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Visceral organ growth patterns in Saanen goats

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Abstract

Visceral organs play an important role in animals' energy requirements, so their growth must be well understood. The objective of the current study was to fit and compare growth curves that best describe body and visceral organ growth over time in Saanen goats of different sexes. Data were synthesized from seven studies in which curves were fitted to visceral organ growth over time for female, intact male and castrated male Saanen goats from 5 to 45 kg body weight. The liver, pancreas, spleen, rumen–reticulum, omasum, abomasum, small intestine, large intestine and mesenteric adipose tissue (MAT) data were fitted to eight models: simple linear regression, quadratic, monomolecular, Brody, Von Bertalanffy, logistic, Gompertz and Richards. The best-fit model was chosen based on the corrected Akaike information criterion and the concordance correlation coefficient. Model parameters for each sex were compared. Overall, the model that best described visceral organ growth was the logistic model. Sex did not influence the parameters that predicted organ growth (g), except for MAT, where females presented a lower tissue deposition rate and greater inflection point than males. Irrespective of sex, at the beginning of the growth curve, the liver accounted for 28 ± 1.1 g/kg of empty body weight, and the inflection point occurred at 1.7 months. The rumen–reticulum and large intestine presented higher growth rates in the first 2 months of life. Knowledge of the visceral organ growth curve is useful in improving the understanding of the effect of nutritional requirements for goats and must be used to optimize the nutritional plans.

Introduction

Animal growth involves dynamic changes in visceral organ size and body tissue deposition (Crickmore and Mann, 2008). The rates of weight gain are greater from birth to puberty due to deposition of bone and muscular tissues (Owens *et al*., 1993). However, the rates may differ among sexes, because the rate of adipose tissue deposition differs (Almeida *et al*., 2016). Changes in body tissue deposition over time implies differences in energy requirements, for instance older animals have a greater fat deposition rate and consequently greater net energy requirements for growth than young animals (Souza *et al*., 2017). Moreover, the net energy requirements for maintenance are associated with the mass of gastrointestinal tract (GIT) and liver (Baldwin *et al*., 2004), because these visceral organs are metabolically very active and show high energy expenditure for their maintenance functions (i.e. protein synthesis and degradation, nutrient cycling and the sodium–potassium pump activity, among others) (McBride and Kelly, 1990). In ruminants, the visceral organs may account for up to 0.40–0.60 of the whole body oxygen consumption and ATP use (McBride and Kelly, 1990; Baldwin *et al*., 2004). Considering the important role the visceral organs play on the energy costs of an animal, their growth pattern needs to be better understood.

The knowledge of growth is an important step for developing models that predict the nutritional requirements of ruminants over time, because they summarize valuable information into a few parameters that have biological meaning (Goliomytis *et al*., 2006; Pittroff *et al*., 2008). Studies on growth curves of farm animals have been used to assess how body components (e.g. carcass, fat and organs) develop over time (Goliomytis *et al*., 2006; Regadas Filho *et al*., 2014). However, to the authors' knowledge, no studies to date have evaluated the differences of visceral organs growth curve parameters between sexes in goats. Therefore, the objective of the current study was to fit and compare growth curves that best describe body and visceral organs growth over time in Saanen goats of different sexes.

Materials and methods

The procedures were reviewed and approved by São Paulo State University's Ethics and Animal Welfare Commission. Systematization of the results was achieved by applying a comprehensive statistical procedure to obtain the general growth pattern over time of the visceral organs of female, castrated male and intact male Saanen goats from 5 to 45 kg body weight (BW). This weight range corresponded to 0.5- to 19.5-month-old females and 0.5- to

Table 1. Summary characteristics of the seven studies used in the data set

Studies	N[a]	Sex	Age (months)	Phase[b]	BW[c] (kg)	EBW[d] (kg)
Gomes (2011)	18	Intact male	9.5–10.7	Weaned	28.5–46.2	22.4–40.2
Bompadre *et al.* (2014)	18	Female	0.5–6.7	Suckling	4.7–16.3	4.2–13.4
	15	Castrated male	0.5–3.8	Suckling	4.9–16.7	3.9–13.7
	22	Intact male	0.5–4.7	Suckling	4.2–16.5	3.9–12.8
Medeiros *et al.* (2014)	23	Intact male	0.5–3.8	Suckling	5.0–20.8	4.9–17.5
Almeida *et al.* (2015)	17	Female	9.3–19.5	Weaned	27.5–44.8	21.8–38.2
	16	Castrated male	6.4–13.3	Weaned	27.5–47.3	21.3–39.7
	14	Intact male	6.8–13.0	Weaned	27.3–46.6	23.3–39.7
Ferreira *et al.* (2015)	18	Castrated male	4.3–6.2	Weaned	27.2–33.9	20.5–30.3
Leite *et al.* (2015*a*)	18	Female	3.2–7.1	Weaned	16.1–31.4	12.6–25.4
	20	Castrated male	2.4–9.8	Weaned	14.8–32.6	11.5–25.9
	20	Intact male	2.4–11.7	Weaned	15.3–34.0	12.1–27.3
Figueiredo *et al.* (2016)	18	Female	8.2–15.3	Weaned	28.2–44.7	20.9–39.2
Total	237					

[a]Total number of records in the study.
[b]Suckling refers to goats that were fed both milk and solid diet and weaned refers to goats that were fed only a solid feed.
[c]Body weight.
[d]Empty body weight.

13.5-month-old intact and castrated males. Moreover, allometric coefficients were calculated to explore how body traits change with body size.

Data set

A data set was developed based on seven studies composed of 237 individual records for visceral organ weight of female ($n = 71$), castrated male ($n = 69$) and intact male ($n = 97$) Saanen goats fed *ad libitum* (Table 1).

In all studies, goats were fed similar diets that consisted of dehydrated maize (*Zea mays*, whole maize plants chopped, when the kernel milk line was approximately two-thirds of the way down the kernel and then dehydrated) or Tifton hay (*Cynodon* spp.), maize grain, soybean meal (*Glycine max*), soybean oil, limestone and a mineral and vitamin supplement. The roughage-to-concentrate ratio ranged between 25 : 75 and 50 : 50. Crude protein and metabolizable energy composition of the goat diets in the studies ranged from 137 to 204 g/kg dry matter and from 10.0 to 11.3 MJ/kg dry matter, respectively. Further details about the goats and diets used in each study can be found in Gomes (2011), Bompadre *et al.* (2014), Medeiros *et al.* (2014), Almeida *et al.* (2015), Ferreira *et al.* (2015), Leite *et al.* (2015*a*) and Figueiredo *et al.* (2016) (Table 1 and Table A1 of the Appendix). The dry matter intake (DMI) in grams per day per kilogram of empty body weight (EBW) (g/day/kg EBW) was calculated by the sum of the DMI (g) of milk (for pre-weaned goat kids) and the DMI (g) of ration, and the result divided by the days on feed and further divided by final EBW in kg.

In each of the selected studies, serial slaughters at different ages were conducted. Moreover, the slaughter procedures were similar in all studies. In summary, BW was recorded immediately before slaughter, then goats were stunned using a captive bolt pistol, followed by severing the carotid artery and jugular vein. The metabolic EBW (MEBW) was obtained by taking EBW to the power of 0.75. The liver, pancreas, spleen, mesenteric adipose tissue (MAT) and GIT were removed and their weights recorded: the sum constitutes the total visceral organs (Table 2). The GIT was separated into rumen–reticulum, omasum, abomasum, small intestine (SI; sum of duodenum, jejunum and ileum) and large intestine (LI; sum of cecum, colon and rectum). The weight of each segment of the GIT was recorded before and after emptying, to obtain the weight of GIT content. The EBW was calculated as BW minus the weight of wet content of bladder, GIT and biliary vesicle. Stomach weight (STO, g) was composed of the sum of rumen–reticulum, omasum and abomasum, while intestine weight (IN, g) was the sum of SI and LI, and GIT weight (g) was obtained as the sum of STO and IN. Data for the weight of visceral organs and MAT are summarized in Table 2.

Statistical analyses and parameter estimation

Initially, eight models were evaluated: simple linear regression (Eqn (1)), quadratic (Eqn (2)), monomolecular (Eqn (3); Mitscherlich, 1909), Brody (Eqn (4); Brody, 1945), Von Bertalanffy (Eqn (5); Von Bertalanffy, 1957), logistic (Eqn (6); Verhulst, 1838), Gompertz (Eqn (7); Gompertz, 1825) and Richards (Eqn (8); Richards, 1959). These models were chosen in order to investigate the carcass and visceral organ growth over time.

$$\hat{y}_{ijk} = a + bx_{ijk} + S_k + e_{ijk} \quad (1)$$

$$\hat{y}_{ijk} = a + bx_{ijk} + cx_{ijk}^2 + S_k + e_{ijk} \quad (2)$$

$$\hat{y}_{ijk} = A(1-e^{-CXijk}) + S_k + e_{ijk} \quad (3)$$

$$\hat{y}_{ijk} = A(1-B\,e^{-CXijk}) + S_k + e_{ijk} \quad (4)$$

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Table 2. Summary of statistics related to body weight and empty body weight (kg), visceral organs (g) and dry matter intake (DMI; g/day/kg EBW) of Saanen goats

Variables	N^a	Mean	Median	Minimum	Maximum	Standard error
Body weight	237	24	27	4.2	47	8.1
Empty body weight	235	20	20	3.9	40	6.9
Total visceral organs	159	2788	2860	513	4896	87.0
Liver	234	469	473	93	945	13.4
Pancreas	212	44	41	6.2	106	1.8
Spleen	214	45	43	7.9	103	1.5
Mesenteric adipose tissue	210	468	337	8.7	1851	28.6
Gastrointestinal tract	184	1744	1839	357	2827	39.8
Stomachs	195	777	827	53	1360	22.2
Rumen–reticulum	211	535	590	6.2	1050	17.5
Omasum	199	68	70	4.0	158	2.4
Abomasum	213	136	130	16	352	4.3
Intestines	197	944	987	211	1600	20.9
Small intestine	203	600	605	146	1069	12.1
Large intestine	208	341	345	32	740	10.7
DMI	80	31.3	30	17	49	0.72

[a]Total number of records used in the study, after removing outliers.

$$\hat{y}_{ijk} = A(1 - B\,e^{-CXijk})^3 + S_k + e_{ijk} \quad (5)$$

$$\hat{y}_{ijk} = A/(1 + B\,e^{-CXijk}) + S_k + e_{ijk} \quad (6)$$

$$\hat{y}_{ijk} = A\,e^{-B\,e - CXijk} + S_k + e_{ijk} \quad (7)$$

$$\hat{y}_{ijk} = A(1 - B\,e^{-CXijk})^M + S_k + e_{ijk} \quad (8)$$

where $\hat{y}_{ijk}$ is the value of the dependent variable (the mass of a given organ expressed in g, or as g/kg EBW, or as g/kg GIT (only for rumen–reticulum, omasum, abomasum, SI and LI)), for the i^{th} animal of the j^{th} sex in the k^{th} study; X is the age (months) of the animals; S_k is the random effect of the k^{th} study ($S \sim N(0, \sigma_S^2)$), and e_{ijk} is the residual error ($e \sim N(0, \sigma_e^2)$); $i = 1, \ldots, n_{ij}$; $j = 1, 2, 3$; $k = 1, \ldots, 7$; a is the regression constant, which represents the intercept of the line with the y-axis; b is a regression coefficient, which represents the slope of the line; c is a constant coefficient; A is the weight of the organ when the age tends to infinity, that is, the asymptotic weight of the organ; B is the constant of integration; e is a base of the natural logarithm; C is the rate that determines the curve span along the x-axis (age), that is, the growth rate relative to the maximum weight; and M is the constant that determines the final BW ratio when the inflection point occurs (only in the Richards model). Additionally, to explore how the visceral organs change with body size, the relationship between the size of visceral organs and the size of the EBW was scaled by fitting allometric models.

$$\hat{y}_{ijk} = a \times \mathrm{EBW}_{ijk}^b + S_k + e_{ijk} \quad (9)$$

where $\hat{y}_{ijk}$ is the value of the dependent variable (the mass of a given organ expressed in g), for the i^{th} animal of the j^{th} sex in the k^{th} study; EBW is the empty body weight of the animals expressed in kg; S_k is the random effect of the k^{th} study ($S \sim N(0, \sigma_S^2)$), and e_{ijk} is the residual error ($e \sim N(0, \sigma_e^2)$); $i = 1, \ldots, n_{ij}$; $j = 1, 2, 3$; $k = 1, \ldots, 7$; a is the regression constant, which represents the intercept of the line with the y-axis; b is an allometric coefficient, which represents the 'differential growth ratio' (Huxley, 1924). Isometric growth was considered when the allometric coefficient was equal to 1 ($P \geqslant 0.10$), hypoallometric growth when the allometric coefficient b was smaller than 1 ($P < 0.10$), and hyperallometric growth when the allometric coefficient b was greater than 1 ($P < 0.10$).

Data were fitted to the models using the NLMIXED procedure in SAS (version 9.4), considering sex as a fixed effect and study and residual errors as the random effects (St-Pierre, 2001). The diet used by the studies was not included in the models because only one diet was used per study, thus diet effect was indirectly accounted for in the analysis when the effect of study was considered. Because of large data variability, outliers from different studies were removed when their normalized residuals were >|3|. The variability within studies was modelled by introducing a parameter μ into A (for Eqns (3)–(8)) or a (for Eqns (1), (2) and (9)) (Sauvant *et al*., 2008). The study effect was considered on the parameters a and A of the models, i.e. the intercept and the asymptote parameter. 'Dummy' variables were created to test the fixed effect of sex on all estimated parameters of the equations and not only on the intercept. Therefore, three dummy variables (z_1, z_2 and z_3) were created. For females, $z_1 = 1$, $z_2 = 0$ and $z_3 = 0$; for castrated males, $z_1 = 0$, $z_2 = 1$ and $z_3 = 0$; and for intact males, $z_1 = 0$, $z_2 = 0$ and $z_3 = 1$ (Draper and Smith, 1998). Growth curve parameters for each sex were estimated using the ESTIMATE statement, and they were compared using the CONTRAST ($P <$ 0.10).

Table 3. Comparison of models for predicting the growth of visceral organs (g, g/kg EBW or g/kg GIT) and dry matter intake (DMI; g/day/kg EBW) of Saanen goats

	Simple regression (Eqn (1))		Quadratic (Eqn (2))		Monomolecular (Eqn (3))		Brody (Eqn (4))		Von Bertalanffy (Eqn (5))		Logistic (Eqn (6))		Gompertz (Eqn (7))		Richards (Eqn (8))	
Variable	AICc	CCC	AICc	CCC	AICc	CCC	AICc	CCC	AICc	CCC	AICc	CCC	AICc	CCC	AICc	CCC
Gram																
Body weight	8466	0.77	7340	0.82	7646	0.87	7524	0.86	7468	0.87	**7297**[a]	**0.88**	7374	0.87	8804	0.84
Empty body weight	6610	0.76	7982	0.80	7045	0.85	6914	0.84	6865	0.83	**6658**	**0.86**	6865	0.85	11 287	0.85
Empty body weight metabolic	3238	0.73	3198	0.79	3252	0.81	3186	0.83	3187	0.84	**3184**	**0.84**	3185	0.83	3349	0.81
Total visceral organs	2407	0.53	2366	0.70	2388	0.74	2379	0.73	2364	0.73	**2360**	**0.72**	2377	0.74	–	–
Liver	2768	0.55	2732	0.70	2742	0.74	2734	0.74	2731	0.74	**2727**	**0.75**	2729	0.75	2735	0.59
Pancreas	1691	0.61	1678	0.72	1671	0.74	1676	0.73	1673	0.75	**1670**	**0.76**	1672	0.75	1679	0.75
Spleen	1637	0.66	1633	0.75	1644	0.75	**1628**	**0.74**	1628	0.74	1628	0.74	1628	0.77	1634	0.74
Mesenteric adipose tissue	2792	0.59	2784	0.58	2765	0.65	2769	0.67	2761	0.71	**2754**	**0.70**	2758	0.71	2768	0.71
Gastrointestinal tract	2567	0.43	2521	0.70	2534	0.74	2525	0.73	2523	0.73	**2520**	**0.73**	2523	0.73	2685	0.77
Stomachs	2447	0.45	2405	0.66	2412	0.72	2411	0.72	2408	0.75	**2406**	**0.71**	2407	0.72	–	–
Rumen–reticulum	2549	0.50	2495	0.71	2499	0.80	2501	0.80	2497	0.80	2496	0.79	**2496**	**0.80**	2501	0.79
Omasum	1710	0.43	1675	0.53	1681	0.68	1686	0.38	1679	0.71	**1674**	**0.71**	1677	0.71	–	–
Abomasum	2022	0.35	2015	0.46	2032	0.20	2017	0.27	2016	0.53	**2015**	**0.54**	2016	0.53	–	–
Intestines	2566	0.34	2528	0.64	2546	0.69	2534	0.68	2532	0.68	**2529**	**0.69**	2532	0.69	–	–
Small intestine	2481	0.26	2455	0.56	2475	0.48	2460	0.57	2459	0.57	**2458**	**0.58**	2459	0.57	2469	0.57
Large intestine	2426	0.30	2394	0.59	2395	0.67	2399	0.65	2396	0.66	**2393**	**0.67**	2395	0.67	2402	0.67
g/kg Empty body weight																
Total visceral organs	**1267**	**0.23**	1271	0.20	1277	0.06	1284	0.22	1274	0.20	1280	0.01	1280	0.01	–	–
Liver	1213	0.41	**1206**	**0.42**	1237	0.04	1229	0.32	1211	0.32	1211	0.32	1211	0.32	1218	0.37
Pancreas	283	0.24	**276**	**0.23**	288	0.21	284	0.18	284	0.18	284	0.19	284	0.18	291	0.18
Spleen	367	0.18	366	0.01	383	0.02	366	0.21	366	0.21	**366**	**0.22**	366	0.21	380	0.21
Mesenteric adipose tissue	1295	0.39	1295	0.41	1302	0.20	1289	0.45	**1288**	**0.45**	1288	0.42	1288	0.44	1288	0.28
Gastrointestinal tract	**1431**	**0.32**	1435	0.29	1440	0.02	1441	0.31	1437	0.31	1439	0.02	1442	0.02	1451	0.02
Stomachs	1261	0.00	1252	0.11	1248	0.19	1249	0.19	1249	0.20	**1248**	**0.20**	1248	0.20	–	–
Rumen–reticulum	1329	0.05	1301	0.30	1285	0.41	1286	0.42	1285	0.43	**1283**	**0.44**	1284	0.43	1291	0.43
Omasum	439	0.10	409	0.36	414	0.44	413	0.41	412	0.42	**409**	**0.43**	411	0.42	–	–
Abomasum	798	0.24	789	0.45	818	0.00	**770**	**0.47**	770	0.47	791	0.46	770	0.46	–	–
Intestines	**1398**	**0.43**	1399	0.45	1415	0.02	1402	0.40	1402	0.40	1403	0.39	1402	0.40	1409	0.40
Small intestine	1337	0.48	**1330**	**0.59**	1363	0.09	1333	0.46	1333	0.47	1332	0.46	1332	0.46	1339	0.46
Large intestine	1133	0.22	**1132**	**0.20**	1136	0.09	1134	0.04	1134	0.04	1134	0.04	1134	0.04	1140	0.04

g/kg Gastrointestinal tract														
Rumen–reticulum	1852	0.43	1832	0.62	1817	0.56	1816	0.42	1816	0.59	**1815**	**0.59**	1815	0.54	1819	0.55
Omasum	1241	0.21	**1215**	**0.51**	1229	0.38	1220	0.40	1219	0.41	1218	0.41	1218	0.41	1225	0.41
Abomasum	1430	0.04	**1401**	**0.13**	1431	0.00	1406	0.09	1407	0.10	1407	0.07	1407	0.10	1411	0.11
Small intestine	1176	0.01	1154	0.63	1201	0.00	1173	0.40	**1138**	**0.54**	1139	0.49	1138	0.32	1139	0.44
Large intestine	1012	0.00	1013	0.06	1015	0.00	1012	0.09	1011	0.09	1010	0.09	**1010**	**0.09**	1017	0.09
DMI (g/day/kg EBW)	**450**	**0.25**	457	0.08	–	–	–	–	–	–	451	0.04	451	0.11	–	–

–, Model did not converge; AICc, corrected Akaike information criterion for small samples; CCC, concordance correlation coefficient.
[a]Chosen models, in bold.

Table 4. Akaike information criterion corrected for small samples (AICc), concordance correlation coefficient (CCC), precision and accuracy obtained with the models fitted to visceral organ growth (g, g/kg EBW and g/kg GIT), and dry matter intake (DMI; g/day/kg EBW) of Saanen goats

Variable	n[a]	AICc	CCC	Precision[b]	Accuracy[c]
Gram					
Body weight[d]	237	4521	0.91	0.92	1.00
Empty body weight[d]	235	4423	0.90	0.90	1.00
Empty body weight metabolic[d]	235	3129	0.86	0.91	0.86
Visceral organs[d]	159	2334	0.81	0.86	0.94
Liver[d]	234	2672	0.76	0.85	0.90
Pancreas[d]	212	1574	0.77	0.84	0.92
Spleen[e]	214	1613	0.63	0.79	0.80
Mesenteric adipose tissue[d]	210	2574	0.72	0.81	0.89
Rumen–reticulum[f]	211	2477	0.80	0.85	0.93
Omasum[d]	199	1641	0.71	0.80	0.89
Abomasum[d]	213	1976	0.55	0.79	0.69
Stomachs[d]	195	2388	0.83	0.86	0.71
Small intestine[d]	203	2437	0.58	0.66	0.87
Large intestine[d]	208	2357	0.67	0.90	0.75
Intestines[d]	197	2507	0.68	0.76	0.90
Gastrointestinal tract[d]	184	2497	0.74	0.82	0.90
g/kg Empty body weight					
Total visceral organs[g]	159	1271	0.24	0.51	0.47
Liver[h]	231	1187	0.42	0.54	0.78
Pancreas[h]	210	283	0.23	0.39	0.59
Spleen[d]	212	373	0.22	0.35	0.61
Mesenteric adipose tissue[i]	208	1245	0.37	0.59	0.62
Gastrointestinal tract[g]	184	1429	0.32	0.65	0.49
Rumen–reticulum[d]	209	1221	0.43	0.50	0.86
Omasum[d]	199	1248	0.42	0.52	0.80
Abomasum[e]	211	399	0.46	0.57	0.81
Stomachs[d]	195	767	0.14	0.24	0.56
Small intestine[h]	201	1390	0.54	0.77	0.69
Large intestine[h]	205	1309	0.13	0.22	0.58
Intestines[g]	195	1133	0.42	0.72	0.59
g/kg Gastrointestinal tract					
Rumen–reticulum[d]	182	1805	0.57	0.69	0.83
Omasum[h]	184	1206	0.67	0.88	0.77
Abomasum[h]	183	1409	0.14	0.19	0.71
Small intestine[i]	183	1854	0.50	0.72	0.69
Large intestine[f]	184	1759	0.09	0.18	0.48
DMI (g/day/kg EBW)[g]	80	442	0.25	0.45	0.53

[a]Total number of records.
[b]Pearson correlation coefficient estimate accounts for precision.
[c]Bias correction factor accounts for accuracy.
[d]Logistic : $\hat{y} = A/(1 + B\,e^{-CX})$.
[e]Brody : $\hat{y} = A(1 - B\,e^{-CX})$.
[f]Gompertz : $\hat{y} = A\,e^{-B\,e^{-CX}}$.
[g]Simple linear regression : $\hat{y} = a + bx$.
[h]Quadratic : $\hat{y} = a + bx + cx^2$.
[i]Von Bertalanffy : $\hat{y} = A(1 - B\,e^{-CX})^3$.

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The models were evaluated using the lowest value of Akaike information criterion (Akaike, 1974), corrected for small samples (AICc) (Sugiura, 1978), and the concordance correlation coefficient (CCC). The CCC was used as an indicator of how well the model fits the data, as a reproducibility index (Lin, 1989), to account for accuracy and precision at the same time:

$$\text{CCC} = \rho C_\text{b} \tag{10}$$

where ρ is the Pearson correlation coefficient estimate that accounts for precision, and C_b is a bias correction factor that accounts for accuracy.

From the fitted models for carcass or visceral organs growth over time, the models that showed the best fit were chosen. In the second step, the error structure of the previously selected models and allometric models was modelled to refine its adjustments and to seek homogeneous variance of the residuals. Therefore, the variance (σ_e^2) for the model selected for each variable was modelled according to Araújo *et al.* (2015):

$$V_1 = (\sigma_e^2) \tag{11}$$

$$V_2 = (\sigma_e^2)\exp(c \times \text{age}) \tag{12}$$

$$V_3 = (\sigma_e^2) \times \mu^{2\varphi} \tag{13}$$

where c and φ are the parameters, and μ is the predicted value of the weight of a specific organ. Following these tests, the models with modelled error structure were evaluated using the lowest value of AICc. Moreover, because age was not the predictor in the allometric model, the error structure of the allometric model was modelled using only V_1 and V_3.

The organ growth rate in g/month was calculated as the first derivative and the inflection point was calculated as the second derivative of the models (Stewart, 2013).

Results

Model evaluation and variance modelling

According to the evaluation criteria established for assessing the model (lowest AICc and highest CCC), monomolecular (Eqn (3)) and Richards (Eqn (8)) models did not fit the growth of the visceral organs evaluated; the simple linear regression (Eqn (1)) was the one that best fit the growth of the total visceral organs, GIT, intestines (g/kg EBW) and DMI (g/day/kg EBW) (Table 3). The quadratic model (Eqn (2)) best fits the growth of the liver, pancreas, SI, LI (g/kg EBW) and omasum (g/kg GIT) (Table 3). The Brody model (Eqn (4)) best fits the growth of the spleen (g) and abomasum (g/kg EBW and g/kg GIT) (Table 3). The Von Bertalanffy model (Eqn (5)) best fits the growth of the MAT (g/kg EBW) and SI (g/kg GIT) (Table 3). The logistic model (Eqn (6)) best fits the growth of the liver, pancreas, MAT, GIT, omasum, abomasum, stomachs, intestines, SI, LI, total visceral organs, BW, MEBW and EBW (g) (Table 3). The logistic model (Eqn (6)) was also the best fit for the growth of the spleen, rumen–reticulum, omasum, stomachs (g/kg EBW) and rumen–reticulum (g/kg GIT) (Table 3). The Gompertz model (Eqn (7)) best fits the growth of the rumen–reticulum (g) and LI (g/kg GIT) (Table 3).

The models fitted to the growth of the pancreas (g/kg EBW), spleen (g/kg EBW) and LI (g/kg GIT) presented homogenous variance (Table A2 of the Appendix). For the models that presented non-homogeneous variance, the variance was modelled to seek a better fit. The V_2 (Eqn (12)) was used to model the variance of MAT, omasum and abomasum (g/kg EBW) (Table A2 of the Appendix). The V_3 (Eqn (13)) was used to model the variance of all organs (except pancreas, spleen and GIT; g), DMI (g/day/kg EBW), total visceral organs (g/kg EBW), liver (g/kg EBW), rumen–reticulum (g/kg EBW), GIT (g/kg EBW), stomachs (g/kg EBW), SI (g/kg EBW), LI (g/kg EBW), intestines (g/kg EBW), all organs (except LI; g/kg GIT) and all allometric models (g/kg EBW) (Tables A2 and A3 of the Appendix). The AICc and CCC information for the best-fit models and allometric models is presented in Tables 3–5, as well as Tables A2 and A3 of the Appendix.

Dry matter intake, body weight and organ growth

Sex did not affect any parameters of the models fitted to total visceral organs, liver, pancreas and spleen (g), or total visceral organs, pancreas, spleen and MAT (g/kg EBW) ($P > 0.10$; Table 6). Sex also did not affect any parameters of the allometric models fitted for all organs (g/kg EBW; $P > 0.10$), except to the liver (g/kg EBW; $P \leqslant 0.07$; Table 5). Moreover, sex did not affect the parameter b of the model fitted to DMI (g/day/kg EBW) and the allometric model fitted to the liver (g/kg EBW), parameter A of the model fitted to BW (g), parameters A and B of the model fitted to EBW (g), parameter B of the models fitted to MEBW and MAT (g), parameter a of the model fitted to the liver (g/kg EBW) ($P > 0.10$; Tables 5 and 6 and Fig. 1).

Castrated males and intact males had similar model parameters for predicting the growth of BW (g, parameters B and C), EBW (g, parameter C), MEBW (g, parameters A and C), MAT (g, parameters A and C) and liver (g/kg EBW, parameters b and c) ($P > 0.10$; Table 6), but they differed from females ($P <$ 0.09; Table 6). In addition, females and castrated males had a similar model parameter a for predicting DMI (g/day/kg EBW; $P > 0.10$) and an allometric model parameter a for the liver (g/kg EBW; $P = 0.40$), but they differed from intact males ($P \leqslant 0.07$; Fig. 1 and Table 5).

Males reached 45 kg BW 6 months earlier than females because of faster growth (0.52 ± 0.032 *v.* 0.34 ± 0.027, respectively). Therefore, the inflection point of the female growth curve occurred at 4.9 months, while for males, it occurred at 3.7 months. These findings – greater growth rate and earlier inflection point of male goat kids – indicate greater growth of males at a younger age (up to 3.7 months old) (Table 6; Fig. 2).

Irrespective of sex, at the beginning of the growth curve (0.5 months old), liver accounted for 28 ± 1.1 g/kg EBW and grew at a maximum rate of 0.53 ± 0.062 g/month, and pancreas accounted for 1.7 ± 0.16 g/kg EBW and grew at a maximum rate of 0.50 ± 0.052 g/month (Table 6; Fig. 3). The inflection point of the curve for the liver (g) occurred at 1.7 months and for the pancreas (g) at 3.1 months (Table 6 and Fig. 3). Liver presented a hypoallometric relationship to EBW (0.80 ± 0.027; Table 5). However, pancreas presented an isometric relationship to EBW (allometry coefficient of 1.1 ± 0.05; Table 5).

Males stabilized MAT growth (g) earlier than females (inflection point of 3.7 *v.* 7.7 months) because of a faster maximum growth rate of 0.66 ± 0.062 *v.* 0.32 ± 0.034 g/month (Table 6). Therefore, males and females reached a maximum MAT of

Table 5. Parameter estimates and fit statistics of allometric relationships between organs (g) and empty body weight (EBW, kg) of male, castrated male and female growing Saanen goats

		P values									
		A			*B*						
Variable (g)	Allometric model[a]	F × CM	F × IM	CM × IM	F × CM	F × IM	CM × IM	AICc[b]	CCC[c]	Precision[d]	Accuracy[e]
Total visceral organs	$\hat{y} = (239 \pm 22.9) \times \text{EBW}^{(0.80 \pm 0.030)}$	0.327	0.740	0.256	0.380	0.436	0.168	2215	0.96	0.96	1.00
Liver		0.396	0.021	0.070	0.562	0.134	0.299	2502	0.93	0.94	1.00
Female and castrated male	$\hat{y} = (42 \pm 3.6) \times \text{EBW}^{(0.80 \pm 0.027)}$										
Intact male	$\hat{y} = (40 \pm 3.4) \times \text{EBW}^{(0.80 \pm 0.027)}$										
Pancreas	$\hat{y} = (1.8 \pm 0.26) \times \text{EBW}^{(1.1 \pm 0.05)}$	0.331	0.113	0.361	0.415	0.191	0.550	1462	0.90	0.90	1.00
Spleen	$\hat{y} = (4.5 \pm 0.59) \times \text{EBW}^{(0.77 \pm 0.044)}$	0.346	0.560	0.678	0.396	0.232	0.672	1513	0.87	0.88	0.99
Mesenteric adipose tissue	$\hat{y} = (4.8 \pm 0.90) \times \text{EBW}^{(1.5 \pm 0.05)}$	0.407	0.663	0.248	0.427	0.887	0.365	2392	0.88	0.89	0.98
GIT	$\hat{y} = (250 \pm 32.0) \times \text{EBW}^{(0.63 \pm 0.040)}$	0.353	0.832	0.489	0.405	0.994	0.421	2522	0.88	0.88	1.00
Rumen–reticulum	$\hat{y} = (67 \pm 13.2) \times \text{EBW}^{(0.69 \pm 0.059)}$	0.497	0.847	0.622	0.614	0.779	0.461	2470	0.90	0.93	0.97
Omasum	$\hat{y} = (2.5 \pm 0.49) \times \text{EBW}^{(1.1 \pm 0.06)}$	0.624	0.294	0.524	0.673	0.328	0.546	1617	0.88	0.89	1.00
Abomasum	$\hat{y} = (26 \pm 4.5) \times \text{EBW}^{(0.55 \pm 0.052)}$	0.310	0.448	0.775	0.350	0.780	0.549	1954	0.77	0.84	0.91
Stomachs	$\hat{y} = (99 \pm 17.8) \times \text{EBW}^{(0.67 \pm 0.056)}$	0.360	0.854	0.477	0.456	0.837	0.372	2393	0.90	0.93	0.97
Small intestine	$\hat{y} = (146 \pm 24.3) \times \text{EBW}^{(0.47 \pm 0.052)}$	0.782	0.299	0.430	0.817	0.376	0.504	2452	0.64	0.65	0.99
Large intestine	$\hat{y} = (28 \pm 5.9) \times \text{EBW}^{(0.83 \pm 0.065)}$	0.307	0.588	0.528	0.244	0.708	0.342	2351	0.79	0.80	1.00
Intestines	$\hat{y} = (161.7 \pm 0.05) \times \text{EBW}^{(0.59 \pm 0.050)}$	0.751	0.528	0.741	0.766	0.667	0.892	2507	0.77	0.77	1.00

[a]Allometric model: $\hat{y} = a \times \text{EBW}^{b}$.
[b]Akaike information criterion corrected for small samples.
[c]Concordance correlation coefficient.
[d]Pearson correlation coefficient estimate accounts for precision.
[e]Bias correction factor accounts for accuracy.

Table 6. Model that best fits body weight and organ growth in gram (g) and the proportion of empty body weight (g/kg EBW) of Saanen goats per age (months)

			P values								
			A/a			*B/b*			*C/c*		
Variable	Model	IP (months)	F × CM	F × IM	CM × IM	F × CM	F × IM	CM × IM	F × CM	F × IM	CM × IM
Gram											
Body weight (logistic)			0.210	0.240	0.800	0.070	0.050	0.250	0.010	0.004	0.670
Female	$\hat{y} = (40\,026 \pm 1238.6)/(1 + (5.2 \pm 0.60)\ e^{-(0.34 \pm 0.027) \times Age})$	4.9									
Intact male and castrated male	$\hat{y} = (40\,026 \pm 1238.6)/(1 + (6.9 \pm 0.55)\ e^{-(0.52 \pm 0.032) \times Age})$	3.7									
Empty body weight (logistic)			0.730	0.800	0.930	0.700	0.390	0.690	0.0004	0.002	0.210
Female	$\hat{y} = (35\,747 \pm 1384.7)/(1 + (6.4 \pm 0.34)\ e^{-(0.32 \pm 0.021) \times Age})$	5.8									
Intact male and castrated male	$\hat{y} = (35\,747 \pm 1384.7)/(1 + (6.4 \pm 0.36)\ e^{-(0.45 \pm 0.021) \times Age})$	4.1									
Empty body weight metabolic (logistic)			0.050	0.070	0.560	0.690	0.180	0.470	0.010	0.002	0.950
Female	$\hat{y} = (2645 \pm 191.1)/(1 + (2.4 \pm 0.22)\ e^{-(0.22 \pm 0.033) \times Age})$	3.9									
Intact male and castrated male	$\hat{y} = (2234 \pm 109.1)/(1 + (2.4 \pm 0.22)\ e^{-(0.48 \pm 0.044) \times Age})$	1.8									
Total visceral organs (logistic; all sexes)	$\hat{y} = (3646 \pm 154.5)/(1 + (3.1 \pm 0.36)\ e^{-(0.42 \pm 0.045) \times Age})$	2.7	0.250	0.250	0.980	0.250	0.420	0.510	0.110	0.110	0.420
Liver (logistic; all sexes)	$\hat{y} = (585 \pm 40.7)/(1 + (2.4 \pm 0.34)\ e^{-(0.53 \pm 0.062) \times Age})$	1.7	0.850	0.420	0.470	0.470	0.140	0.440	0.240	0.110	0.590
Pancreas (logistic; all sexes)	$\hat{y} = (62 \pm 5.3)/(1 + (4.7 \pm 0.79)\ e^{-(0.50 \pm 0.052) \times Age})$	3.1	0.450	0.740	0.660	0.490	0.270	0.690	0.640	0.520	0.910
Spleen (Brody; all sexes)	$\hat{y} = (0.053 \pm 0.0416) \times (1 + (579 \pm 464.3)\ e^{(0.058 \pm 0.0101) \times Age})$	–	0.230	0.320	0.730	0.830	0.740	0.990	0.110	0.340	0.290
Mesenteric adipose tissue (logistic)			0.020	0.020	0.940	0.940	0.760	0.940	0.020	0.010	0.610
Female	$\hat{y} = (1044 \pm 140.2)/(1 + (11 \pm 1.8)\ e^{-(0.32 \pm 0.034) \times Age})$	7.7									
Intact male and castrated male	$\hat{y} = (700 \pm 90.5)/(1 + (11 \pm 1.8)\ e^{-(0.66 \pm 0.062) \times Age})$	3.7									
g/kg EBW											

(*Continued*)

Table 6. (*Continued.*)

Variable	Model	IP (months)	*P* values								
			A/a			*B/b*			*C/c*		
			F × CM	F × IM	CM × IM	F × CM	F × IM	CM × IM	F × CM	F × IM	CM × IM
Total visceral organs (simple regression all sexes)	$\hat{y} = (142 \pm 5.5) - (1.3 \pm 0.52) \times \text{Age}$		0.280	0.320	0.930	0.150	0.110	0.470			
Liver (quadratic)			0.110	0.850	0.110	0.010	0.090	0.200	0.010	0.010	0.20
Female	$\hat{y} = (28 \pm 1.1) - (0.30 \pm 0.182) \times \text{Age} - (0.017 \pm 0.0091) \times \text{Age}^2$										
Intact male and castrated male	$\hat{y} = (28 \pm 1.1) - (0.14 \pm 0.263) \times \text{Age} + (0.068 \pm 0.0191) \times \text{Age}^2$										
Pancreas (quadratic; all sexes)	$\hat{y} = (1.7 \pm 0.16) + (0.13 \pm 0.032) \times \text{Age} - (0.0069 \pm 0.00179) \times \text{Age}^2$		0.910	0.150	0.210	0.260	0.610	0.540	0.170	0.420	0.600
Spleen (logistic; all sexes)	$\hat{y} = (2.2 \pm 0.12)/(1 - (0.28 \pm 0.058)\, e^{-(0.34 \pm 0.240) \times \text{Age}})$		0.890	0.990	0.890	0.800	0.780	0.930	0.990	0.220	0.270
Mesenteric adipose tissue (Von Bertalanffy; all sexes)	$\hat{y} = (24 \pm 3.2) \times (1 - (0.23 \pm 0.034)\, e^{-(0.41 \pm 0.162) \times \text{Age}})^3$		0.170	0.180	0.760	0.230	0.330	0.500	0.420	0.140	0.740

IP, inflection point; F, female; CM, castrated male; IM, intact male.

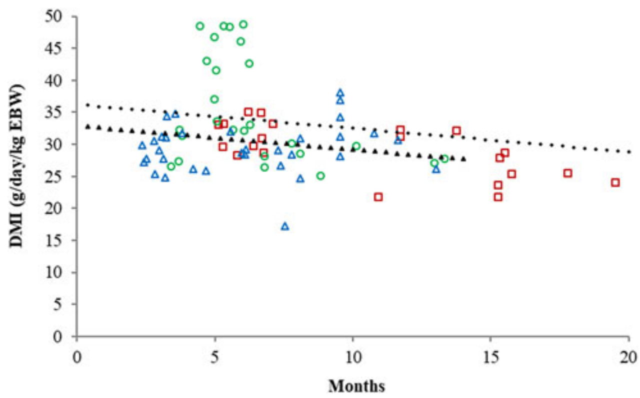

Fig. 1. Colour online. Dry matter intake (DMI) in grams per day per kilogram of empty body weight (g/day/kg EBW) of Saanen goats of different sexes (□ represents the observed records of females, ○ castrated males and △ intact males; +++ represents the predicted females and castrated males ($\hat{y}$ = (36.2 ± 2.50) − (0.37 ± 0.15) × Age), and ▲▲▲ intact males ($\hat{y}$ = (32.9 ± 2.42) − (0.37 ± 0.15) × Age).

700 ± 90.5 g (within 13.5 months) and 1044 ± 140.2 g (within 19.5 months), respectively (Table 6 and Fig. 3). Irrespective of sex, MAT reached the maximum weight as 24 ± 3.2 g/kg EBW, within the evaluated period (Table 6 and Fig. 3). Mesenteric adipose tissues presented a hyperallometric relationship to EBW (1.5 ± 0.05; Table 5).

Gastrointestinal tract growth

Sex did not affect any model parameters for predicting the growth of rumen–reticulum, omasum, abomasum, stomachs, SI, LI, intestines or GIT (g); neither did it affect rumen–reticulum, omasum, stomachs or GIT (g/kg EBW), or rumen–reticulum, SI or LI (g/kg GIT) ($P > 0.10$; Table 7). In addition, sex did not affect the growth model parameters for abomasum (g/kg EBW, parameter B), SI (g/kg EBW; parameter a), LI (g/kg EBW; parameters b and c), intestines (g/kg EBW; parameter b) or omasum (g/kg GIT, parameter a) ($P > 0.10$; Table 7). Sex also did not affect any

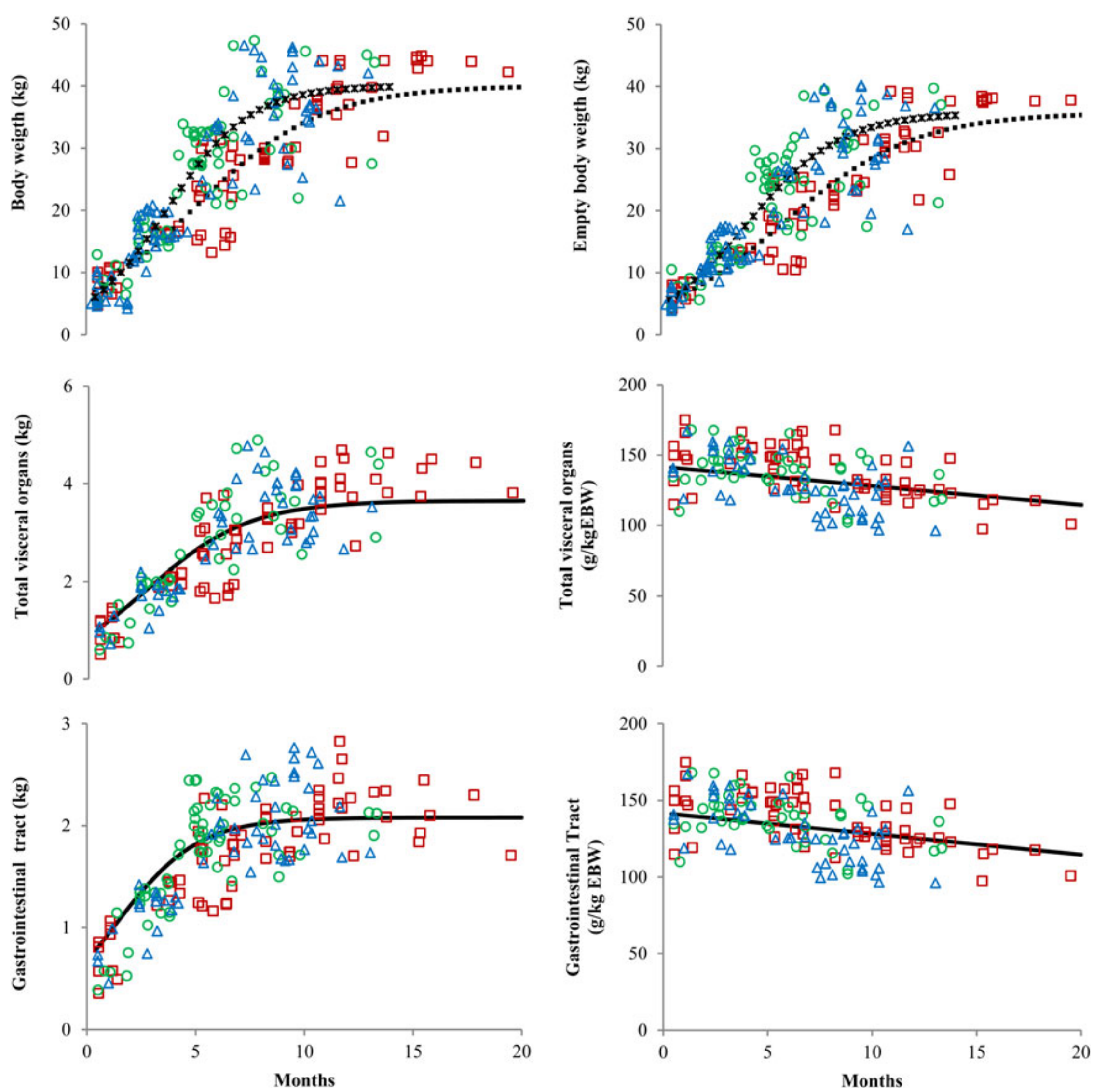

Fig. 2. Colour online. Body weight, empty body weight in kilogram, total visceral organs and gastrointestinal tract in kg and the proportion of empty body weight (g/kg EBW) of Saanen goats of different sexes (□ represents the observed records of females, ○ castrated males and △ intact males; ■■■ represents the predicted females, ✱✱✱ castrated males and intact males, — all sexes).

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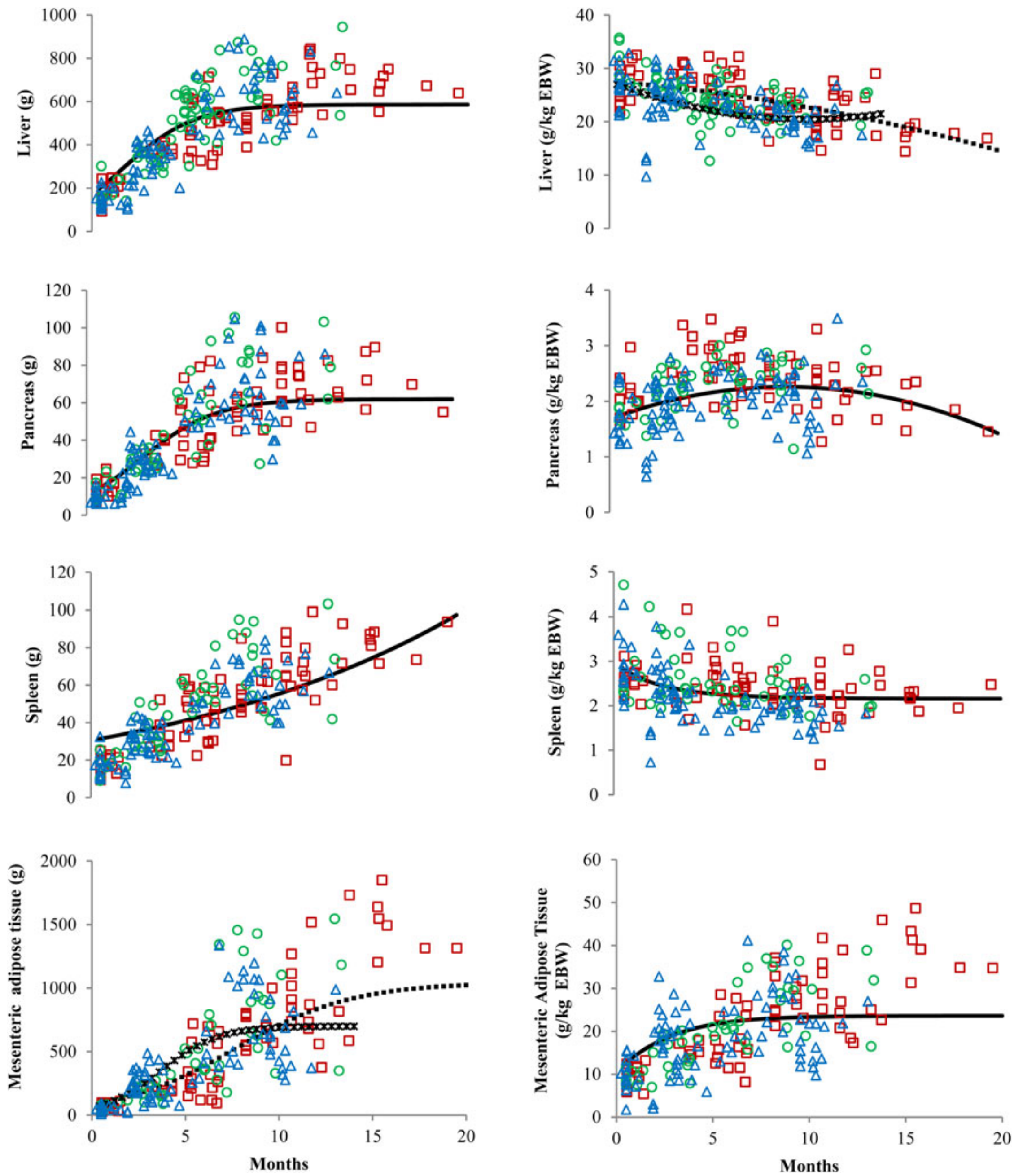

Fig. 3. Colour online. Liver, pancreas, spleen and mesenteric adipose tissue in grams (g) and the proportion of empty body weight (g/kg EBW) of Saanen goats of different sexes (□ represents the observed records of females, ○ castrated males and △ intact males; ■■■ represents the predicted females, ✱✱✱ castrated males and intact males, — all sexes).

parameters of allometric models fitted between GIT segments and EBW ($P > 0.10$; Table 5).

Intact males and castrated males had similar parameters *b* and *c* for the growth models of SI (g/kg EBW) and omasum (g/kg GIT) ($P > 0.10$), but these parameters differed from females ($P < 0.09$; Table 7). Females and castrated males had similar model parameters for predicting LI and intestines (g/kg EBW, parameter *a*) and abomasum (g/kg GIT, parameters *a* and *b*) ($P > 0.10$), but these parameters differed for intact males ($P < 0.09$; Table 7). Females and intact males had different parameters *A* and *C* for predicting abomasum growth (g/kg EBW) ($P < 0.06$; Table 7). Castrated males and intact males had a different parameter *c* for predicting abomasum growth (g/kg GIT) ($P < 0.04$; Table 7).

Overall, rumen–reticulum and LI increased relative to EBW and GIT, whereas abomasum and SI decreased, as the animal grew (Figs 4 and 5). The inflection point of the abomasum (g) growth curve occurred at 0.5 months and had a maximum growth rate of 0.31 ± 0.062 g/month, whereas the inflection point of the rumen–reticulum (g) occurred at 1.4 months and had a maximum growth rate of 0.60 ± 0.082 g/month (Table 7). Moreover, rumen–reticulum and abomasum presented a hypoallometric growth to EBW (0.69 ± 0.059 and 0.55 ± 0.052, respectively). On the other hand, omasum showed an isometric relationship to EBW (allometry coefficient of 1.1 ± 0.06; Table 5).

Irrespective of sex, the maximum growth rate of GIT (g) was 0.53 ± 0.075 g/month and its inflection point was at 1.4 months

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Table 7. Model that best fits the gastrointestinal tract (GIT) growth in gram (g), in the proportion of empty body weight (g/kg EBW) and in the proportion of gastrointestinal tract (g/kg GIT) of Saanen goats per age (months)

			P values								
			A/a			*B/b*			*C/c*		
Variable	Model	IP (months)	F × CM	F × IM	CM × IM	F × CM	F × IM	CM × IM	F × CM	F × IM	CM × IM
Gram											
GIT (Logistic; all sexes)	$\hat{y} = (2077 \pm 94.5)/(1 + (2.1 \pm 0.33)\ e^{-(0.53 \pm 0.075) \times Age})$	1.4	0.330	0.430	0.850	0.250	0.670	0.350	0.110	0.320	0.230
Rumen–reticulum (Gompertz; all sexes)	$\hat{y} = (677 \pm 59.6)\ e^{-(2.3 \pm 0.32)\ e-(0.60 \pm 0.082) \times Age}$	1.4	0.170	0.110	0.540	0.270	0.280	0.500	0.140	0.590	0.270
Omasum (logistic; all sexes)	$\hat{y} = (85 \pm 7.5)/(1 + (6 \pm 1.2)\ e^{-(0.63 \pm 0.076) \times Age})$	2.7	0.400	0.480	0.810	0.480	0.390	0.640	0.130	0.110	0.700
Abomasum (logistic; all sexes)	$\hat{y} = (169 \pm 17.7)/(1 + (1.2 \pm 0.25)\ e^{-(0.31 \pm 0.062) \times Age)}$	0.5	0.320	0.270	0.900	0.930	0.630	0.600	0.280	0.110	0.800
Stomachs (logistic; all sexes)	$\hat{y} = (921 \pm 76.7)/(1 + (3.2 \pm 0.73)\ e^{-(0.64 \pm 0.102) \times Age})$	1.8	0.180	0.140	0.710	0.310	0.450	0.430	0.110	0.110	0.320
Small intestine (logistic; all sexes)	$\hat{y} = (700 \pm 43.3)/(1 + (1.2 \pm 0.24)\ e^{-(0.45 \pm 0.092) \times Age})$	0.5	0.890	0.920	0.970	0.910	0.290	0.380	0.650	0.450	0.890
Large intestine (logistic; all sexes)	$\hat{y} = (449 \pm 41.8)/(1 + (3.1 \pm 0.60)\ e^{-(0.62 \pm 0.093) \times Age})$	1.9	0.400	0.910	0.330	0.470	0.410	0.980	0.330	0.530	0.690
Intestines (logistic; all sexes)	$\hat{y} = (1140 \pm 75.9)/(1 + (1.6 \pm 0.29)\ e^{-(0.52 \pm 0.087) \times Age})$	0.9	0.890	0.840	0.950	0.610	0.310	0.640	0.320	0.430	0.740
g/kg EBW											
GIT (simple regression; all sexes)	$\hat{y} = (91 \pm 4.9) - (1.3 \pm 0.46) \times Age$		0.200	0.390	0.680	0.620	0.630	0.420			
Rumen–reticulum (logistic; all sexes)	$\hat{y} = (26 \pm 1.0)/(1 + (1.6 \pm 0.82)\ e^{-(0.87 \pm 0.201) \times Age})$		0.250	0.110	0.460	0.290	0.990	0.290	0.310	0.940	0.300
Omasum (logistic; all sexes)	$\hat{y} = (3.1 \pm 0.11)/(1 + (1.7 \pm 0.56)\ e^{-(0.88 \pm 0.190) \times Age})$		0.710	0.430	0.620	0.420	0.780	0.500	0.300	0.570	0.520
Abomasum (Brody)			0.100	0.060	0.790	0.230	0.530	0.360	0.140	0.060	0.240
Female	$\hat{y} = (4.5 \pm 0.57) \times (1 + (0.95 \pm 0.189)\ e^{-(0.098 \pm 0.0380) \times Age})$										
Castrated male	$\hat{y} = (5.8 \pm 0.42) \times (1 + (0.95 \pm 0.189)\ e^{-(0.58 \pm 0.254) \times Age})$										
Intact male	$\hat{y} = (5.9 \pm 0.32) \times (1 + (0.95 \pm 0.189)\ e^{-(1.1 \pm 0.40) \times Age})$										
Stomachs (logistic; all sexes)	$\hat{y} = (36 \pm 1.1)/(1 + (0.94 \pm 0.356)\ e^{-(0.92 \pm 0.205) \times Age})$		0.240	0.110	0.420	0.300	0.930	0.300	0.460	0.850	0.580
Small intestine (quadratic)			0.260	0.450	0.110	0.070	0.070	0.300	0.010	0.010	0.500

(*Continued*)

Table 7. (*Continued.*)

Variable	Model	IP (months)	*P* values								
			A/a			*B/b*			*C/c*		
			F × CM	F × IM	CM × IM	F × CM	F × IM	CM × IM	F × CM	F × IM	CM × IM
Female	$\hat{y} = (43 \pm 3.8) - (1.7 \pm 0.59) \times Age + (0.023 \pm 0.0283) \times Age^2$										
Castrated male and intact male	$\hat{y} = (43 \pm 3.8) - (3.9 \pm 0.77) \times Age + (0.21 \pm 0.055) \times Age^2$										
Large intestine (quadratic)			0.620	0.080	0.050	0.670	0.570	0.420	0.740	0.700	0.580
Female and castrated male	$\hat{y} = (15 \pm 1.6) + (0.85 \pm 0.274) \times Age - (0.053 \pm 0.0170) \times Age^2$										
Intact male	$\hat{y} = (13 \pm 1.7) + (0.85 \pm 0.274) \times Age - (0.053 \pm 0.0170) \times Age^2$										
Intestines (simple regression)			0.260	0.020	0.090	0.710	0.440	0.340			
Female and castrated male	$\hat{y} = (58 \pm 4.0) - (1.3 \pm 0.030) \times Age$										
Intact male	$\hat{y} = (53 \pm 4.0) - (1.3 \pm 0.030) \times Age$										
g/kg GIT											
Rumen–reticulum (logistic; all sexes)	$\hat{y} = (328 \pm 12.2)/(1 + (2.2 \pm 1.01)\ e^{-(1.1 \pm 0.24) \times Age})$		0.450	0.270	0.640	0.120	0.630	0.110	0.190	0.580	0.860
Omasum (quadratic)			0.280	0.650	0.570	0.040	0.050	0.940	0.020	0.020	0.720
Female	$\hat{y} = (16 \pm 2.7) + (3.4 \pm 0.56) \times Age - (0.10 \pm 0.032) \times Age^2$										
Castrated male and intact male	$\hat{y} = (16 \pm 2.7) + (5.9 \pm 0.71) \times Age - (0.32 \pm 0.052) \times Age^2$										
Abomasum (quadratic)			0.900	0.060	0.080	0.280	0.060	0.040	0.110	0.140	0.040
Female	$\hat{y} = (104 \pm 7.7) - (6.0 \pm 1.20) \times Age + (0.30 \pm 0.061) \times Age^2$										
Castrated male	$\hat{y} = (103 \pm 8.4) - (7.9 \pm 1.92) \times Age + (0.52 \pm 0.136) \times Age^2$										
Intact male	$\hat{y} = (87 \pm 8.6) - (1.2 \pm 2.12) \times Age + (0.075 \pm 0.1598) \times Age^2$										
Small intestine (Von Bertalanffy; all sexes)	$\hat{y} = (336 \pm 15.7) \times (1 + (0.20 \pm 0.034)\ e^{-(0.57 \pm 0.119) \times Age})^3$		0.960	0.660	0.660	0.110	0.190	0.110	0.210	0.800	0.600
Large intestine (Gompertz; all sexes)	$\hat{y} = (215 \pm 10.5)\ e^{-(0.32 \pm 0.113)\ e-(0.68 \pm 0.289) \times Age}$		0.170	0.800	0.320	0.840	0.820	0.980	0.780	0.760	0.930

IP, inflection point; F, female; CM, castrated male; IM, intact male.

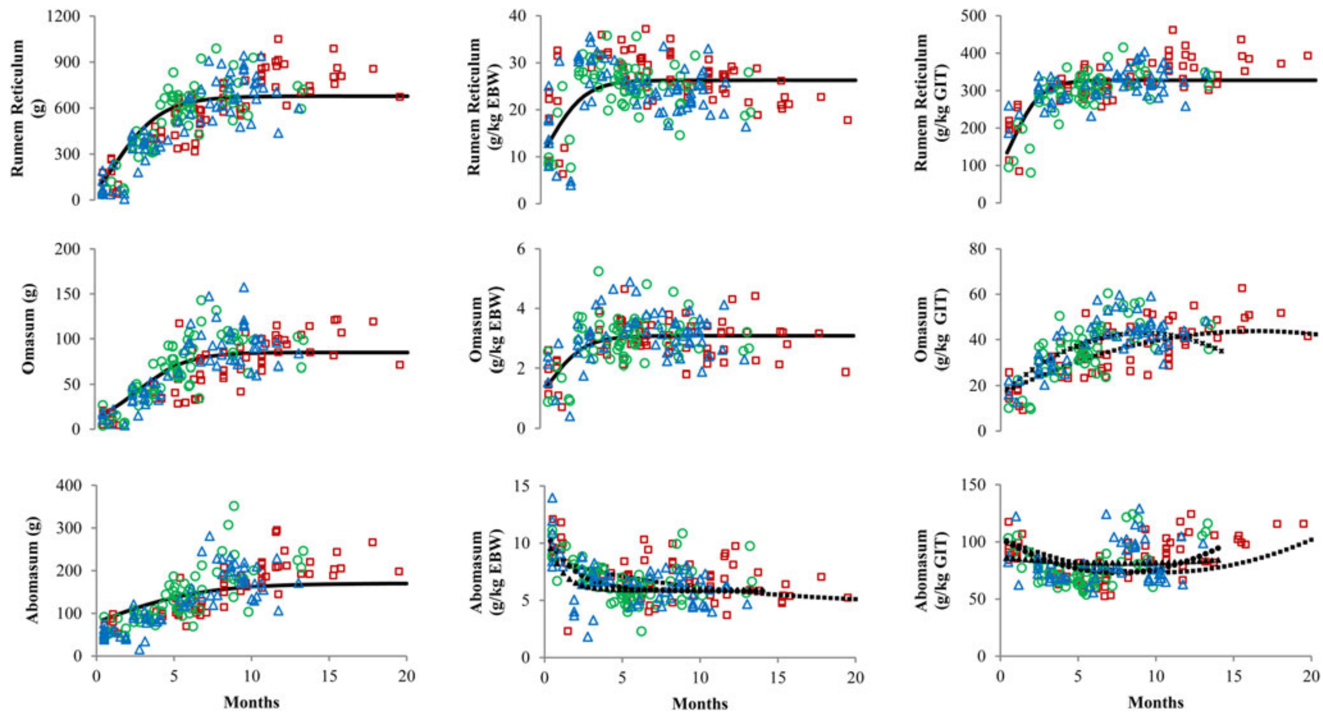

Fig. 4. Colour online. Rumen–reticulum, omasum and abomasum in grams (g), the proportion of empty body weight (g/kg EBW) and the proportion of gastro-intestinal tract (g/kg GIT) of Saanen goats of different sexes (□ represents the observed records of females, ○ castrated males and △ intact males; ■■■ represents the predicted females, ●●● castrated males, ▲▲▲ intact males, ⁎⁎⁎ castrated males and intact males, — all sexes).

(Table 7). At birth, the GIT accounted for 91 ± 4.9 g/kg EBW and decreased at a constant rate of 1.3 ± 0.46 g/kg EBW/month as the animal grew (Table 7). Gastrointestinal tract presented a hypoallometric relationship to EBW (0.63 ± 0.040; Table 5).

When the stomachs and intestines of males and females reached their maximum growth, the intestines constituted 548 ± 17 g/kg of GIT, and the stomachs accounted for 449 ± 18 g/kg GIT (Table 7). The inflection point of SI (g) and LI (g) growth curves was at 0.5 and 1.9 months, respectively (Table 7 and Fig. 5). The SI had a maximum growth rate that was lower than the LI (0.45 ± 0.092 *v.* 0.62 ± 0.093 g/month; Table 7). Small intestine and LI showed a hypoallometric relationship to EBW (0.47 ± 0.052 and 0.83 ± 0.065, respectively; Table 5).

Discussion

In general, the logistic model showed the best fit for modelling visceral organ growth over time. This result is understandable because at birth, animals show a greater anabolic rate compared to catabolic rate, resulting in body tissue accretion. However, with ageing, the ratio between anabolism and catabolism tends to become one; consequently, the rate of tissue growth decreases (Owens *et al.*, 1993). The logistic model assumes that after the inflection point, growth rates tend to decrease with time until stabilizing (Verhulst, 1838; Thornley and France, 2007; Mischan *et al.*, 2015). The inflection point is reached when the instantaneous absolute growth rate (i.e. the change in mass in respect to time) changes from an increasing to a decreasing function (Regadas Filho *et al.*, 2014).

Goats with BW varying from 5 to 45 kg were used in the current study. Intact and castrated males grew faster than females, which enabled them to reach the final BW of 45 kg before the females. On average, the adult BW of male Saanen goats varies from 80 to 91 kg and that of female Saanen goats is around 68 kg (Solaiman, 2010). Thus, the BW range covered in the current work represents proportions of approximately 0.50 of intact males and 0.66 of females along the growth curve.

It has been reported that the inflection point of a growth curve represents puberty (the stage of sexual maturation) and afterwards, the growth rate decreases quickly until it reaches zero (Araújo *et al.*, 2015). In the current study, the inflection point of the BW growth curve occurred at 147 days (4.9 months) for females and 111 days (3.7 months) for castrated males and intact males. Thus, Saanen goats reached puberty between 4 and 5 months old. These results concur with the previous reports, such as Freitas *et al.* (2004), who reported puberty of female Saanen goats at 4.9 months old, Solaiman (2010), who reported that the onset of puberty occurs at 4–6 months for males and 5–7 months for females and Regadas Filho *et al.* (2014), who reported puberty of female Saanen goats at 4.4 months. Considering the EBW, which is narrowly related to BW (Campos *et al.*, 2017), it was observed in the current study that the inflection point of intact and castrated males occurred at 4.1 months, whereas that of females occurred at 5.8 months. The inflection point represents the age in which the EBW growth rate is maximal, indicating changes in body fattening. Thus, it is suggested that the inflection point of the EBW growth curve, when combined with economic indices, may be used to indicate the economically optimum slaughter age of goats.

The current results led to the rejection of the hypothesis that sex affects visceral organ growth over time. Regardless of sex, total visceral organ weight decreased in proportion to EBW with ageing. This finding was also demonstrated by the hypoallometric growth of total visceral organs to EBW, in which total

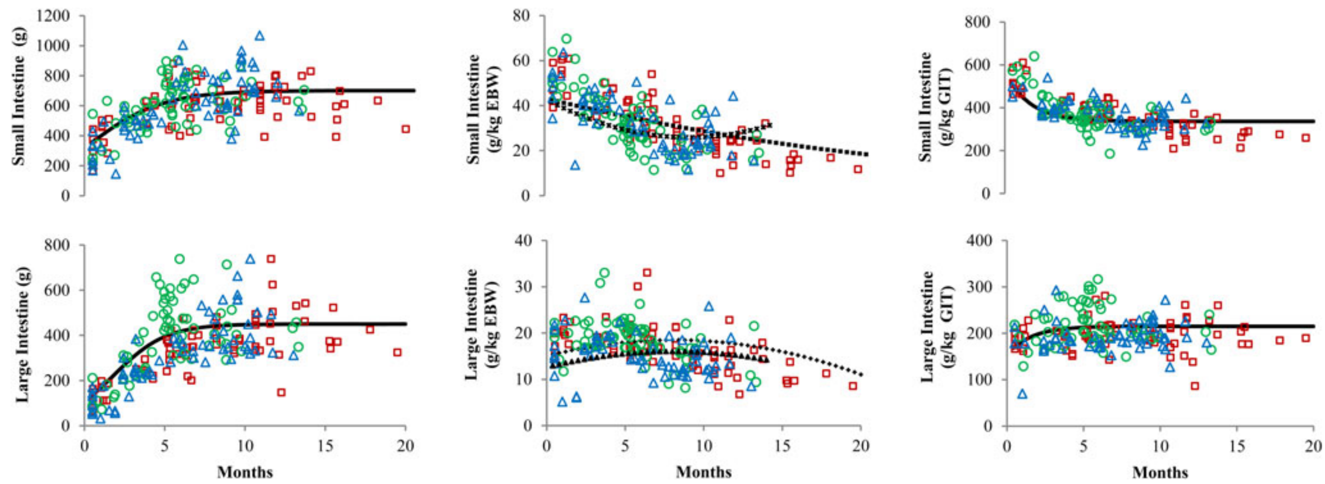

Fig. 5. Colour online. Small intestine and large intestine in grams (g), the proportion of empty body weight (g/kg EBW) and the proportion of gastrointestinal tract (g/kg GIT) of Saanen goats of different sexes (□ represents the observed records of females, ○ castrated males and △ intact males; ■■■ represents the predicted females, ▲▲▲ intact males, ✱✱✱ castrated males and intact males, +++ females and castrated males, — and all sexes).

visceral organs grow more slowly than EBW (Lyford, 1993). This difference in growth pattern is related to the existence of different ages at the detected points of inflection (age at which maturity is reached) of EBW and total visceral organs, i.e. around 5 months for EBW and 3 months for total visceral organs. Consequently, these findings suggest that the energy expenditure for visceral organs in the proportion of total energy expenditure decreases as the animals become older. This concurs with the results of McCGraham (1966), who reported that young Merino wethers showed metabolic rates double those of adults. More recently, a study showed that energy requirements for the maintenance of adult dairy goats are lower than those for young goats (Härter *et al.*, 2017). Energy maintenance requirements involve the energy costs of the vital functions of an organism (AFRC, 1998). Total visceral organs account for approximately 0.10 of the total BW; however, they consume approximately 0.50 of the total energy expenses of a given animal (Huntington, 1990; Seal and Reynolds, 1993). Thus, knowledge of visceral organ growth curve might be very useful in enhancing the understanding of their impact on energy maintenance requirements. Therefore, it is suggested that decreased maintenance energy requirements in adult goats could be partially related to decreased total visceral organ weight as a proportion of EBW, which is not influenced by animal sex.

All visceral organs grow as animals age. However, when based on EBW, each organ has a different growth pattern (Clauss *et al.*, 2003). Liver and GIT growths are highly responsive to nutrient intake (Ortigues and Doreau, 1995) and their weights, as a proportion of EBW at birth, indicate that nutrient intake relative to EBW is high in young animals and reduces with ageing. Moreover, the hypoallometric relationship between the liver and GIT to EBW demonstrated that the liver and GIT grow at a lower growth rate than EBW (Kamalzadeh *et al.*, 1998; Al-Owaimer *et al.*, 2013). According to Church (1988), GIT size, the absorption capacity of its epithelium and the liver's ability to metabolize nutrients are affected by feed intake. Young animals eat more in proportion to BW, leading to the greatest development of GIT tissues due to increased digesta flow, digesta mixture and absorption of water and nutrients (Ortigues and Doreau, 1995). In addition, the current results on liver weight as a proportion of EBW and the allometric relationship to EBW are in accordance with those of previous studies: the livers of pre-ruminants represent a greater proportion of EBW than that of adult ruminants (Baldwin *et al.*, 2004). This occurs because younger goats tend to select diets with greater energy content (Leite *et al.*, 2015*b*).

In addition, liver weight, as a proportion of EBW, may also be related to feed intake. It was observed that females and castrated males ate more relative to EBW than did intact males; however, EBW of castrated males increased at a greater rate than that in females. Therefore, this might be the main reason why females differ from intact and castrated males, regarding liver weight as a proportion of EBW. Similarly, abomasum, SI and LI also seem to be more affected by feed intake, because females generally showed the greatest weights for these organs as a proportion of EBW.

Animal's fattening has labile nature regarding its development (Fisher, 1984) because of its association to a wide range of factors, such as gender, nutritional supply, age and mature size (Wattanachant, 2018). In addition, there is a common view that fattening differences between the sexes are basically attributed to higher proportions of subcutaneous fat (Negussie *et al.*, 2003). In goats, MAT represents around 0.30 of total abdominal fat and females have around 40% more MAT than males (Wattanachant, 2018). Studies have demonstrated that MAT deposition may be twice as fast as EBW (Teixeira *et al.*, 1995; Kamalzadeh *et al.*, 1998; Al-Owaimer *et al.*, 2013). The current results demonstrated MAT growths 1.5 times faster than EBW regardless of sex, which is in accordance with the previous studies (Kirton *et al.*, 1972; Thonney *et al.*, 1987; Wattanachant, 2018).

As digestion and absorption are accelerated in the first days of life (Guilloteau *et al.*, 2009), low pancreas weight (g/kg EBW) may be related to low demand for digestive enzymes and high SI weight (g/kg EBW) may be due to the high absorption capability during this time. Accordingly, Ruckebusch *et al.* (1983) reported that the secretory potentialities of the pancreas are minimal during the first week of life in new-born lambs and are mainly influenced by animal age, following the EBW growth, as observed by the isometric coefficient. However, it was possible to verify the decreased abomasum and SI, expressed as the proportion of

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EBW, concomitantly to the development of rumen–reticulum, omasum and LI, which increased with animal age. This is related to the transition from pre-ruminant to ruminant, which occurs during the first weeks of life and is associated with increased intake of solid food (Church, 1988); this makes the rumen–reticulum, omasum and LI grow slowly in young goats and reach their full development later. Furthermore, regardless of sex, the current results show that growth of the rumen–reticulum stabilized (asymptotic weight) in proportion to EBW at approximately 8 months, indicating that the rumen–reticulum was completely developed.

It was observed in the current study that fermentative organs (i.e. rumen–reticulum and LI) showed a high growth rate at birth and a later inflection point compared to abomasum and SI (g). Younger animals eat more in proportion to BW and their rumen content is greater. Thus, they need thicker rumen and LI tissue to avoid distension, thereby increasing digesta flow (Ortigues and Doreau, 1995). Furthermore, ruminants are born with non-functional forestomachs; when they are stimulated with a solid diet, they face a transition period to becoming a functional ruminant (Church, 1988). In goat kids, this transition period occurs at 3–4 weeks of age, according to their feeding management, and at around 8 weeks old, the forestomachs reach the weight they will have as adults (Church, 1988). Amaral *et al.* (2005), evaluating Saanen goats kids weaned at 45 days (week 6) and later slaughtered, showed that the rumen–reticulum weight and papillae size increased with age. The goat kids used in the current study started eating a solid diet around 30 days old and increased their DMI afterwards; milk intake was terminated when they were 60 days old. In the current work, rumen–reticulum and LI presented inflection points at 43 days (week 6) and 55 days (week 7), respectively, and abomasum and SI at 15 days (week 2). Considering that the inflection point indicates the point where the growth rate begins to decrease, rumen–reticulum and LI growth rate begins to decrease later than abomasum and SI, and both are earlier than EBW. These explain why rumen–reticulorumen and LI had numerically greater allometric coefficient than abomasum and SI (Kirton *et al.*, 1972; Galvani *et al.*, 2010). Moreover, because the inflection point for the rumen–reticulum was seen in week 6, it can be said that the animals were becoming functional ruminants around week 6. Thus, if goat kids show effective solid diet intake, they can be weaned at 6 weeks of age without impairing their development. This practice might be combined with appropriate nutritional management, such as supplementing with solid feed earlier.

As a proportion of GIT, the rumen–reticulum, SI and LI at birth accounted for 0.18, 0.72 and 0.17, respectively. Growth stabilization of the rumen–reticulum, SI and LI occurred approximately at 7.5, 4.5 and 7.5 months, when they reached their asymptotic weight in which they represented approximately 0.33, 0.34 and 0.22 of GIT, respectively. The complete development of LI occurred close to that of the rumen–reticulum, and it may be related to the type of digestion performed in these organs. As discussed previously, after the transition period from pre-ruminant to ruminant, the increased solid diet intake by goat kids led to the development of the rumen–reticulum and LI, which are both involved in fibre fermentation.

Similar to the rumen–reticulum, as age increased, the omasum increased its proportion of the GIT, whereas the abomasum decreased its proportion of the GIT. However, they differed among sexes and did not reach growth stabilization. These results illustrate the transition of goats from pre-ruminant to ruminant and the role of each GIT organ in this process. The greatest proportion of the abomasum in the GIT occurs at birth, while the omasum, compared to the forestomach organs, takes more time to develop (Church, 1988). The current results are in agreement with this; the later omasum growth may be the main reason why a cubic model best fitted the omasum data, in which it was not possible to obtain an asymptotic point, and omasum had the greatest allometric coefficient of the GIT segments (Kirton *et al.*, 1972; Galvani *et al.*, 2010). In addition, abomasum differences among sexes were also reported in studies involving feed restriction in Saanen goats from 30 kg BW (Leite *et al.*, 2015*b*). However, there is no clear explanation that can justify such differences among sexes on omasum and abomasum size as the proportion of GIT. Thus, additional studies need to be performed to better address these differences.

In general, the logistic model best described the growth of the visceral organs over time, especially when they are evaluated in gram. Sex did not affect the growth of visceral organs (g) but affected MAT deposition. However, when expressed as g/kg EBW, some organs showed differences between the sexes, such as the liver, abomasum, SI and LI. Overall, females showed greater organ weights (g/kg EBW) than males, which may be related to the greater DMI of females. The rumen–reticulum and LI show higher growth rates in the first 2 months of life. Irrespective of sex, the visceral organs had higher growth rates up to 3 months old. The knowledge of the visceral organ growth curve might be very useful in enhancing the understanding of their impact on energy requirements.

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Conflict of interest. Authors declared no conflicts of interest.

Ethical standards. Humane animal care and handling procedures were conducted in accordance with the Animal Care Committee (Comissão de Ética e Bem Estar Animal) of the Sao Paulo State University and with the instructions from the Ministry of Agriculture in Brazil (instruction number 56/2008).

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Appendix

Table A1. Summary of statistics related to visceral organs in grams (g) of Saanen goats

Variables	N^a	Mean	Median	Minimum	Maximum	Standard error
Gomes (2011)						
Body weight (kg)	18	37	36	29	46	1.5
Empty body weight (kg)	18	31	29	22	40	1.5
DMI (g/day/kg EBW)	6	33	33	28	38	1.5
Liver	18	579	540	420	790	30.6
Pancreas	18	57	50	30	101	5.0
Spleen	18	54	50	30	84	3.6
Mesenteric adipose tissue	18	466	400	260	915	47.1
Rumen–reticulum	18	775	746	660	942	20.3
Omasum	18	95	97	60	158	5.9
Abomasum	18	169	165	130	220	5.9
Small intestine	17	795	761	610	1069	30.7
Large intestine	17	456	410	320	740	30.3
Bompadre *et al.* (2014)						
Body weight (kg)	55	10.1	10	4.2	16	0.57
Empty body weight (kg)	53	8.6	8.4	3.9	13	0.41
DMI (g/day/kg EBW)	15	29.1	28	25	35	0.75
Liver	55	222	206	93	380	11.4
Pancreas	55	18	16	6.3	37	1.2
Spleen	55	20.9	21	8.9	38	0.99
Mesenteric adipose tissue	55	89	89	9.7	218	7.6
Rumen–reticulum	53	190	179	6.2	433	19.2
Omasum	42	24	21	3.96	72	2.5
Abomasum	54	67	63	16	110	3.3
Small intestine	49	402	431	146	633	18.2
Large intestine	54	166	157	32	414	13.1
Medeiros *et al.* (2014)						
Body weight (kg)	23	13	12	5.0	21	13.4
Empty body weight (kg)	23	11	11	4.9	18	10.7
DMI (g/day/kg EBW)	9	31	31	25	35	1.0
Liver	20	289	280	110	464	26.4

(*Continued*)

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Table A1. (*Continued.*)

Variables	N^a	Mean	Median	Minimum	Maximum	Standard error
Pancreas	20	21	20	6.2	38	2.6
Spleen	20	30	34	10	44	2.4
Mesenteric adipose tissue	19	255	269	50	487	32.6
Rumen–reticulum	0	–	–	–	–	–
Omasum	0	–	–	–	–	–
Abomasum	0	–	–	–	–	–
Small intestine	0	–	–	–	–	–
Large intestine	0	–	–	–	–	–
Almeida *et al.* (2015)						
Body weight (kg)	47	38.2	39	27	47	0.88
Empty body weight (kg)	47	32.0	32	21	40	0.82
DMI (g/day/kg EBW)	18	27.6	28	24	31	0.53
Liver	47	709	730	431	945	16.7
Pancreas	44	72	73	28	106	2.7
Spleen	46	69	68	42	103	2.2
Mesenteric adipose tissue	46	968	946	351	1851	51.1
Rumen–reticulum	47	730	732	478	989	18.0
Omasum	47	99	100	42	148	2.9
Abomasum	47	215	208	138	352	6.2
Small intestine	45	643	631	380	866	18.0
Large intestine	46	418	394	148	739	16.4
Ferreira *et al.* (2015)						
Body weight (kg)	18	30.3	31	27	34	0.64
Empty body weight (kg)	18	25.9	26	21	30	0.63
DMI (g/day/kg EBW)	9	46.1	47	42	49	0.92
Liver	18	565	553	303	713	22.2
Pancreas	0	–	–	–	–	–
Spleen	0	–	–	–	–	–
Mesenteric adipose tissue	0	–	–	–	–	–
Rumen–reticulum	18	623	629	504	833	20.9
Omasum	17	74	69	57	106	3.7
Abomasum	18	135	141	70	187	6.6
Small intestine	17	664	665	460	896	30.2
Large intestine	18	557	558	428	738	19.1
Leite *et al.* (2015*a*)						
Body weight (kg)	58	23.3	23	15	34	0.81
Empty body weight (kg)	58	18.6	18	12	27	0.69
DMI (g/day/kg EBW)	17	31	32	17	37	1.1
Liver	58	475	453	308	726	14.1
Pancreas	58	46	46	22	82	2.0
Spleen	57	45	45	23	77	1.7
Mesenteric adipose tissue	56	350	303	105	794	22.1
Rumen–reticulum	57	509	501	328	697	14.6

(*Continued*)

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Table A1. (*Continued.*)

Variables	N^a	Mean	Median	Minimum	Maximum	Standard error
Omasum	58	62	57	31	119	3.0
Abomasum	58	113	109	80	184	3.1
Small intestine	57	662	644	425	1005	17.8
Large intestine	58	318	317	206	478	9.3
Figueiredo *et al.* (2016)						
Body weight (kg)	18	37	37	28	45	1.5
Empty body weight (kg)	18	30	30	21	39	1.6
DMI (g/day/kg EBW)	6	27	28	22	32	2.0
Liver	18	572	564	390	760	21.4
Pancreas	17	65	62	45	100	3.5
Spleen	18	67	65	20	93	4.5
Mesenteric adipose tissue	16	999	880	510	1733	96.2
Rumen–reticulum	18	802	791	575	1050	28.7
Omasum	17	78	82	57	100	3.2
Abomasum	18	185	188	115	221	6.9
Small intestine	18	596	593	392	734	23.5
Large intestine	15	441	447	334	625	21.6

[a]Total number of records used in the study, after removing outliers.

Table A2. Comparison to choose the best variance modeling (in bold) of the chosen model to predict visceral organ growth (g, g/kg EBW, or g/kg GIT), and dry matter intake (DMI; g/day/kg EBW) of Saanen goats using Akaike information criterion corrected for small samples (smaller the better)

Variable	V_0^a	V_1^b	V_2^c	V_3^d
Gram				
Body weight	7297	4609	4584	**4521**[e]
Empty body weight	6658	4529	4482	**4423**
Empty body weight metabolic	3178	3178	3152	**3129**
Total visceral organs	2373	2356	2345	**2334**
Liver	2720	2720	2701	**2672**
Pancreas	1661	1661	1765	**1574**
Spleen	1632	1632	1628	**1613**
Mesenteric adipose tissue	2746	2746	2599	**2574**
Gastrointestinal tract	2514	2514	2512	**2497**
Stomachs	2404	2404	2400	**2388**
Rumen–reticulum	2494	2494	2490	**2477**
Omasum	1675	1675	1668	**1641**
Abomasum	2009	2009	1989	**1976**
Intestines	2521	2521	2520	**2507**
Small intestine	2448	2448	2449	**2437**
Large intestine	2387	2387	2366	**2357**
g/kg Empty body weight				
Total visceral organs	1276	1275	1276	**1271**
Liver	1206	1206	1193	**1187**

(*Continued*)

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Table A2. (*Continued.*)

Variable	V_0^a	V_1^b	V_2^c	V_3^d
Pancreas	**283**	283	283	292
Spleen	**373**	373	367	379
Mesenteric adipose tissue	1290	1290	**1245**	1251
Gastrointestinal tract	1431	1431	1433	**1429**
Stomachs	1243	1243	1235	**1221**
Rumen–reticulum	1279	1279	1252	**1248**
Omasum	400	400	**399**	403
Abomasum	770	770	**767**	767
Intestines	1394	1394	1392	**1390**
Small intestine	1326	1326	1316	**1309**
Large intestine	1143	1143	1139	**1133**
g/kg Gastrointestinal tract				
Rumen–reticulum	1825	1825	1824	**1805**
Omasum	1209	1209	1211	**1206**
Abomasum	1411	1411	1413	**1409**
Small intestine	1872	1872	1867	**1854**
Large intestine	**1759**	1759	1757	1765
DMI (g/day/kg EBW)	450	446	448	**442**

[a]V_0, previously the variance modelled.
[b]$V_1 = (\sigma_e^2)$.
[c]$V_2 = (\sigma_e^2)\exp(c \times \text{age})$.
[d]$V_3 = (\sigma_e^2) \times \mu^{2\varphi}$.
[e]Chosen best modelled variance, in bold.

Table A3. Comparison to choose the best modelled variance (in bold) of an allometric model for predicting the growth of visceral organs in gram (g) per empty body weight (EBW) in kg of Saanen goats using Akaike information criterion corrected for small samples (smaller the better)

Variable	V_0^a	V_1^b	V_3^c
Total visceral organs	2246	2246	**2215** [d]
Liver	2588	2588	**2502**
Pancreas	1571	1571	**1462**
Spleen	1581	1581	**1513**
Mesenteric adipose tissue	2632	2632	**2392**
Gastrointestinal tract	2547	2547	**2522**
Stomachs	2405	2405	**2393**
Rumen–reticulum	2496	2496	**2470**
Omasum	1645	1645	**1617**
Abomasum	2020	2020	**1954**
Intestines	2554	2554	**2507**
Small intestine	2491	2491	**2452**
Large intestine	2400	2400	**2351**

[a]V_0, previously the modelled variance.
[b]$V_1 = (\sigma_e^2)$.
[c]$V_3 = (\sigma_e^2) \times \mu^{2\varphi}$.
[d]Chosen best modelled variance, in bold.