed ruminants (0.01) and diverse topics (0.17). A variable identified the research team with a senior researcher (TEAM; 1: Field; 2: Braithwaite; 3: Guéguen; 4: Scott; 5: Ternouth; 6: Pfeffer; 7: Grace; 8: Tillman and Brethour; 9: Lofgreen and Kleiber; 10: Vitti; 11: Compère; 12: Morse; 13: other researchers).

The animal groups of each treatment were quantitatively described by their number (ANIM), mean age (AGE, in months), body weight (BW, in kg), dry matter intake (DMI, in $g \cdot day^{-1}$) and qualitatively by species (SPE: sheep, cattle, goats), production status (PROD: maintenance, growth, pregnancy, lactation) and the combination of the last two variables (SPEPROD) (1: lamb, 2: sheep, 3: pregnant ewe, 4: lactating ewe, 5: calf, 6: non-lactating cow, 7: lactating cow, 8: kid, 9: lactating goat).

The dietary composition (expressed in DM content) was quantitatively documented in terms of the percentage of total concentrates (%CONC) and forages (%FOR). When available, the percentages of individual feedstuffs such as straw (%STRAW), hay (%HAY), corn silage (%CORNSIL) and total silage (%TOTSIL) were recorded. The feed concentrates were also listed separately (%SOYMEAL, %WHEAT for example). The total content in oilseed meals (%TOTMEAL) as in cereal and by-products (%CERBP) was noted, as well.

The chemical composition of the diet was documented in terms of g of phosphorus per kg of DM (PDIET) and g of calcium per kg of DM (CADIET). Because the diet content (in $g \cdot kg^{-1}$ DM) in phytic phosphorus (PHYT) and crude fibre (CF) were potentially interesting information not present in the original articles, they were estimated from feed tables [3, 10] when the type of feed was indicated.

The phosphorus metabolism was described using the different phosphorus flux data (expressed in $g \cdot day^{-1}$): ingested phosphorus (PING), faecal phosphorus ($PFEC_{TOT}$), endogenous faecal phosphorus ($PFEC_{ENDO}$), urinary phosphorus (PURI), salivary phosphorus (PSAL), bone phosphorus accretion ($PBONE_{+}$), release of bone phosphorus ($PBONE_{-}$) and balance of bone phosphorus (PBONE). Plasma phosphorus content was reported when indicated (PPLASM, in $mmol \cdot L^{-1}$).

The following parameters were also calculated:

– total phosphorus entering into the digestive tract: PTOT = PING + PSAL;

– dietary phosphorus absorption: $PABS_{ING} = PING - PFEC_{TOT} + PFEC_{ENDO}$;

– salivary phosphorus absorption: $PABS_{SAL} = PSAL - 0.80 \times PFEC_{ENDO}$, considering that endogenous faecal phosphorus corresponds to 0.80 of non-reabsorbed salivary phosphorus;

– total phosphorus absorption: $PABS_{TOT} = PTOT - PFEC_{TOT}$;

– exogenous faecal phosphorus: $PFEC_{EXO} = PFEC_{TOT} - PFEC_{ENDO}$;

– the efficiency of absorption of dietary phosphorus: $EFFABS_{ING} = PABS_{ING}/PING$;

– the efficiency of absorption of salivary phosphorus: $EFFABS_{SAL} = PABS_{SAL}/PSAL$;

– the efficiency of total phosphorus absorption: $EFFABS_{TOT} = PABS_{TOT}/PTOT$.

The phosphorus flux values were also expressed per kg of body weight or per kg of DM intake (e.g., PING/BW or $PABS_{SAL}$/BW, respectively, for the flux of ingested phosphorus and the absorption of salivary phosphorus). DM intake was also expressed per kg of body weight (DMI/BW). All the abbreviations are presented in Table I.

2.3. Statistical methods

Methodological care and specific statistical treatment were applied to this database, which was compiled from an unbalanced series of non-orthogonal variables. This analysis was performed using procedures of SAS [11].

Verification of the consistency of each variable was based upon straightforward means including histograms, extrema, mean, and standard deviation values. The normality of the distribution of each variable was also investigated using the Wilk-Shapiro test that verified the "normality of the distribution" versus the "non-normality of the distribution". All the relationships were monofactorial. In all the subsequent statistics, weighted models were employed using the number of animals involved in each treatment (ANIM) as an input factor of the whole analysis and by defining $\omega_i = ANIM_i / \sum_{j=1}^{n} ANIM_j$, with $ANIM_i$ = the number of animals involved in the treatment i and n = the total number of treatments used in the model. This procedure was applied using the WEIGHT instruction of SAS [11].

Table I. Variables abbreviations (code, unit and definition).

Code	Definition (formulae)
%CONC (%)	Dietary concentrate content (DM basis)
%FOR (%)	Total dietary forage content (DM basis)
%STRAW (%)	Individual dietary component content (straw in this example...)
BW (g)	Body weight
CF ($g \cdot kg^{-1}$ DM)	Dietary crude fibre content
DM (%)	Dietary dry matter content
DMI ($g \cdot day^{-1}$)	Daily dry matter intake
$EFFABS_{ING}$ ($g \cdot g^{-1}$)	Efficiency of absorption of dietary phosphorus (= $PABS_{ING}$/PING)
$EFFABS_{SAL}$ ($g \cdot g^{-1}$)	Efficiency of absorption of salivary phosphorus (= $PABS_{SAL}$/PSAL)
$EFFABS_{TOT}$ ($g \cdot g^{-1}$)	Efficiency of absorption of total phosphorus (= $PABS_{TOT}$/PTOT)
$PABS_{ING}$ ($g \cdot day^{-1}$)	Daily dietary phosphorus absorption flux (= PING – $PFEC_{TOT}$ + $PFEC_{ENDO}$)
$PABS_{SAL}$ ($g \cdot day^{-1}$)	Daily salivary phosphorus absorption flux (= PSAL – $PFEC_{ENDO}$)
$PABS_{TOT}$ ($g \cdot day^{-1}$)	Daily total phosphorus absorption flux (= PTOT – $PFEC_{TOT}$)
$PBONE_{+}$ ($g \cdot day^{-1}$)	Daily bone phosphorus accretion flux
$PBONE_{-}$ ($g \cdot day^{-1}$)	Daily bone phosphorus release flux
PBONE ($g \cdot day^{-1}$)	Daily bone phosphorus balance (= $PBONE_{+}$ – $PBONE_{-}$)
PDIET ($g \cdot kg^{-1}$ DM)	Dietary phosphorus content
$PFEC_{ENDO}$ ($g \cdot day^{-1}$)	Daily endogenous faecal phosphorus flux
$PFEC_{EXO}$ ($g \cdot day^{-1}$)	Daily exogenous faecal phosphorus flux (= $PFEC_{TOT}$ – $PFEC_{ENDO}$)
$PFEC_{TOT}$ ($g \cdot day^{-1}$)	Daily total faecal phosphorus flux
PING ($g \cdot day^{-1}$)	Daily ingested phosphorus flux (= DMI × PDIET)
PHYT ($g \cdot kg^{-1}$ DM)	Dietary phytate content
PPLASM ($mmol \cdot L^{-1}$)	Plasma phosphorus concentration
PURI ($g \cdot day^{-1}$)	Daily urinary phosphorus flux
PSAL ($g \cdot day^{-1}$)	Daily salivary phosphorus flux
PTOT ($g \cdot day^{-1}$)	Total phosphorus entering daily into the digestive tract (= PING + PSAL)

Varying conditions can hide within-trial variations. In the present study, within-trial variability was addressed using the covariance analysis. For each trial, a correction factor α was determined (variable TRIAL) from the following relationship:

$$Y_i = \mu + \alpha_i + a \times X_i \times \omega_i + \varepsilon_i.$$

Where Y = response, μ = overall mean, α = effect of the variable TRIAL, X = tested variable used as a covariable, a = coefficient of the regression of X with respect to Y, ε = residual error not taken into account in the model. These models are called "within-trial models".

The overall variations were also taken into account using the following succession of models. The first model determined the effect of X on Y by regression analysis with the number of animals in each treatment (ANIM) as a statistical weight:

$$Y_i = a \times X_i \times \omega_i + b + \varepsilon_i \text{ (model 1).}$$

Where a and b = coefficients of the regression of X with respect to Y, ε_{ij} = residual variations of Y independent of X (i.e., variations in Y with X held constant) encoded RES[Y(X)].

The second step was to investigate the influence of a third variable (Z) on RES[Y(X)]. Z was not introduced in the first regression (model 1) since the number of treatments with Z was lower than that with X. The following regression analysis was used:

$$RES[Y(X)]_{ij} = c \times Z_{ij} \times \omega_i + d + \varepsilon'_{ij},$$

where c and d = coefficients of the regression of Z with respect to RES[Y(X)], ε'_{ij} = variations of Y independent of X and Z (i.e., variations in Y with X and Z held constant) encoded RES[Y(X,Z)].

Regression analyses of trial mean values of the variable X with respect to the mean values of the variable Y were called "inter-trial models":

$$MEAN[Y]_{ij} = a \times MEAN[X]_i \times \omega_i + b + \varepsilon_{ij}.$$

All the statistical models were presented with the number of treatments (TRT), the number of experiments (EXP), the number of animals involved (ANIM), the square of the correlation coefficient (r^2), the root mean square error (RMSE) and the level of significance of the *t*-test probability for the model (*P*). In all the models presented, the coefficients are followed by their standard errors in brackets.

3. RESULTS AND DISCUSSION

The number of references and the publications recorded for each type of animal are presented in Table II.

3.1. General results

The database compiled 100 trials, among which 95 have been published. We also included 5 unpublished trials [12–16]. The 100 trials represented 652 treatments. Reports were published between 1953 [17] and 1999 [18]. Eight research teams published 0.80 of the studies: Braithwaite (0.14), Ternouth (0.12) and Guéguen (0.10), Field, Scott, and Vitti (0.08 each), Pfeffer (0.06) and Lofgreen (0.05).

Table II. Publications involved for each different production status (PROD) and animal species (SPE), with number of references (EXP).

SPE	PROD	EXP	Code of the publication in the reference appendix list
Sheep	Growth	33	B6, B7, B12, B14, B15, B23, B32, B33, B35, B37, B38, B40, B45, B46, B47, B48, B49, B50, B55, B61, B67, B75, B77, B82, B84, B85, B87, B88, B90, B91, B92, B98, B100
	Maintenance	37	B2, B7, B10, B11, B13, B16, B25, B26, B30, B31, B34, B36, B38, B39, B41, B42, B43, B54, B56, B57, B58, B62, B65, B66, B70, B71, B72, B73, B74, B75, B76, B79, B83, B94, B96, B97, B99
	Pregnancy	4	B13, B16, B36, B80
	Lactation	5	B8, B9, B13, B16, B68
Cattle	Growth	20	B3, B4, B5, B19, B20, B21, B22, B24, B27, B28, B44, B51, B52, B70, B81, B86, B89, B93, B95, B97
	Maintenance	1	B59
	Lactation	6	B17, B18, B53, B60, B63, B78
Goats	Growth	1	B1
	Lactation	3	B29, B64, B69

3.2. Animals (Tab. III)

Overall, 2 982 animals were involved in the database (0.58 sheep, 0.35 cattle, 0.07 goats). Lambs were 7.4 months old, weighed 33.6 kg and ingested 858 g of DM on the average. The youngest lambs (9 kg) were used for the determination of calcium and phosphorus retention in milk-fed lambs [19]. [20] used the heaviest lambs (60 kg) to study calcium and phosphorus metabolism during the end of the growth period. On average, the calves were 10.2 months old and ingested 4.70 kg of DM. The youngest and lightest calves were milk fed (15 days old, 65 kg body weight) and were involved in the

Table III. Mean animal characteristics (standard deviation): age (Age), body weight (BW) and dry matter intake (DMI) for the different production status (PROD) and animal species (SPE), with number of references (EXP) and animals (ANIM) involved.

	SPE	PROD	EXP	ANIM	Mean (standard deviation)
Age (months)	Sheep	Growth	13	155	7.4 (8.4)
		Maintenance	12	307	22.7 (9.0)
		Pregnancy	3	30	53.2 (9.3)
		Lactation	5	71	40.5 (2.6)
	Cattle	Growth	8	225	10.2 (5.5)
		Maintenance	ND	ND	ND
		Lactation	ND	ND	ND
	Goats	Growth	1	42	7.0 (0)
		Lactation	ND	ND	ND
BW (kg)	Sheep	Growth	26	77	33.6 (8.4)
		Maintenance	35	1039	46.6 (9.0)
		Pregnancy	4	64	60.4 (9.0)
		Lactation	5	213	59.6 (9.9)
	Cattle	Growth	14	308	185 (77)
		Maintenance	ND	ND	ND
		Lactation	4	439	585 (28)
	Goats	Growth	1	42	10 (1)
		Lactation	3	175	45.7 (6.6)
DMI ($g \cdot day^{-1}$)	Sheep	Growth	26	318	858 (271)
		Maintenance	37	1050	864 (337)
		Pregnancy	3	30	859 (222)
		Lactation	5	181	1288 (353)
	Cattle	Growth	16	366	4704 (3694)
		Maintenance	1	160	8618 (0)
		Lactation	5	519	16992 (7199)
	Goats	Growth	1	42	430 (87)
		Lactation	2	69	1851 (327)

ND: no data was available for the calculation.

measurement of endogenous faecal phosphorus and the evaluation of the maintenance requirements [21]. [22] used the heaviest calves for phosphorus metabolism studies in cattle grazing on phosphorus-deficient Australian pastures. Kids (African dwarf goat) were used in only one study (42 animals, [23]) and were, on the average, 7 months old, weighed 10 kg and ingested 430 g DM.

The most frequently studied animals were sheep in the maintenance phase, used in 37 trials (1 078 animals, 285 treatments). On the average, they were 22.7 months old, weighed 46.6 kg, and ingested 864 g DM. The heaviest sheep weighed on average 87 kg [24], 76 kg [25]. Two trials assimilated ewes during the three last weeks of lactation as sheep in the maintenance phase [26, 27]. The non-lactating cows were used in only one trial (4 animals) for the study of the relationship between phosphorus and calcium absorption and their concentration in the diet [28]. The only pregnant animals of our database were ewes used in 4 trials (64 animals) and weighing 46 kg [29], 50 kg [26], 65 kg [30], and 70 kg [27]. The lactating ewes ingested 859 g DM and weighed on average 59.6 kg. The lightest (50 and 57.5 kg) and heaviest (70 kg) ewes were used by [26, 31]. The lactating cows weighed 585 kg and ingested 17.0 kg DM, on the average. The heaviest lactating cows (645 kg) were used to define the true phosphorus availability for alfalfa and corn silage [32]. The lightest lactating cows (590 kg) were involved in a phosphorus excretion study [33]. On the average, the lactating goats weighed 45.7 kg and the ingested 1.85 kg DM. The heaviest lactating goats averaged 60 kg [34] and the lightest 40 kg [35].

The animals described in the database were very diverse. Because each physiological state was unequally represented, the "physiological state" effect should be interpreted carefully.

3.3. Experimental diets (Tab. IV)

All forage diets were used for different experimental purposes. They were fed to lambs for the determination of phosphorus requirements [36] and the availability of phosphorus in corn silage [37] and alfalfa hay [17]. Pure forage diets were administered to grazing calves in a study of phosphorus metabolism [22]. On this type of diet phosphorus repletion after nitrogen and phosphorus deficiency was also analysed

Table IV. Mean diet characteristics (standard deviations): dietary phosphorus (PDIET), crude fibre (CF), phytate phosphorus (PHYT), cereals contents (%CERBP) and forages contents (%FOR) for the different production status (PROD) and animal species (SPE), with number of references (EXP) and animals (ANIM) involved.

	SPE	PROD	EXP	ANIM	Mean (standard deviation)
PDIET ($g \cdot kg^{-1}$ DM)	Sheep	Growth	23	345	3.3 (2.6)
		Maintenance	33	1022	3.4 (2.2)
		Pregnancy	3	25	4.0 (2.1)
		Lactation	5	181	4.4 (2.8)
	Cattle	Growth	15	354	2.0 (2.3)
		Maintenance	1	120	6.4 (1.0)
		Lactation	6	519	4.1 (1.3)
	Goat	Growth	1	42	5.7 (1.9)
		Lactation	3	181	2.8 (1.0)

Table IV. *(continued)*

	SPE	PROD	EXP	ANIM	Mean (standard deviation)
CF (g·kg^{-1} DM)	Sheep	Growth	18	204	145 (100)
		Maintenance	20	1235	233 (67)
		Pregnancy	2	38	231 (27)
		Lactation	5	176	192 (46)
	Cattle	Growth	10	355	247 (89)
		Maintenance	ND	ND	ND
		Lactation	ND	ND	ND
	Goats	Growth	ND	ND	ND
		Lactation	1	32	273 (12)
PHYT (g·kg^{-1} DM)	Sheep	Growth	19	204	0.83 (0.94)
		Maintenance	19	821	0.49 (0.58)
		Pregnancy	2	38	0.48 (0.68)
		Lactation	5	176	0.85 (0.51)
	Cattle	Growth	9	211	0.03 (0.06)
		Maintenance	ND	ND	ND
		Lactation	ND	ND	ND
	Goats	Growth	ND	ND	ND
		Lactation	1	32	0.25 (0.01)
%CERBP (% DM)	Sheep	Growth	13	206	21.8 (26.0)
		Maintenance	15	317	15.5 (21.4)
		Pregnancy	1	4	3.8 (9.4)
		Lactation	5	126	34.6 (14.7)
	Cattle	Growth	9	138	5.6 (14.3)
		Maintenance	ND	ND	ND
		Lactation	4	84	28.0 (18.6)
	Goat	Growth	ND	ND	ND
		Lactation	2	69	3.0 (4.6)
%FOR (% DM)	Sheep	Growth	20	308	26.8 (28.5)
		Maintenance	28	880	45.8 (40.9)
		Pregnancy	2	22	39.6 (11.4)
		Lactation	5	144	53.4 (19.9)
	Cattle	Growth	13	443	57.5 (36.9)
		Maintenance	ND	ND	ND
		Lactation	4	84	29.4 (23.6)
	Goats	Growth	ND	ND	ND
		Lactation	3	175	59.9 (18.2)

ND: no data was available for the calculation.

[18]. In sheep, 100%-forage diets were given in order to determine the availability of phosphorus in forages [38, 39], maintenance phosphorus requirements [40, 41] and the phosphorus metabolism [29, 42–49]. [50] used 100% chopped hay diet for the determination of net intestinal exchange of ions.

Incorporation of cereals into the diet reached 75.3% barley in the evaluation of dried poultry manure as a source of phosphorus for lambs [51]. The highest incorporation of dried beet pulp (88%) was used for the evaluation of ammonium polyphosphate in lambs [52]. The diets fed to lambs were the richest in concentrate feed (71.0% ± 42.3%). One third of them consisted of 100% concentrate and the two remaining thirds contained more than 40% concentrates.

Diets with concentrates were only given for the determination of phosphorus requirements for growth [40, 53] and in a study of phosphorus metabolism in milk-fed lambs [19]. Pure concentrate diets were also given to lambs for the evaluation of various phosphorus sources [51, 54], in another study of phosphorus metabolism [55, 56], for the determination of the availability of phosphorus in different feedstuffs [38, 57], and for studies of phosphorus excretion [45, 58] and phosphorus metabolism [59]. In calves, 100%-concentrate diets were used for studying the influence of diet structure on phosphorus excretion [58, 60] as well as the phosphorus metabolism [21]. A 100%-concentrate diet was also given to lactating goats in an investigation of phosphorus metabolism during phosphorus depletion [61].

3.4. Description of the major phosphorus flux values (Tab. V)

Most of the quantitative variables of the database had a normal distribution as shown

Table V. Mean phosphorus flows and data characteristics (standard deviation): phosphorus intake (PING), faecal phosphorus (PFEC-TOT), endogenous faecal phosphorus (PFEC-ENDO), urinary phosphorus (PURI), absorbed phosphorus (PABS-ING) and efficiency of phosphorus absorption ($EFFABS_{ING}$) for the different production status (PROD) and animal species (SPE), with number of references (EXP) and animals (ANIM) involved.

	SPE	PROD	EXP	ANIM	Mean (standard deviation)
PING ($g \cdot day^{-1}$)	Sheep	Growth	24	69	3.2 (3.2)
		Maintenance	32	622	3.5 (2.8)
		Pregnancy	3	30	3.7 (2.9)
		Lactation	5	173	6.0 (4.6)
	Cattle	Growth	15	334	7.6 (3.9)
		Maintenance	1	10	56.0 (4.0)
		Lactation	5	94	78.4 (28.1)
	Goats	Growth	1	42	2.5 (1.3)
		Lactation	2	144	4.0 (2.1)
$PFEC_{TOT}$ ($g \cdot day^{-1}$)	Sheep	Growth	22	309	2.1 (2.1)
		Maintenance	30	538	2.5 (2.3)
		Pregnancy	3	30	3.0 (2.4)
		Lactation	5	173	5.1 (3.9)
	Cattle	Growth	12	280	4.8 (2.4)
		Maintenance	1	10	46.5 (18.5)

Table V. *(continued)*

	SPE	PROD	EXP	ANIM	Mean (standard deviation)
		Lactation	5	42	46.3 (17.7)
	Goats	Growth	1	42	1.1 (0.5)
		Lactation	2	136	2.5 (1.1)
$PFEC_{ENDO}$ ($g \cdot day^{-1}$)	Sheep	Growth	22	279	1.1 (0.8)
		Maintenance	22	457	1.2 (0.6)
		Pregnancy	2	12	2.2 (0.8)
		Lactation	4	155	2.5 (1.2)
	Cattle	Growth	11	264	3.0 (1.5)
		Maintenance	1	10	12.7 (3.3)
		Lactation	1	4	7.7 (2.7)
	Goats	Growth	1	42	0.8 (0.3)
		Lactation	ND	ND	ND
PURI ($g \cdot day^{-1}$)	Sheep	Growth	20	282	0.72 (1.09)
		Maintenance	23	490	0.56 (1.00)
		Pregnancy	3	30	0.42 (0.62)
		Lactation	5	173	0.12 (0.19)
	Cattle	Growth	9	113	1.00 (1.50)
		Maintenance	ND	ND	ND
		Lactation	3	14	1.36 (1.50)
	Goats	Growth	1	42	0.004 (0.003)
		Lactation	1	112	0.09 (0.13)
$PABS_{ING}$ ($g \cdot day^{-1}$)	Sheep	Growth	22	279	2.2 (1.9)
		Maintenance	22	457	2.0 (1.0)
		Pregnancy	2	12	2.7 (1.0)
		Lactation	4	155	3.2 (1.7)
	Cattle	Growth	11	264	5.3 (2.3)
		Maintenance	1	10	22.2 (11.1)
		Lactation	1	4	28.3 (10.7)
	Goats	Growth	1	42	2.2 (1.1)
		Lactation	ND	ND	ND
$EFFABS_{ING}$ (%)	Sheep	Growth	22	279	0.72 (0.14)
		Maintenance	22	457	0.71 (0.14)
		Pregnancy	2	12	0.56 (0.13)
		Lactation	4	155	0.71 (0.12)
	Cattle	Growth	11	264	0.76 (0.11)
		Maintenance	1	10	0.52 (0.19)
		Lactation	1	4	0.69 (0.06)
	Goats	Growth	1	42	0.87 (0.03)
		Lactation	ND	ND	ND

ND: no data was available for the calculation.

for plasma phosphorus (Wilk-Shapiro test: $P > 0.1$, Fig. 1). Urinary phosphorus did not present a normal distribution (Fig. 2) whether normalised according to body weight or not (in both cases, the Wilk-Shapiro test: $P < 0.01$) illustrating the homeostatic control on phosphorus excretion by the urine route. The low number of animals investigated for bone and salivary phosphorus flux did not permit to determine if their distribution is normal.

The lowest phosphorus intakes were reported in experiments on phosphorus depletion in lambs: 0.273 g·day^{-1} [62], 0.300 g·day^{-1} [63] and 0.350 g·day^{-1} [64], in sheep in the maintenance phase [63, 65] and 21.50 g·day^{-1} in lactating cows [66]. Calves were fed a low-phosphorus diet (0.68 g·day^{-1}) to determine its influence on dietary phosphorus and aluminum availability [67]. The highest phosphorus intakes were studied for their influence on phosphorus metabolism and excretion in ewes in the maintenance phase [26, 58]. Total faecal phosphorus ($PFEC_{TOT}$) represented 0.60 to 0.70 of the daily ingested phosphorus. This ratio was lower in kids (0.44) and lactating cows (0.58) and higher in lactating ewes (0.83). The endogenous faecal phosphorus

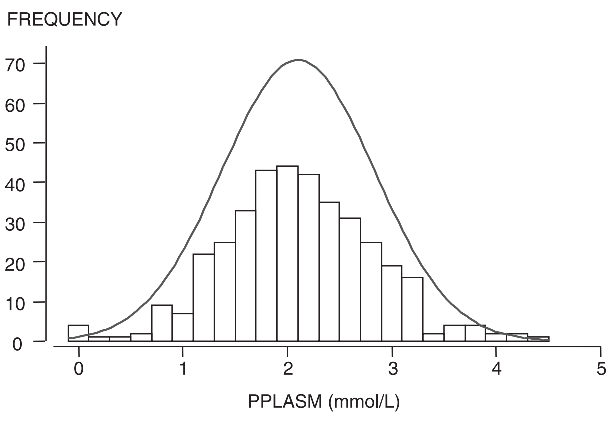

Figure 1. Frequency histogram for plasma phosphorus concentration (PPLASM).

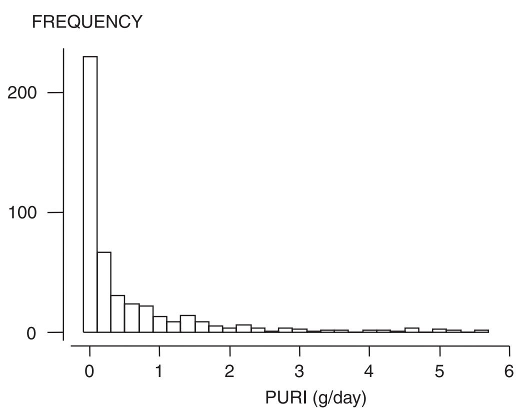

Figure 2. Frequency histogram for urinary phosphorus (PURI).

represented around 0.75 of the total faecal phosphorus loss (0.79 for cows in the maintenance phase and 0.75 for kids), except in lactating cows (0.16).

The phosphorus fluxes (faecal, faecal endogenous, urinary and ingested) were determined according to digestibility trials. In the original papers, salivary phosphorus was determined in sheep by the difference between duodenal phosphorus flux and ingested phosphorus flux [45–49]. Salivary phosphorus was also calculated [26, 68–70] using the equation of Conrad (1955) cited by [B99]: $PSAL = PFEC_{ENDO}/1–EFFABS_{ING}$. [71] did not precise the method they used for the measurement of salivary phosphorus.

The bone phosphorus exchanges were assessed in growing lambs [20, 53], in pregnant and lactating ewes [26, 27, 31, 72], in sheep [25, 44, 73–75], and growing calves [21, 68, 69]. The radioisotopic dilution method employed by [74] was similar to that used by [76] for a calcium kinetics study. The method assumes that no radioactivity returns to the exchangeable phosphorus pool. Given the constant cycle of formation – mineral release of bone and the role of phosphorus in numerous metabolic pathways, the bone phosphorus accretion and release estimations may be subject to error [25].

In this work, we did not take into account calcium metabolism since calcium flows were not always present in the publications compiled and despite the known interactions between calcium and phosphorus metabolisms.

4. CONCLUSIONS

This paper presents an original database on phosphorus fluxes in ruminants, compiling 652 distinct experimental situations from 100 trials. The three livestock ruminant species and the main production stages were represented. The range of treatments included types of diets commonly used on farms as well as some extreme diets leading to variations in phosphorus metabolism.

The database consistency was verified. The high number of treatments and the use of adapted statistical methodology can be applied to draw general relationships. That is the purpose of the two companion articles in order to improve the knowledge of the quantitative aspects of (i) phosphorus digestive availability and absorption and (ii) phosphorus metabolism and excretion.

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REFERENCES

[1] Tamminga S. Nutrition management of dairy cows as a contribution to pollution control. J Dairy Sci 1992, 75: 345–357.

[2] Jongbloed AW. Phosphorus in the feeding of pig. Ph.D thesis. University of Wageningen, The Netherlands, 1987.

[3] Jarrige R. Institut National de la Recherche Agronomique. Ruminant nutrition recommanded allowances and feed tables. John Libbey and Co. Ltd, London, 1989.

[4] AFRC. Technical committee on responses to nutrients. Report 6. A reappraisal of the calcium and phosphorus requirements of sheep and cattle. Nutr Abstr Rev 1991, 61: 573–612.

[5] Pignon JP, Stewart LA. Randomized trials of radiotherapy alone versus combined chemotherapy and radiotherapy in stages IIIa and IIIb non small cell lung cancer: a meta analysis (letter). Cancer 1996, 77: 2413–2414.

[6] Del Castillo J, Elsener J, Martineau GP. Stratégies métaphylactiques par voie orale chez le porc en croissance. Méta-analyse et modélisation appliquées aux tétracyclines. Journées Rech Porcine en France 1997, 29: 39–46.

[7] Archimède H, Sauvant D, Schmidely P. Quantitative review of ruminal and total tract digestion of mixed diet organic matter and carbohydrates. Reprod Nutr Dev 1997, 37: 173–189.

[8] Sauvant D, Van Milgen J. Les conséquences de la dynamique de la digestion des aliments sur le métabolisme ruminal et les performances animales. INRA Prod Anim 1995, 8: 353–367.

[9] Pignon JP, Poynard T. Méta-analyse d'essais thérapeutiques. Gastroenterol Clin Biol 1991, 15: 229–238.

[10] Pointillart A. Phytates, phytases : leur importance dans l'alimentation des monogastriques. INRA Prod Anim 1994, 7: 29–39.

[11] SAS Institute, SAS User's Guide: Statistics SAS Institute INC., Cary.

[12] Guéguen L. Compte rendu d'expérience sur l'utilisation digestive réelle du phosphore du phosphate bicalcique DICALPHOS chez le mouton en croissance. Unpublished data, 1979.

[13] Guéguen L, Bouchet JP. Compte-rendu d'expérience sur l'utilisation réelle du phosphore du phosphate triple de sodium, calcium et magnésium HOSTAPHOS chez le mouton en croissance. Unpublished data, 1980.

[14] Guéguen L, Bouchet JP. Compte rendu d'expérience sur l'utilisation digestive réelle du phosphore du phosphate monomagnésique MONOMAG chez le mouton en croissance. Unpublished data, 1980.

[15] Guéguen L, Durand M. Étude comparée de l'utilisation du phosphore du phosphate monocalcique, du phosphate bicalcique et du phosphate d'urée par le mouton en croissance. Unpublished data, 1976.

[16] Walker DM. Calcium and phosphorus retention by the milk-fed lambs, with estimates of the endogenous losses. J Agric Sci 1972, 79: 171–179.

[17] Lofgreen GP, Kleiber M. The availability of the phosphorus in alfalfa hay. J Anim Sci 1953, 12: 366–371.

[18] Bortolussi G, Ternouth JH, McMeniman NP. Phosphorus repletion of cattle previously exposed to dietary nitrogen and phosphorus deficiencies. Aust J Agric Res 1999, 50: 93–99.

[19] Walker DM. Calcium and phosphorus retention by the milk-fed lambs, with estimates of the endogenous losses. J Agric Sci 1972, 79: 171–179.

[20] Field AC, Woolliams JA, Dingwall RA. The effect of dietary intake of calcium and dry matter on the absorption and excretion of calcium and phosphorus by growing lambs. J Agric Sci 1985, 105: 237–243.

[21] Challa J, Braithwaite GD. Phosphorus and calcium metabolism in growing calves with special emphasis on phosphorus homeostasis. 4. Studies on milk-fed calves given different amounts of dietary phosphorus but a constant intake of calcium. J Agric Sci 1989, 113: 285–289.

[22] Coates DB, Ternouth JH. Phosphorus kinetics of cattle grazing tropical pastures and implications for the estimation of their phosphorus requirements. J Agric Sci 1992, 119: 401–409.

[23] Adeloye AA, Akinsoyinu AO. Phosphorus requirement of the young west african dwarf (Fouta djallon) goat for maintenance and growth. Nutr Rep Int 1985, 32: 239–244.

[24] Meschy F, Guéguen L. Évaluation du besoin minimum d'entretien en phosphore chez l'agneau. Reprod Nutr Dev 1990, 12: 189–190.

[25] Braithwaite GD. Effect of 1-α-hydroxycholecalciferol on calcium and phosphorus metabolism in sheep given high or low calcium diets. J Agric Sci 1981, 96: 291–299.

[26] Braithwaite GD. Calcium and phosphorus requirements of the ewe during pregnancy and lactation. 2- Phosphorus. Br J Nutr 1983, 50: 723–736.

[27] Braithwaite GD. Phosphorus requirements of ewes in pregnancy and lactation. J Agric Sci 1986, 106: 271–278.

[28] Manston R. The influence of dietary calcium and phosphorus concentration on their absorption in the cow. J Agric Sci 1967, 68: 263–268.

[29] Field AC, Sykes AR, Gunn RG. Effects of age and state of incisor dentition on faecal output of dry matter and on faecal and urinary output of nitrogen and minerals, of sheep grazing hill pastures. J Agric Sci 1974, 83: 151–160.

[30] Sykes AR, Dingwall RA. The phosphorus requirement of pregnant sheep. J Agric Sci 1976, 86: 587–594.

[31] Braithwaite GD. The effect of 1-α-hydroxycholecalciferol on calcium and phosphorus metabolism in the lactating ewe. Br J Nutr 1978, 40: 387–392.

[32] Martz FA, Belo AT, Weiss MF, Belyea RL. True absorption of calcium and phosphorus from alfalfa and corn silage when fed to lactating cows. J Dairy Sci 1990, 73: 1288–1295.

[33] Morse D, Head HH, Wilcox CJ, van Horn HH, Hissem CD, Harris Jr B. Effects of concentration of dietary phosphorus on amount and route of excretion. J Dairy Sci 1992, 75: 3039–3049.

[34] Müschen H, Petri A, Breves G, Pfeffer E. Response of lactating goats to low phosphorus intake. 1. Milk yield and faecal excretion of P and Ca. J Agric Sci 1988, 111: 253–263.

[35] Deitert C, Pfeffer E. Effects of a reduced P supply in combination with adequate or high Ca intake on performance and mineral balances in dairy goats during pregnancy and lactation. J Anim Physiol A Anim Nutr 1993, 69: 12–21.

[36] Field AC. Maintenance requirements of phosphorus and absorbability of dietary phosphorus in sheep. J Agric Sci 1983, 100: 231–233.

[37] Guéguen L, Durand M. Utilisation des principaux éléments minéraux du maïs ensilé par le mouton en croissance. Ann Zootech 1976, 25: 543–549.

[38] Field AC, Woolliams JA, Dingwall RA, Munro CS. Animal and dietary variation in the absorption and metabolism of phosphorus by sheep. J Agric Sci 1984, 103: 283–291.

[39] Guéguen L. L'utilisation digestive réelle du phosphore du foin de luzerne pour le mouton mesurée à l'aide de ^{32}P. Ann Biol Anim Bioch Biophys 1962, 2: 143–149.

[40] Field AC, Coop RL, Dingwall RA, Munro CS. The phosphorus requirements for growth and maintenance of sheep. J Agric Sci 1982, 99: 311–317.

[41] Grace ND. Effect of increasing phosphorus intake on the phosphorus faecal endogenous loss in the sheep. Proc NZ Soc Anim Prod 1980, 40: 221–228.

[42] Compère R. L'alimentation en calcium et en phos phore et l'équilibre Ca-P de la ration. In: Duculot J (Ed), L'étude de l'équilibre phosphocalcique du régime basée sur les variations du métabolisme phosphoré, Les presses agronomiques de Gembloux, A.S.B.L., Gembloux, 1967. p 84–109.

[43] Compère R. Influence de la nature de l'aliment sur le métabolisme phosphoré. In: Duculot J (Ed), L'étude de l'équilibre phosphocalcique du régime basée sur les variations du métabolisme phosphoré, Les presses agronomiques de Gembloux, A.S.B.L., Gembloux, 1967. p 109–113.

[44] Grace ND. Phosphorus kinetics in the sheep. Br J Nutr 1981, 45: 367–374.

[45] Scott D, Buchan W. The effects of feeding either roughage or concentrate diets on salivary phosphorus secretion, net intestinal phosphorus absorption and urinary phosphorus in the sheep. Q J Exp Physiol 1985, 70: 365–375.

[46] Scott D, Buchan W. The effects of feeding either hay or grass diets on salivary phosphorus secretion, net intestinal phosphorus absorption and on the partition of phosphorus excretion between urine and faeces in the sheep. Q J Exp Physiol 1987, 72: 331–338.

[47] Scott D, Buchan W. Effect of reduction in phosphorus intake on salivary secretion and in duodenal digesta and dry-matter flow in sheep. J Agric Sci 1988, 110: 411–413.

[48] Scott D, Buchan W. The effects of feeding pelleted diets made from either coarsely or finely ground hay on phosphorus balance and on the partition of phosphorus excretion between urine and faeces in the sheep. Q J Exp Physiol 1988, 73: 315–322.

[49] Scott D, Rajaratne AJ, Buchan W. Factors affecting faecal endogenous phosphorus loss in the sheep. J Agric Sci 1995, 124: 145–151.

[50] Pfeffer E, Thompson A, Armstrong DG. Studies on intestinal digestion in the sheep. 3. Net movement of certain inorganic elements in the digestive tract on rations containing different proportions of hay and rolled barley. Br J Nutr 1970, 24: 197–204.

[51] Field AC, Munro CS, Suttle NF. Dried poultry manure as a source of phosphorus for sheep. J Agric Sci 1977, 89: 599–604.

[52] Fishwick G. Utilization of dietary ammonium polyphosphate by growing wether lambs. Proc Nutr Soc 1974, 33: 46A–47A.

[53] Braithwaite GD. Endogenous faecal loss of phosphorus in growing lambs and the calculation of phosphorus requirements. J Agric Sci 1985, 105: 67–72.

[54] Tillman AD, Brethour JR. Ruminant utilization of sodium meta-, ortho- and pyrophosphates. J Anim Sci 1958, 17: 792–796.

[55] Field AC, Woolliams JA. Genetic control of phosphorus metabolism in sheep. Can J Anim Sci 1984, 64: 232–233.

[56] Louvandini H, Vitti DMSS. Perda endógena de fósforo em ovinos com diferentes níveis do elemento na dieta. Pesq Agropec Bras 1994, 29: 145–149.

[57] Ellis LC, Tillman AD. Utilization of phytin phosphorus in wheat bran by sheep. J Anim Sci 1960, 50: 606–607.

[58] Scott D. Excretion of phosphorus and acid in the urine of sheep and calves fed either roughage or concentrate diets. Q J Exp Physiol 1972, 57: 379–392.

[59] Field AC, Kamphues J, Woolliams JA. The effect of dietary intake of calcium and phosphorus on the absorption and excretion of phosphorus in chimaera-derived sheep. J Agric Sci 1983, 101: 597–602.

[60] Field AC, Kamphues J, Woolliams JA. The effect of dietary intake of calcium and phosphorus on the absorption and excretion of phosphorus in chimaera-derived sheep. J Agric Sci 1983, 101: 597–602.

[61] Rodehutscord M, Pauen A, Windhausen P, Pfeffer E. Balances of phosphorus and calcium in dairy goats during periods of phosphorus depletion and subsequent phosphorus repletion. J Anim Physiol a Anim Nutr 1994, 72: 54–64.

[62] Ternouth JH, Mc Lachlan BP, Clarke JM, Thomas BJ. Effects of dietary phosphorus and nitrogen deficiencies on the intake, growth and metabolism of lambs. J Agric Sci 1993, 121: 409–419.

[63] Young VR, Lofgreen GP, Luick JR. The effects of phosphorus depletion, and of calcium and phosphorus intake, on the endogenous excretion of these elements by sheep. Br J Nutr 1966, 20: 795–805.

[64] Ternouth JH, Sevilla CC. The effects of low levels of dietary phosphorus upon the dry matter

intake and metabolism of lambs. Aust J Agric Res 1990, 41: 175–184.

[65] Ternouth JH, Davies HMS. The absorption and faecal losses of phosphorus by mature sheep. Proc Nutr Soc 1984, 44: 49A.

[66] Spiekers H, Brintrup R, Balmelli M, Pfeffer E. Influence of dry matter intake on faecal phosphorus losses in dairy cows fed rations low in phosphorus. J Anim Physiol a Anim Nutr 1993, 69: 37–43.

[67] Crowe NA, Neathery MW, Miller WJ, Muse LA, Crowe CT, Varnadoe JL, Blackmon DM. Influence of high dietary aluminum on performance and phosphorus bioavailability in dairy calves. J Dairy Sci 1990, 73: 808–818.

[68] Challa J, Braithwaite GD. Phosphorus and calcium metabolism in growing calves with special emphasis on phosphorus homeostasis. 1. Studies of the effect of changes in the dietary phosphorus intake on phosphorus and calcium metabolism. J Agric Sci 1988, 110: 573–581.

[69] Challa J, Braithwaite GD. Phosphorus and calcium metabolism in growing calves with special emphasis on phosphorus metabolism. 2. Studies of the effect of different levels of phosphorus, infused abomasally, on phosphorus metabolism. J Agric Sci 1988, 110: 583–589.

[70] Challa J, Braithwaite GD. Phosphorus and calcium metabolism in growing calves with special emphasis on phosphorus homeostasis. 3. Studies of the effect of continuous intravenous infusion of different levels of phosphorus in ruminating calves receiving adequate dietary phosphorus. J Agric Sci 1988, 110: 591–595.

[71] Louvandini H, Vitti DMSS. Phosphorus metabolism and estimation of phosphorus requirements for sheep. Sci Agric Piracicaba 1996, 53: 184–189.

[72] Braithwaite GD. The effect of dietary calcium intake of ewes in pregnancy on their Ca and phosphorus metabolism in lactation. Br J Nutr 1978, 39: 213–218.

[73] Braithwaite GD. Calcium and phosphorus metabolism in sheep. Ann Rech Vet 1979, 10: 359–361.

[74] Braithwaite GD. The effect of a dose rate of 1-α-hydroxycholecalciferol on calcium and phosphorus metabolism in sheep. Br J Nutr 1980, 44: 183–191.

[75] Braithwaite GD. Changes in phosphorus metabolism of sheep in response to the increased demands for P associated with an intravenous infusion of calcium. J Agric Sci 1984, 102: 135–139.

[76] Aubert JP, Milhaud G. Méthode de mesure des principales voies du métabolisme calcique chez l'Homme. Biochim Biophys 1960, 39: 122–139.

REFERENCES – APPENDIX

The publications included in the database are found in the list below, preceded by a number between brackets corresponding to the codification of the variable PUB (see also Tab. II).

[B1] Adeloye AA, Akinsoyinu AO. Phosphorus requirement of the young west african dwarf (Fouta djallon) goat for maintenance and growth. Nutr Rep Int 1985, 32: 239–244.

[B2] Astrup HN, Nordrum E, Steenberg K, Nedkvitne JJ. The true digestibility of phosphorus in the ewe. Acta Vet Scand 1974, 15: 448–450.

[B3] Bortolussi G, Ternouth JH, McMeniman NP. The effects of dietary nitrogen and calcium supplementation in *Bos indicus* cross cattle offered low P diets. Proc Aust Soc Anim Prod 1992, 19: 381–384.

[B4] Bortolussi G, Ternouth JH, McMeniman NP. Dietary nitrogen and phosphorus depletion in cattle and their effects on liveweight gain, blood metabolite concentrations and phosphorus kinetics. J Agric Sci 1996, 126: 493–501.

[B5] Bortolussi G, Ternouth JH, McMeniman NP. Phosphorus repletion of cattle previously exposed to dietary nitrogen and phosphorus deficiencies. Aust J Agric Res 1999, 50: 93–99.

[B6] Boxebeld A, Guéguen L, Hannequart G, Durand M. Utilization of phosphorus and calcium and minimal maintenance requirement for phosphorus in growing sheep fed a low-phosphorus diet. Reprod Nutr Dev 1983, 23: 1043–1053.

[B7] Braithwaite GD. Studies on the absorption and retention of calcium and phosphorus by young and mature Ca-deficient sheep. Br J Nutr 1975, 34: 311–324.

[B8] Braithwaite GD. The effect of dietary calcium intake of ewes in pregnancy on their Ca and phosphorus metabolism in lactation. Br J Nutr 1978, 39: 213–218.

[B9] Braithwaite GD. The effect of 1-α-hydroxycholecalciferol on calcium and phosphorus metabolism in the lactating ewe. Br J Nutr 1978, 40: 387–392.

[B10] Braithwaite GD. Calcium and phosphorus metabolism in sheep. Ann Rech Vet 1979, 10: 359–361.

[B11] Braithwaite GD. The effect of a dose rate of 1-α-hydroxycholecalciferol on calcium and phosphorus metabolism in sheep. Br J Nutr 1980, 44: 183–191.

[B12] Braithwaite GD. Effect of 1-α-hydroxycholecalciferol on calcium and phosphorus metabolism in sheep given high or low calcium diets. J Agric Sci 1981, 96: 291–299.

[B13] Braithwaite GD. Calcium and phosphorus requirements of the ewe during pregnancy and lactation. 2- Phosphorus. Br J Nutr 1983, 50: 723–736.

[B14] Braithwaite GD. Changes in phosphorus metabolism of sheep in response to the increased demands for P associated with an intravenous infusion of calcium. J Agric Sci 1984, 102: 135–139.

[B15] Braithwaite GD. Endogenous faecal loss of phosphorus in growing lambs and the calculation of phosphorus requirements. J Agric Sci 1985, 105: 67–72.

[B16] Braithwaite GD. Phosphorus requirements of ewes in pregnancy and lactation. J Agric Sci 1986, 106: 271–278.

[B17] Brintrup R, Mooren T, Meyer U, Spiekers H, Pfeffer E. Effects of two levels of phosphorus intake on performance and faecal phosphorus excretion of dairy cows. J Anim Physiol A Anim Nutr 1993, 69: 29–36.

[B18] Brodison JA, Goodall EA, Armstrong JD, Givens DI, Gordon FJ, McCaughey WJ, Todd JR. Influence of dietary phosphorus on the performance of lactating dairy cattle. J Agric Sci 1989, 112: 303–311.

[B19] Challa J, Braithwaite GD. Phosphorus and calcium metabolism in growing calves with special emphasis on phosphorus homeostasis. 1. Studies of the effect of changes in the dietary phosphorus intake on phosphorus and calcium metabolism. J Agric Sci 1988, 110: 573–581.

[B20] Challa J, Braithwaite GD. Phosphorus and calcium metabolism in growing calves with special emphasis on phosphorus metabolism. 2. Studies of the effect of different levels of phosphorus, infused abomasally, on phosphorus metabolism. J Agric Sci 1988, 110: 583–589.

[B21] Challa J, Braithwaite GD. Phosphorus and calcium metabolism in growing calves with special emphasis on phosphorus homeostasis. 3. Studies of the effect of continuous intravenous infusion of different levels of phosphorus in ruminating calves receiving adequate dietary phosphorus. J Agric Sci 1988, 110: 591–595.

[B22] Challa J, Braithwaite GD. Phosphorus and calcium metabolism in growing calves with special emphasis on phosphorus homeostasis. 4. Studies on milk-fed calves given different amounts of dietary phosphorus but a constant intake of calcium. J Agric Sci 1989, 113: 285–289.

[B23] Chicco CF, Ammerman CB, Feaster JP, Dunavant BG. Nutritional interrelationships of dietary calcium, phosphorus and magnesium in sheep. J Anim Sci 1973, 36: 986–993.

[B24] Coates DB, Ternouth JH. Phosphorus kinetics of cattle grazing tropical pastures and implications for the estimation of their phosphorus requirements. J Agric Sci 1992, 119: 401–409.

[B25] Compère R. L'alimentation en calcium et en phosphore et l'équilibre Ca-P de la ration. In: Duculot J (Ed), L'étude de l'équilibre phosphocalcique du régime basée sur les variations du métabolisme phosphoré, Les presses agronomiques de Gembloux, A.S.B.L., Gembloux, 1967. p 84–109.

[B26] Compère R. Influence de la nature de l'aliment sur le métabolisme phosphoré. In: Duculot J (Ed), L'étude de l'équilibre phosphocalcique du régime basée sur les variations du métabolisme phosphoré, Les presses agronomiques de Gembloux, A.S.B.L., Gembloux, 1967. p 109–113.

[B27] Crowe NA. Neathery MW, Miller WJ, Muse LA, Crowe CT, Varnadoe JL, Blackmon DM. Influence of high dietary aluminum on performance and phosphorus bioavailability in dairy calves. J Dairy Sci 1990, 73: 808–818.

[B28] Da Silva Lopes HO, Vitti DMSS, Pereira EA, Abdala AL, De Moraes EA, Da Silva Fihlo JC, Fichtner SS. Disponibilidade biológica do fósforo de fosfatos naturais para bovinos pela técnica de diluição isotópica. Pesq Agropec Bras 1990, 25: 421–425.

[B29] Deitert C, Pfeffer E. Effects of a reduced P supply in combination with adequate or high Ca intake on performance and mineral balances in dairy goats during pregnancy and lactation. J Anim Physiol a Anim Nutr 1993, 69: 12–21.

[B30] Durand M, Bertier B, Hannequart G, Guéguen L. Influence d'une subcarence en phosphore et d'un excès de calcium alimentaire sur la phosphatémie et les teneurs en phosphore et calcium des contenus de rumen du mouton. Reprod Nutr Dev 1982, 22: 865–879.

[B31] Ellis LC, Tillman AD. Utilization of phytin phosphorus in wheat bran by sheep. J Anim Sci 1960, 50: 606–607.

[B32] Field AC. Maintenance requirements of phosphorus and absorbability of dietary phosphorus in sheep. J Agric Sci 1983, 100: 231–233.

[B33] Field AC, Woolliams JA. Genetic control of phosphorus metabolism in sheep. Can J Anim Sci 1984, 64: 232–233.

[B34] Field AC, Kamphues J, Woolliams JA. The effect of dietary intake of calcium and phosphorus on the absorption and excretion of phosphorus in chimaera-derived sheep. J Agric Sci 1983, 101: 597–602.

[B35] Field AC, Munro CS, Suttle NF. Dried poultry manure as a source of phosphorus for sheep. J Agric Sci 1977, 89: 599–604.

[B36] Field AC, Sykes AR, Gunn RG. Effects of age and state of incisor dentition on faecal output of dry matter and on faecal and urinary output of nitrogen and minerals, of sheep grazing hill pastures. J Agric Sci 1974, 83: 151–160.

[B37] Field AC, Woolliams JA, Dingwall RA. The effect of dietary intake of calcium and dry matter on the absorption and excretion of calcium and phosphorus by growing lambs. J Agric Sci 1985, 105: 237–243.

[B38] Field AC, Coop RL, Dingwall RA, Munro CS. The phosphorus requirements for growth and maintenance of sheep. J Agric Sci 1982, 99: 311–317.

[B39] Field AC, Woolliams JA, Dingwall RA, Munro CS. Animal and dietary variation in the absorption and metabolism of phosphorus by sheep. J Agric Sci 1984, 103: 283–291.

[B40] Fishwick G. Utilization of dietary ammonium polyphosphate by growing wether lambs. Proc Nutr Soc 1974, 33: 46A–47A.

[B41] Grace ND. Effect of increasing phosphorus intake on the phosphorus faecal endogenous loss in the sheep. Proc NZ Soc Anim Prod 1980, 40: 221–228.

[B42] Grace ND. Phosphorus kinetics in the sheep. Br J Nutr 1981, 45: 367–374.

[B43] Guéguen L. L'utilisation digestive réelle du phosphore du foin de luzerne pour le mouton mesurée à l'aide de ^{32}P. Ann Biol Anim Biochim Biophys 1962, 2: 143–149.

[B44] Field AC, Kamphues J, Woolliams JA. The effect of dietary intake of calcium and phosphorus on the absorption and excretion of phosphorus in chimaera-derived sheep. J Agric Sci 1983, 101: 597–602.

[B45] Guéguen L. Compte rendu d'expérience sur l'utilisation digestive réelle du phosphore du phosphate bicalcique DICALPHOS chez le mouton en croissance. Unpublished data, 1979.

[B46] Guéguen L, Bouchet JP. Compte rendu d'expérience sur l'utilisation digestive réelle du phosphore du phosphate monomagnésique MONOMAG chez le mouton en croissance. Unpublished data, 1980.

[B47] Guéguen L, Bouchet JP. Compte-rendu d'expérience sur l'utilisation réelle du phosphore du phosphate triple de sodium, calcium et magnésium HOSTAPHOS chez le mouton en croissance. Unpublished data, 1980.

[B48] Guéguen L, Durand M. Étude comparée de l'utilisation du phosphore du phosphate monocalcique, du phosphate bicalcique et du phosphate d'urée par le mouton en croissance. Unpublished data, 1976.

[B49] Guéguen L, Durand M. Utilisation des principaux éléments minéraux du maïs ensilé par le mouton en croissance. Ann Zootech 1976, 25: 543–549.

[B50] Guéguen L, Foret R, Durand M. Utilisation du phosphate monoammonique chez le mouton. I. Utilisation comparée, du phosphore des phosphates monoamoniques et monosodique et influence sur le métabolisme du calcium et du magnésium. Ann Zootech 1976, 25: 111–118.

[B51] Jackson Jr JA, Langer DL, Hemken RW. Evaluation of content and source of phosphorus fed to dairy calves. J Dairy Sci 1988, 71: 2187–2192.

[B52] Jenny BF, O'Dell GD. Ration digestibility and mineral balance in steers fed a complete ensiled diet. J Anim Sci 1979, 48: 1525–1529.

[B53] Khorasani GR, Janzen RA, McGill WB, Kennelly JJ. Site and extent of mineral absorption in lactating cows fed whole-crop cereal grain silage or alfalfa silage. J Anim Sci 1997, 75: 239–248.

[B54] Lofgreen GP, Kleiber M. The availability of the phosphorus in alfalfa hay. J Anim Sci 1953, 12: 366–371.

[B55] Lofgreen GP, Kleiber M. Further studies on the availability of phosphorus in alfalfa hay. J Anim Sci 1958, 17: 258–264.

[B56] Louvandini H, Vitti DMSS. Perda endógena de fósforo em ovinos com diferentes níveis do elemento na dieta. Pesq Agropec Bras 1994, 29: 145–149.

[B57] Louvandini H, Vitti DMSS. Phosphorus metabolism and estimation of phosphorus requirements for sheep. Sci Agric Piracicaba 1996, 53: 184–189.

[B58] Lueker CE, Lofgreen GP. Effects of intake and calcium to phosphorus ratio on absorption of these elements by sheep. J Nutr 1961, 74: 233–238.

[B59] Manston R. The influence of dietary calcium and phosphorus concentration on their absorption in the cow. J Agric Sci 1967, 68: 263–268.

[B60] Martz FA, Belo AT, Weiss MF, Belyea RL. True absorption of calcium and phosphorus from alfalfa and corn silage when fed to lactating cows. J Dairy Sci 1990, 73: 1288–1295.

[B61] Meschy F, Guéguen L. Evaluation du besoin minimum d'entretien en phosphore chez l'agneau. Reprod Nutr Dev 1990, 12: 189–190.

[B62] Milton JTB, Ternouth JH, Weir EA, Moon BJ. Phosphorus supplementation at three sites along the digestive tract of sheep fed high and low calcium diets. Proc Aust Soc Anim Prod 1983, 14: 459–462.

[B63] Morse D, Head HH, Wilcox CJ, Van Horn HH, Hissem CD, Harris Jr B. Effects of concentration of dietary phosphorus on amount and route of excretion. J Dairy Sci 1992, 75: 3039–3049.

[B64] Müschen H, Petri A, Breves G, Pfeffer E. Response of lactating goats to low phosphorus intake. 1. Milk yield and faecal excretion of P and Ca. J Agric Sci 1988, 111: 253–263.

[B65] Pfeffer E, Thompson A, Armstrong DG. Studies on intestinal digestion in the sheep. 3. Net movement of certain inorganic elements in the digestive tract on rations containing different proportions of hay and rolled barley. Br J Nutr 1970, 24: 197–204.

[B66] Poppi DP, Ternouth JH. Secretion and absorption of phosphorus in the gastrointestinal tract of sheep fed on four diets. Aust J Agric Res 1979, 30: 503–512.

[B67] Preston RL, Pfander WH. Phosphorus metabolism in lambs fed varying phosphorus intakes. J Nutr 1964, 83: 369–378.

[B68] Rajaratne AAJ, Scott D, Buchan W, Duncan A. The effect of variation in dietary protein or mineral supply on calcium and phosphorus metabolism in lactating ewes. Br J Nutr 1960, 64: 147–160.

[B69] Rodehutscord M, Pauen A, Windhausen P, Pfeffer E. Balances of phosphorus and calcium in dairy goats during periods of phosphorus depletion and subsequent phosphorus repletion. J Anim Physiol a Anim Nutr 1994, 72: 54–64.

[B70] Scott D. Excretion of phosphorus and acid in the urine of sheep and calves fed either roughage or concentrate diets. Q J Exp Physiol 1972, 57: 379–392.

[B71] Scott D, Buchan W. The effects of feeding either roughage or concentrate diets on salivary phosphorus secretion, net intestinal phosphorus absorption and urinary phosphorus in the sheep. Q J Exp Physiol 1985, 70: 365–375.

[B72] Scott D, Buchan W. The effects of feeding either hay or grass diets on salivary phosphorus secretion, net intestinal phosphorus absorption and on the partition of phosphorus excretion between urine and faeces in the sheep. Q J Exp Physiol 1987, 72: 331–338.

[B73] Scott D, Buchan W. Effect of reduction in phosphorus intake on salivary secretion and in duodenal digesta and dry-matter flow in sheep. J Agric Sci 1988, 110: 411–413.

[B74] Scott D, Buchan W. The effects of feeding pelleted diets made from either coarsely or finely ground hay on phosphorus balance and on the partition of phosphorus excretion between urine and faeces in the sheep. Q J Exp Physiol 1988, 73: 315–322.

[B75] Scott D, Rajaratne AJ, Buchan W. Factors affecting faecal endogenous phosphorus loss in the sheep. J Agric Sci 1995, 124: 145–151.

[B76] Scott D, Whitelaw FG, Buchan W, Bruce LA. The effect of variation in phosphorus intake on salivary phosphorus secretion, net intestinal phosphorus absorption and faecal endogenous phosphorus excretion in sheep. J Agric Sci 1985, 105: 271–277.

[B77] Shroder JD, Hansard SL. Effects of orally administered stilbestrol upon growth and upon calcium and phosphorus metabolism in lambs. J Agric Sci 1958, 17: 343–352.

[B78] Spiekers H, Brintrup R, Balmelli M, Pfeffer E. Influence of dry matter intake on faecal phosphorus losses in dairy cows fed rations low in phosphorus. J Anim Physiol A Anim Nutr 1993, 69: 37–43.

[B79] Stevenson MH, Unsworth EF. Studies on the absorption of calcium, phosphorus, magnesium, copper and zinc by sheep fed on roughage-cereal diets. Br J Nutr 1978, 40: 491–496.

[B80] Sykes AR, Dingwall RA. The phosphorus requirement of pregnant sheep. J Agric Sci 1976, 86: 587–594.

[B81] Teh TH, Hemken RW, Bull LS. Evaluation of urea ammonium polyphosphate as a phosphorus source for dairy calves. J Anim Sci 1982, 55: 174–179.

[B82] Ternouth JH. Endogenous losses of phosphorus by sheep. J Agric Sci 1989, 113: 291–297.

[B83] Ternouth JH, Davies HMS. The absorption and faecal losses of phosphorus by mature sheep. Proc Nutr Soc 1984, 44: 49A.

[B84] Ternouth JH, Sevilla CC. Effects of phosphorus deficiency on food intake, growth and absorption of calcium and phosphorus by lambs. Can J Anim Sci 1984, 64: 221–222.

[B85] Ternouth JH, Sevilla CC. The effects of low levels of dietary phosphorus upon the dry matter intake and metabolism of lambs. Aust J Agric Res 1990, 41: 175–184.

[B86] Ternouth JH, McLean RW, McDonald RN, Adamu A. Field estimates of the phosphorus kinetics of grazing cattle. Proc Aust Soc Anim Prod 1989, 18: 396–399.

[B87] Ternouth JH, McLachlan BP, Clarke JM, Thomas BJ. Effects of dietary phosphorus and nitrogen deficiencies on the intake, growth and metabolism of lambs. J Agric Sci 1993, 121: 409–419.

[B88] Thompson A, Hansard SL, Bell MC. The influence of aluminum and zinc upon the absorption and retention of calcium and phosphorus in lambs. J Anim Sci 1959, 18: 187–197.

[B89] Tillman AD, Brethour JR. Dicalcium phosphate and phosphoric acid as phosphorus sources for beef cattle. J Anim Sci 1958, 17: 100–103.

[B90] Tillman AD, Brethour JR. Utilization of phytin phosphorus by sheep. J Anim Sci 1958, 17: 104–112.

[B91] Tillman AD, Brethour JR. The effect of corn oil upon the metabolism of calcium and phosphorus by sheep. J Anim Sci 1958, 17: 782–786.

[B92] Tillman AD, Brethour JR. Ruminant utilization of sodium meta-, ortho- and pyrophosphates. J Anim Sci 1958, 17: 792–796.

[B93] Tillman AD, Brethour JR, Hansard SL. Comparative procedures for measuring the phosphorus requirement of cattle. J Anim Sci 1959, 18: 249–255.

[B94] Vitti DMSS, Abdalla AL, Da Silva Filho JC. Avaliação da disponibilidade biológica do fósforo do fosfato bicálcico. Pesq Agropec Bras 1991, 26: 1113–1118.

[B95] Vitti DMSS, Abdalla AL, Da Silva Filho JC, Ambrosano EJ. Métodos para o diagnóstico da deficiéncia de fósforo em ruminantes. Pesq Agropec Bras 1988, 23: 645–651.

[B96] Vitti DMSS, Abdalla AL, Meirelles CF, Da Silva Filho JC, Louvandini H. Absorção real do fósforo de diferentes fontes para ovinos, através do uso de radiofósforo (P-32). Pesq Agropec Bras 1992, 27: 1405–1408.

[B97] Vitti DMSS, Abdalla AL, Da Silva Filho JC, Lopes HOS, Meirelles CF, Pereira EA. The availability and influence of minerals on reproductive parameters in ruminants. Unpublished data.

[B98] Walker DM. Calcium and phosphorus retention by the milk-fed lambs, with estimates of the endogenous losses. J Agric Sci 1972, 79: 171–179.

[B99] Young VR, Lofgreen GP, Luick JR. The effects of phosphorus depletion, and of calcium and phosphorus intake, on the endogenous excretion of these elements by sheep. Br J Nutr 1966, 20: 795–805.

[B100] Young VR, Luick JR, Lofgreen GP. The influence of dietary phosphorus intake on the rate of bone metabolism in sheep. Br J Nutr 1966, 20: 727–732.