



## Original Article

# Across and within breed differences in the relationship between packed cell volume and fecal egg count in growing meat goat and hair sheep males naturally and artificially infected with gastrointestinal nematodes

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## ABSTRACT

The relationship between packed cell volume (PCV) and fecal egg count (FEC) in different breeds of meat goats and hair sheep infected with gastrointestinal nematodes, including *Haemonchus contortus*, was characterized. Growing males from eight commercial and two research farms (one Kiko, Spanish, Dorper, and St. Croix; three Boer; four Katahdin) in the southcentral United States were evaluated in a central performance test with ad libitum intake of a 50% concentrate pelleted diet. There were 84 Boer, 55 Kiko, and 57 Spanish goats and 52 Dorper, 129 Katahdin, and 49 St. Croix sheep. During adaptation, animals were dewormed then dosed with 10,000 infective *H. contortus* larvae. PCV and FEC were determined before deworming (i.e., natural infection potentially with multiple internal parasites) and 21, 28, 35, 42, and 49 days after artificial infection. Effects of species, breed, and year were analyzed with mixed effects models including day of sampling post dosing as a repeated measure and FEC and FEC × breed as covariates. Moreover, differences in correlation coefficients between PCV and logarithmic FEC (lnFEC) among species, breed, year, and day of sampling were evaluated. Breed affected ( $P \leq 0.001$ ) PCV in goats (24.8, 27.2, and 26.0% for Boer, Kiko, and Spanish, respectively; SEM = 0.42) and sheep (29.8, 26.7, and 31.0% for Dorper, Katahdin, and St. Croix, respectively; SEM = 0.28). There were effects of FEC × breed ( $P \leq 0.029$ ) on PCV for Boer, Kiko, Dorper, Katahdin, and St. Croix (−0.31, −0.33, −0.46, −0.46, and −0.49% per 1000 eggs, respectively) but not for Spanish goats ( $P = 0.451$ ). With all data, PCV and lnFEC with natural infection were highly correlated ( $P < 0.001$ ) for Boer and Kiko goats and Dorper and Katahdin sheep ( $r = -0.59, -0.67, -0.77, \text{ and } -0.84$ , respectively) but not for Spanish goats or St. Croix sheep ( $P \geq 0.323$ ). Correlation coefficients for artificial infection with *H. contortus* were significant ( $P \leq 0.002$ ) except for Spanish goats, although values were lower (−0.40, −0.21, −0.23, −0.47, and −0.28 for Boer, Kiko, Dorper, Katahdin, and St. Croix, respectively) compared with natural infection. In conclusion, PCV was not related to FEC in Spanish goats infected either naturally or artificially, and the nature of the relationship varied among breeds of goats and sheep. Based on the magnitude of the FEC × breed coefficient, sheep incurred a relatively greater reduction in PCV as FEC increased, and correlation coefficients indicate stronger relationships with natural than artificial infection.

## 1. Introduction

Internal parasitism, particularly haemonchosis, has become a major constraint to small ruminant production all over the world due to widespread anthelmintic resistance. Packed cell volume (PCV), which assesses the severity of anemia, has been used as an indirect indicator of *Haemonchus contortus* infection because of the blood feeding nature of the worm. The accuracy with which PCV describes the severity of

haemonchosis is not well established (Kaplan et al., 2004), although Le Jambre (1995) noted a strong correlation between blood loss and egg production in sheep infected with *H. contortus*. Fecal egg count (FEC) is the most common veterinary practice for the diagnosis of internal parasitism (Zajac and Conboy, 2006) and has been used as a direct indicator of the level of infection with *H. contortus* (Ngere et al., 2018).

Normal ranges of PCV vary among species of mammals and are higher for sheep than for goats (Byers and Kramer, 2010). Values also

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differ across and within breeds and are affected by conditions including age, health status, and climate (Smith and Sherman, 2009; Mengistu et al., 2017). Responses of PCV and FEC to artificial *H. contortus* infection have varied among sheep breeds (Courtney et al., 1985; Zajac et al., 1990; Notter et al., 2003; Besier et al., 2016), but there have been few comparisons of species (sheep and goats) and breeds of goats. In addition to PCV and FEC, the i.e., FAMACHA® eye color score that reflects level of anemia has been widely used on-farm to assess need for selective treatment of individual animals for haemonchosis. However, there are reports indicating that FEC and FAMACHA® score, determined by trained investigators or producers, differ between goats and sheep of various breeds and ages in the southeastern United States (Kaplan et al., 2004; Burke et al., 2007). This may in part relate to the fact that anemia is not only caused by haemonchosis but also by other parasitic and nonparasitic conditions (e.g., malnutrition and iron deficiency). In contrast to findings of Le Jambre (1995) with sheep, the PCV and FEC of goats of different breeds and ages were not correlated under field conditions in Switzerland (Scheuerle et al., 2010). Relationships between these indicators that vary with small ruminant species and breeds may affect the accuracy of haemonchosis diagnosis and associated treatment decisions. This may also be true for type of infection, such as natural with potentially multiple gastrointestinal nematodes (GIN) vs. artificial infection with *H. contortus* alone. Therefore, objectives of this research were to compare and characterize the relationship between PCV and FEC in different breeds of meat goats and hair sheep with natural infection by GIN and artificial *H. contortus* infection.

## 2. Materials and methods

### 2.1. Animals, housing, and feeding

The experimental protocol was approved by the Langston University Animal Care Committee. There were 196 growing meat goat and 230 hair sheep intact males evaluated in a central performance test at Langston University. Animals were from eight commercial farms in the southcentral United States (states of Arkansas, Kansas, Missouri, and Oklahoma), a sheep flock from the USDA Agricultural Research Service Dale Bumpers Small Farms Research Center (Booneville, AR), and two goat herds from Langston University (Langston, OK). Total animal numbers this study employed were 84 Boer, 55 Kiko, and 57 Spanish goats and 52 Dorper, 129 Katahdin, and 49 St. Croix sheep (Table 1). Boer goats from two farms and Katahdin sheep from two farms were tested only in one year, whereas animal groups from the other locations were tested in three consecutive years. The number of animals from a farm tested each year averaged  $17 \pm 0.1$  and ranged from 8 to 21. After weaning, kids and lambs from each farm were transferred to Langston University and housed together in groups typically of nine in

$6.1 \times 5.6$  m pens that had a  $6.1 \times 1.35$  m area with a concrete floor and a  $6.1 \times 4.25$  m unpaved area in a confinement facility. Before animals were placed in pens, agricultural lime was spread on the unpaved area and covered with bedding of pine shavings, and the concrete area was disinfected with Pine-Sol (The Clorox Company, Oakland, CA). The concrete floor area was cleaned daily and bedding material was added every 2 weeks. Water was provided in all pens via automated waterers.

Sheep in each year and goats in years 2 and 3 had free-choice access to a 50% concentrate pelleted diet through an automated feeding unit (MK 3 FIRE, Feed Intake Recording Equipment, Osborne Industries, Inc., Osborne, KS) situated in each pen, whereas in year 1 goats were fed in Calan gate feeders (American Calan, Inc., Northwood, NH). The diet was 29.23% cottonseed hulls, 20.53% dehydrated alfalfa pellets, 19.64% ground corn, 12.91% wheat middlings, 9.04% cottonseed meal, 4.30% pelleting agent, 1.10% ammonium chloride, and 3.25% other minor ingredients (dry matter basis; DM). Based on ingredient composition values of Preston (2015), crude protein (CP) and total digestible nutrient (TDN) levels were 15.6 and 63.6%, respectively. Moreover, with rumen undegraded intake protein (UIP) levels of Preston (2015) and the relationship between dietary levels of CP and metabolizable protein (MP) of NRC (2000;  $MP, \% DM = (64\% + (16\% \times UIP)) \times CP, \% DM$ ), the MP concentration was 11.0% DM. Likewise, based on the TDN concentration, 18.4 MJ/kg DM of digestible energy, and metabolizable energy (ME) 82% of digestible energy, the dietary ME concentration was 9.61 MJ/kg DM. The diet was very similar to that used previously at Langston University to evaluate average daily gain and efficiency of feed utilization by potential meat goat sires in a central performance test (e.g., Hu et al., 2012). Average DM intake was  $1.4 \pm 0.03$ ,  $1.0 \pm 0.06$ , and  $1.1 \pm 0.07$  kg/day for Boer, Kiko, and Spanish goats and  $1.9 \pm 0.06$ ,  $1.9 \pm 0.04$ , and  $1.5 \pm 0.05$  kg/day for Dorper, Katahdin, and St. Croix sheep, respectively.

### 2.2. Natural infection with GIN and artificial infection with *Haemonchus contortus* larvae

Most animals were born and raised on pasture. Lambs from the Katahdin1 farm were reared in confinement until weaning in year 1 but were exposed to pasture in other years. Along with farm management surveys, fecal samples were collected from each animal during farm visits prior to this experiment. Based on the FEC data collected on-farm, all animals born on pasture were naturally infected with GIN, whereas lambs from Katahdin1 farm in year 1 had a FEC of 0 eggs per gram (EPG).

The test period was normally 9 weeks in length, which included 2 weeks of adaptation and 7 weeks for measurements. When animals arrived at the central performance test facility, PCV, FEC, and body weight were measured. During adaptation, animals except the lambs

**Table 1**

Animal group, species, breed, origin of animals (state), number, nutritional plane, age, BW, PCV, FEC, and years tested<sup>a, b</sup>.

Animal group	Species	Breed	State	n	Nutritional plane	Age (mo)	BW (kg)	PCV (%)	FEC, EPG <sup>c</sup> (range)	Year
Boer1	Goat	Boer	AR	18	Very low		$17.9 \pm 0.92$		3542 (600–10,300)	1
Boer2	Goat	Boer	OK	48	Medium	$3.9 \pm 0.08$	$19.4 \pm 0.78$	$20.7 \pm 0.74$	5033 (0–14,350)	1, 2, 3
Boer3	Goat	Boer	OK	18	Medium		$19.2 \pm 1.06$	$25.6 \pm 0.91$	756 (0–3450)	1
Kiko	Goat	Kiko	KS	55	Medium	$3.7 \pm 0.06$	$19.2 \pm 0.47$	$24.1 \pm 0.76$	1839 (0–7650)	1, 2, 3
Spanish	Goat	Spanish	OK	57	Medium	$4.0 \pm 0.09$	$18.2 \pm 0.44$	$23.6 \pm 0.70$	2223 (0–10,450)	1, 2, 3
Dorper	Sheep	Dorper	MO	52	Medium	$3.9 \pm 0.13$	$28.2 \pm 0.74$	$27.1 \pm 1.10$	3994 (0–25,400)	1, 2, 3
Katahdin1	Sheep	Katahdin	MO	59	High	$3.9 \pm 0.05$	$38.9 \pm 0.74$	$33.8 \pm 0.39$	47 (0–650)	1, 2, 3
Katahdin2	Sheep	Katahdin	OK	18	Low		$24.3 \pm 0.76$	$17.4 \pm 4.86$	11,562 (0–82,500)	1
Katahdin3	Sheep	Katahdin	MO	15	Medium		$29.1 \pm 1.15$		213 (0–650)	1
Katahdin4	Sheep	Katahdin	AR	37	Low	$3.6 \pm 0.10$	$18.6 \pm 0.57$	$23.2 \pm 0.69$	9639 (0–38,500)	1, 2, 3
St. Croix	Sheep	St. Croix	MO	49	Low	$4.3 \pm 0.06$	$19.0 \pm 0.77$	$22.7 \pm 0.84$	5650 (0–44,250)	1, 2, 3

<sup>a</sup> BW = body weight; PCV = packed cell volume, FEC = fecal egg count.

<sup>b</sup> Mean values of age, BW, PCV, and FEC were measured when animals were transported to the facility of the central performance test (i.e., at the beginning of the adaptation period).

<sup>c</sup> EPG = eggs per gram.

from the Katahdin1 farm in year 1 were treated with Valbazen® (Zoetis, Parsippany, NJ; 20.0 and 10.0 mg/kg BW for goats and sheep, respectively) and Prohibit® Soluble Drench Powder (Agri Laboratories, Ltd., St. Joseph, MO; 18.0 and 12.0 mg/kg BW for goats and sheep, respectively), both given at the same time. Animals that had high FEC (> 600 EPG) after 7 days of anthelmintic treatment were re-treated and the adaptation period was extended accordingly. Animals that did not exhibit good health conditions in the 2 weeks of adaptation, such as low PCV or feed intake, were not included in the study. At 1 week after the anthelmintic treatment, animals were administered approximately 10,000 infective larvae of *H. contortus* orally (Notter et al., 2003). The lambs from Katahdin1 farm in year 1 were given a preliminary infection with approximately 2000 infective larvae during the adaptation period, and the artificial challenge with 10,000 larvae occurred 21 days later when the range of FEC of the lambs was between 0 and 600 EPG. The larvae were considered susceptible to anthelmintics and obtained from Texas A&M University, Veterinary Medicine and Biomedical Sciences prior to each challenge. During the test, seven animals with low PCV (< 16%) were administered Red Cell® (Vitamin-Iron-Mineral supplement, Horse Health Products, Phoenix, AZ). Thereafter, one Kiko and two Spanish kids and two Katahdin lambs were dewormed and removed from the test due to very low PCV (< 14%). The other two animals received the supplement on day 42 of the test. For these animals, only data before the treatment were included.

### 2.3. Measures

PCV was determined at the beginning of the adaptation period and 7, 14, 21, 28, 35, 42, and 49 days after artificial infection. Blood was sampled by jugular venipuncture with a 21 gauge (0.81 mm) × 2.5 cm Monoject™ Blood Collection Needle (Covidien Ltd., Dublin, Ireland) and a BD Vacutainer® (K<sub>2</sub>EDTA, Becton, Dickinson and Company, Franklin Lakes, NJ) blood tube. A sample was transferred to two plain micro-hematocrit capillary tubes (75 mm) and centrifuged at 12,000 ×g for 5 min in a Micro-Hematocrit Centrifuge (LWS-M24, LW Scientific, Lawrenceville, GA). Average PCV was determined with a Micro-Capillary Reader 2201 (Damon/IEC Division, Needham Heights, MA). Fecal samples were collected from the rectum at the beginning of the test and at 21, 28, 35, 42, and 49 days after the artificial infection (Notter et al., 2003). A modified McMaster technique (Stafford et al., 1994) with a sensitivity of 50 EPG was employed to determine FEC. The measurements of PCV at 42 and 49 days and FEC at 49 days were not made with all groups in years 1 and 2, but this did occur in year 3. The PCV and FEC at the beginning of adaptation were considered reflective of natural infection with internal parasites, perhaps multiple ones, in addition to *H. contortus*.

**Table 2**  
Effects of breed, year, breed × year, and sampling day on packed cell volume (%) in goat and sheep breeds<sup>1</sup>.

Species	Type	Breed			SEM	Year			SEM	Day post infection					SEM		
		Boer	Kiko	Spanish		1	2	3		21	28	35	42	49			
Goats <sup>2</sup>	Main effect	24.8 <sup>c</sup>	27.2 <sup>a</sup>	26.0 <sup>b</sup>	0.42	25.1 <sup>b</sup>	28.1 <sup>a</sup>	24.7 <sup>b</sup>	0.42	25.6 <sup>bc</sup>	25.2 <sup>c</sup>	25.4 <sup>c</sup>	26.6 <sup>ab</sup>	27.1 <sup>a</sup>	0.36		
	Interaction																
	Boer						24.4 <sup>ef</sup>	27.3 <sup>b</sup>		22.6 <sup>f</sup>							
	Kiko						25.1 <sup>cde</sup>	29.9 <sup>a</sup>		26.6 <sup>bcd</sup>	0.72						
Sheep <sup>3</sup>	Spanish					25.9 <sup>bcd</sup>	27.1 <sup>bc</sup>	25.0 <sup>de</sup>									
	Main effect	29.8 <sup>b</sup>	26.7 <sup>c</sup>	31.0 <sup>a</sup>	0.28	30.6 <sup>a</sup>	28.6 <sup>b</sup>	28.2 <sup>b</sup>	0.28	30.0 <sup>a</sup>	29.0 <sup>b</sup>	28.8 <sup>b</sup>	29.2 <sup>b</sup>	28.9 <sup>b</sup>	0.23		
	Interaction																
	Dorper						31.1	29.2		29.2							
	Katahdin						28.1	25.9		26.0	0.47						
St. Croix						32.6	30.9	29.5									

a-fMeans within breed, year, day, and breed × year grouping without a common superscript letter differ ( $P < 0.05$ ).

<sup>1</sup>Fecal egg count was a covariate.

<sup>2</sup>Breed, year, day post infection, and breed × year  $P$  value of < 0.001, < 0.001, < 0.001, and 0.046, respectively.

<sup>3</sup>Breed, year, day post infection, and breed × year  $P$  value of < 0.001, < 0.001, < 0.001, and 0.507, respectively.

### 2.4. Statistical analysis

FEC was not normally distributed and various transformations were tested with the Univariate procedure of SAS (SAS, 2013a) to evaluate normality. A logarithmic transformation [ $\ln(\text{FEC} + 100)$ ] was most appropriate and selected for the analyses. The distribution of PCV was also evaluated and found to be normally distributed.

Relationships between PCV and FEC were evaluated three ways. First, PCV at multiple days subsequent to artificial infection was evaluated with all the data collected in the 3 years, which consisted of 2887 PCV and 2741 FEC records. With a mixed effects model of SAS (2013b), fixed effects were breed, year, breed × year, sampling day as a repeated measure, and FEC and FEC × breed included as covariates. Secondly, PCV at different times after artificial infection for animals of the three Boer goat and four Katahdin sheep farms tested in year 1 was analyzed with a mixed effects model for each breed, including the fixed effect of animal group or farm, sampling day as a repeated measure, and FEC and FEC × animal group as covariates. Third, based on results of these analyses, Pearson correlation coefficients ( $r$ ) between PCV and  $\ln(\text{FEC})$  for each measurement point were calculated by 1) species and breed for natural infection with data of all animals at the beginning of the adaptation period, 2) species and breed for the artificial infection with data of all animals, 3) species, breed, and day post artificial infection with data of all animals, 4) species, breed, and the 3 years of testing for animals evaluated in all years, and 5) different farms with Boer goats and Katahdin sheep evaluated in year 1.

## 3. Results

### 3.1. Breed PCV

Arithmetic means of PCV and FEC are shown in Table 1. The PCV of goats varied ( $P < 0.001$ ) among breed, year, and sampling day, and there was also a breed × year interaction ( $P = 0.046$ ; Table 2). There were no differences in PCV among breeds in year 1, Kiko goats had greater PCV than Boer and Spanish goats in year 2, and Boer goats had lower PCV in year 3. Goat PCV values were similar at 21, 28, and 35 days and increased at 42 and 49 days after the artificial infection. Conversely, the breed × year interaction for sheep was not significant ( $P = 0.507$ ). St. Croix had greater PCV than Dorper, and Katahdin had the lowest PCV among breeds ( $P < 0.05$ ). The PCV for sheep was greater ( $P < 0.001$ ) in year 1 than in years 2 and 3. The sheep PCV at 21 days was greater ( $P < 0.001$ ) than at 28, 35, 42, and 49 days. There were effects ( $P \leq 0.03$ ) of FEC × breed for Boer, Kiko, Dorper, Katahdin, and St. Croix, and estimates of the reduction in PCV with increasing FEC were  $-0.31$ ,  $-0.33$ ,  $-0.46$ ,  $-0.46$ ,

**Table 3**

Effects of animal group and days of post artificial infection on packed cell volume (PCV) for Boer goats and Katahdin sheep<sup>1</sup>.

Species	Animal group <sup>2</sup>	PCV (%)	SEM	Day post infection	PCV (%)	SEM
Goat <sup>3</sup>	Boer1	28.1 <sup>a</sup>	0.99	21	27.1 <sup>a</sup>	0.50
	Boer2	23.2 <sup>c</sup>	0.69	28	24.9 <sup>b</sup>	0.45
	Boer3	25.5 <sup>b</sup>	0.63	35	26.9 <sup>a</sup>	0.47
Sheep <sup>4</sup>	Katahdin1	28.6 <sup>ab</sup>	0.54	21	29.1	0.35
	Katahdin2	29.2 <sup>a</sup>	0.69	28	28.8	0.34
	Katahdin3	29.9 <sup>a</sup>	0.52	35	28.3	0.34
	Katahdin4	27.5 <sup>b</sup>	0.53	42	29.1	0.80
				49	28.7	0.70

a-cMeans within animal group and day grouping without a common superscript letter differ ( $P < 0.05$ ).

<sup>1</sup>Fecal egg count was covariate.

<sup>2</sup>Goat and sheep groups are addressed in Table 1.

<sup>3</sup>Animal group and day post infection P value of 0.005 and  $< 0.001$ , respectively.

<sup>4</sup>Animal group and day post infection P value of  $< 0.001$  and 0.371, respectively.

and  $-0.49\%$  per 1000 eggs, respectively. Conversely, the FEC  $\times$  breed coefficient for Spanish goats was not different from 0 (i.e.,  $-0.09\%$  per 1000 eggs;  $P = 0.451$ ).

### 3.2. PCV values of different farms with Boer goats and Katahdin sheep

Animal group or farm affected ( $P \leq 0.005$ ) PCV of Boer goats and Katahdin sheep, and sampling day affected ( $P \leq 0.001$ ) the PCV of Boer goats but not of Katahdin sheep ( $P = 0.371$ ; Table 3). The FEC covariate affected ( $P < 0.001$ ) PCV of Katahdin groups but not Boer groups ( $P = 0.85$ ). There were FEC  $\times$  animal group interactions for Boer3 and Katahdin groups ( $P < 0.03$ ) but not for Boer1 and Boer2 ( $P > 0.10$ ). Estimates of the slope or decline in PCV as FEC increased were  $-0.65$ ,  $-0.53$ ,  $-1.43$ ,  $-0.38$ , and  $-0.71\%$  per 1000 eggs for Boer3, Katahdin1, Katahdin2, Katahdin3, and Katahdin4, respectively.

### 3.3. Correlation coefficients between PCV and FEC

The overall arithmetic mean of PCV was  $24.7 \pm 0.19\%$ , with a minimum of 9.0%, maximum of 38.0%, and median of 24.8%. The relationship between PCV and FEC with natural infection varied among breeds of goats and sheep, with highly negative  $r$  ( $P < 0.001$ ) for Boer, Kiko, Dorper, and Katahdin but no association for Spanish or St. Croix ( $P \geq 0.323$ ; Table 4). The  $r$  at 21 to 49 days after artificial infection was significant ( $P \leq 0.002$ ) for all breeds except Spanish goats ( $P = 0.352$ ; Table 4). The  $r$  between PCV and FEC varied among days after infection (Table 5). The relationship was strongest at 42 or 49 days for all sheep and goat breeds. There were also some differences in  $r$  among the 3 years, with no relationship for Boer and Kiko in year 2 or for Spanish in years 1, 2, and

**Table 4**

Number of observations, correlation coefficient ( $r$ ) between PCV and lnFEC, and P values for sheep and goat breeds naturally infected with gastrointestinal nematodes and after the artificial infection (21, 28, 35, 42, and 49 days) with *Haemonchus contortus*<sup>a</sup>.

Infection	Item	Goats			Sheep		
		Boer	Kiko	Spanish	Dorper	Katahdin	St. Croix
Natural	n	50	38	39	39	97	36
	$r$	$-0.59$	$-0.67$	0.07	$-0.77$	$-0.84$	$-0.17$
	P value	$< 0.001$	$< 0.001$	0.659	$< 0.001$	$< 0.001$	0.323
Artificial	n	168	203	187	215	364	187
	$r$	$-0.40$	$-0.21$	$-0.07$	$-0.23$	$-0.47$	$-0.28$
	P value	$< 0.001$	0.002	0.352	0.001	$< 0.001$	$< 0.001$

<sup>a</sup> PCV = packed cell volume; lnFEC = logarithmic transformed fecal egg count,  $\ln(\text{FEC} + 100)$ .

3 (Table 6). The relationship also varied among farms with Boer goats and Katahdin sheep in year 1 (Table 7). Two groups of Boer goats and three Katahdin sheep groups had moderate to highly negative correlations between PCV and FEC, but this was not true for one group of each breed.

## 4. Discussion

### 4.1. Relationship between PCV and FEC

The relationship between PCV and FEC resulting from natural infection with GIN and artificial infection with *H. contortus* varied among breeds of goats and sheep. Although management regimen and anthelmintic history differed among the farms, animals were born and raised on pasture other than lambs from one farm in year 1 that consequently did not require the initial anthelmintic treatment. Only a limited number of the animals received anthelmintic treatment while on the farms and none were treated 2 weeks before the test.

#### 4.1.1. Natural infection

Factors that may affect the relationship between PCV and FEC with natural infection include small ruminant species, breed, infection level, nutritional plane, management regimen, and production stage. Correlation coefficients in the current experiment between PCV and lnFEC for the growing Boer and Kiko goats and Dorper and Katahdin sheep with natural infection were generally greater than observed by Miller et al. (2006) with naturally infected F<sub>2</sub> progeny of Suffolk  $\times$  Gulf Coast Native crossbred lambs in a pasture research setting in Louisiana ( $r = -0.59$  and  $-0.43$  at weaning and after 5 weeks on summer pasture, respectively), with a wide range in infection level (i.e., FEC ranged from 0 to 149,933 EPG). The values were much greater than found with lambs and ewes of undefined breeds on organic and conventional farms in Canada ( $r = -0.26$ ), although the infection level was relatively low (i.e., FEC ranged from 0 to 26,180 EPG; Mederos et al., 2014). Differences in the nutritional plane could have contributed to the disparate findings of these two studies, but neither report included relevant information. Likewise, Moors and Gauly (2009) did not observe a significant relationship between PCV and FEC of female lambs of German sheep breeds with low FEC (geometric mean of FEC = 713 and 656 EPG for Black Head Mutton and Leine sheep, respectively) that consumed a mixed hay-concentrate diet with 10.8 MJ/kg ME and 18% CP.

In the current study, level of infection with internal parasites varied considerably among farms. This does not relate to age, as all animals began the adaptation period soon after the time of weaning. The strong correlations for Boer and Kiko goats and Dorper and Katahdin sheep indicate reasonable reliability of the both indicators (PCV and FEC) to detect level of internal parasitism, presumably primarily infection with *H. contortus*. It is unclear why PCV and FEC for Spanish goats and St. Croix sheep were not related in contrast to the other breeds of goats and sheep. This could involve physiological conditions that varied among animal types or other factors such as differences in management practices on the farms, particularly concerning nutritional plane. However,

**Table 5**  
Correlation coefficient (*r*) between PCV and lnFEC by day for goat and sheep breeds on different sampling days after artificial infection with *Haemonchus contortus*.<sup>a</sup>

Species	Breed	Item	Day					
			21	28	35	42	49	
Goat	Boer	n	46	45	45	16	16	
		<i>r</i>	-0.24	-0.19	-0.39	-0.66	-0.74	
		P value	0.109	0.214	0.008	0.006	0.001	
	Kiko	n	54	54	54	21	20	
		<i>r</i>	-0.24	-0.11	-0.33	-0.50	-0.40	
		P value	0.084	0.431	0.015	0.022	0.083	
	Spanish	n	50	49	50	19	19	
		<i>r</i>	0.18	-0.20	-0.27	-0.53	-0.18	
		P value	0.201	0.169	0.056	0.019	0.450	
	Sheep	Dorper	n	60	59	58	19	19
			<i>r</i>	-0.27	-0.16	-0.02	-0.04	-0.52
			P value	0.040	0.236	0.880	0.866	0.023
Katahdin		n	91	91	90	56	36	
		<i>r</i>	-0.13	-0.38	-0.45	-0.50	-0.42	
		P value	0.231	< 0.001	< 0.001	< 0.001	0.010	
St. Croix		n	49	49	49	20	20	
		<i>r</i>	-0.06	-0.15	-0.24	-0.57	-0.55	
		P value	0.703	0.291	0.096	0.009	0.012	

<sup>a</sup> PCV = packed cell volume; lnFEC = logarithmic transformed fecal egg count, ln(FEC + 100).

**Table 6**  
Correlation coefficient (*r*) between PCV and lnFEC after artificial infection with *Haemonchus contortus* for goat and sheep breeds in different years<sup>a,b</sup>.

Species	Breed	Item	Year		
			1	2	3
Goats	Boer	n	48	40	80
		<i>r</i>	-0.29	-0.24	-0.28
		P value	0.044	0.143	0.011
	Kiko	n	48	51	104
		<i>r</i>	-0.34	-0.23	-0.21
		P value	0.019	0.112	0.030
	Spanish	n	42	51	94
		<i>r</i>	-0.10	0.25	-0.16
		P value	0.527	0.081	0.122
Sheep	Dorper	n	60	59	96
		<i>r</i>	-0.47	-0.44	-0.35
		P value	< 0.001	< 0.001	< 0.001
	Katahdin	n	105	114	145
		<i>r</i>	-0.35	-0.71	-0.27
		P value	< 0.001	< 0.001	< 0.001
	St. Croix	n	39	48	100
		<i>r</i>	-0.33	-0.39	-0.28
		P value	0.042	0.007	0.006

<sup>a</sup> PCV = packed cell volume, lnFEC = logarithmic transformed fecal egg count; ln(FEC + 100).

<sup>b</sup> Goat and sheep breeds with 3 years observation were included.

with Boer and Spanish goats derived from one of the research sites in the study managed under generally similar conditions, the difference in the PCV-FEC relationship may involve unique breed properties.

**Table 7**  
Number of observations, correlation coefficient (*r*) between PCV and lnFEC, and P values for different animal groups for Boer goat and Katahdin sheep in year 1 after the artificial infection with *Haemonchus contortus*.<sup>a</sup>

Item	Goats <sup>b</sup>			Sheep <sup>b</sup>			
	Boer1	Boer2	Boer3	Katahdin1	Katahdin2	Katahdin3	Katahdin4
n	38	48	69	51	54	70	54
<i>r</i>	0.14	-0.29	-0.45	-0.16	-0.60	-0.58	-0.59
P value	0.406	0.044	< 0.001	0.272	< 0.001	< 0.001	< 0.001

<sup>a</sup> PCV = packed cell volume, lnFEC = logarithmic transformed fecal egg count; ln(FEC + 100).

<sup>b</sup> Goat and sheep groups are described in Table 1.

particular Spanish vs. Boer and Kiko. This indicates that the Spanish breed may have specific attribute of resistance and/or resilience to *H. contortus* infection. Conversely, a moderate to highly negative correlation was observed for sheep breeds in each year, even for St. Croix sheep, which differs from findings with natural infection.

#### 4.2. Species

The normal PCV of goats is lower (range 22–38%; mean 28%) than that of sheep (range; 27–45%, mean; 35%; Byers and Kramer, 2010) because erythrocytes of goats are smaller, which results in tighter packing upon centrifugation (Smith and Sherman, 2009). Mean PCV values in this study were within these ranges. Average FEC for goats with PCV above and below the low range value of 22% was  $1271 \pm 101.7$  and  $2392 \pm 213.2$  EPG for Boer,  $1135 \pm 104.6$  and  $1839 \pm 269.8$  EPG for Kiko, and  $1216 \pm 130.4$  and  $1622 \pm 231.8$  EPG for Spanish, respectively. Likewise, average FEC for sheep with PCV above and below the low range value of 27% was  $1303 \pm 89.5$  and  $2448 \pm 306.3$  EPG for Dorper,  $994 \pm 90.9$  and  $3076 \pm 321.5$  EPG for Katahdin, and  $843 \pm 91.6$  and  $2819 \pm 592.5$  EPG for St. Croix, respectively. The relatively small difference in FEC between the ‘above’ and ‘below’ low range PCV value for Spanish compared with Boer and Kiko is in accordance with results of the correlation analysis, as is also true for the substantial differences for each sheep breed. These findings indicate that PCV did not reflect FEC of Spanish goats as accurately as FEC of Boer and Kiko goats and sheep breeds. Similarly, in other studies eye color predicted haemonchosis in goats less accurately than in sheep due to natural infection (Vatta et al., 2001; Sotomaior et al., 2012). Hence, there may be potential benefit from development of a specific eye color system for goats that would more accurately reflect degree of anemia due to internal parasitism, although the conventional FAMACHA© system is still useful under field conditions and widely employed (Kaplan et al., 2004).

#### 4.3. Year, breed, and farm

This study was a part of a project addressing potential genetic improvement in resistance to internal parasitism. However, there were no clear trends of increasing PCV for any of breeds tested as year advanced. Similarly, there was not consistent change in the significance or strength of the relationship between PCV and FEC among these breeds of goats and sheep with genetic selection across the years.

Discrepancies in FEC or abomasal worm recovery and PCV response have been often reported in goats (Hoste and Chartier, 1998; Paolini et al., 2003; Scheuerle et al., 2010). Differences in PCV among breeds of goats but not sheep could relate to greater resistance to internal parasites of sheep (Hoste and Chartier, 1998) or factors such as variability in production practices on these particular farms influencing level of parasitism. The PCV of Boer goats and Katahdin sheep differed among farms, but the variation was less for Katahdin sheep than for Boer goats. Perhaps this relates to the generally greater resistance to internal parasitism of Katahdin sheep than Boer goats and, thus, less impact of parasitism among farm conditions on PCV. Relatedly, Courtney et al. (1985) reported that Florida Native lambs with lower PCV and higher FEC than Barbados lambs had fewer worms at necropsy. This implies that adult worms in the abomasum do not necessarily produce eggs at their maximum ability. For example, administration of tannins elicited a prompt reduction in FEC without effect on the worm population in the abomasum or PCV (Paolini et al., 2003). Moreover, in comparison of susceptible Suffolk and resistant Gulf Coast Native lambs, regardless of infection regimen, the reduction in PCV due to infection reflected the severity of the worm burden more accurately than did FEC, with a higher population of immature than mature worms (Shakya et al., 2011). Hence, the lack of a very strong and consistent relationship between FEC and the amount of blood being lost to *H. contortus* may contribute to lower than desired *r* between FEC and PCV.

Mechanisms involved in development of resistance to *H. contortus* in small ruminants have not been clearly elucidated. Although it has been extensively reported that improvements in the nutritional plane could enhance the immune response to internal parasitism, which is reflected in PCV, FEC, and worm burden, specific lengths of time (e.g., when and how long) for manifestation of effects are unclear (Coop and Holmes, 1996; Hoste et al., 2016). Likewise, detailed knowledge concerning how malnutrition can increase the severity of infection with internal parasites and how long effects continue is lacking. In this regard, a low nutritional plane for the Florida Native lambs in the study of Courtney et al. (1985) may have contributed to high FEC and low PCV. In the current study, it was not possible to acquire detailed information concerning the nutritional plane on the collaborating farms, which is common for on-farm research such as this. Nonetheless, based on animal appearance and information conveyed by producers, the nutritional plane was very low on the Boer1 farm and high on the Katahdin1 farm. The initial development of immunity in young animals might not be greatly affected by protein intake (Hoste et al., 2016) and animals were fed with the same high-quality diet during the test. But, it is still possible that carryover effects of differences in the prior on-farm nutritional plane on the subsequent immune response contributed to the lack of a close relationship between FEC and PCV for some farms.

Based on magnitudes of difference in the FEC  $\times$  breed coefficient, Katahdin2 animals incurred a reduction in PCV as FEC increased three times greater than that of animals from the Katahdin3 farm. The coefficients indicate that the decline in PCV as FEC increased was 30% greater for sheep than for goats, which could be partially attributable to greater PCV in sheep vs. goats as noted earlier.

#### 5. Conclusions

There were considerable differences in the PCV response to GIN infections and the relationship between PCV and FEC across and within breeds of growing meat goat and hair sheep males. Correlations indicate stronger relationships for natural infection with GIN than artificial infection with *H. contortus*. The PCV of goats, especially the Spanish breed, was not highly reflective of FEC with either natural or artificial infection. Sheep breeds incurred greater reduction in PCV than goat breeds as FEC increased. Results of the current study suggest that PCV may not always accurately reflect FEC and, therefore, PCV could lead to misdiagnosis of haemonchosis, especially in goats.

#### Conflicts of interests

The authors declare no conflicts of interest.

#### Ethical statement

The experimental protocol was approved by the Langston University Animal Care Committee.

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#### References

- Besier, R.B., Kahn, L.P., Sargison, N.D., Van Wyk, J.A., 2016. The pathophysiology, ecology and epidemiology of *Haemonchus contortus* infection in small ruminants. *Adv. Parasitol.* 93, 95–143.
- Burke, J.M., Kaplan, R.M., Miller, J.E., Terrill, T.H., Getz, W.R., Mobini, S., Valencia, E., Williams, M.J., Williamson, L.H., Vatta, A.F., 2007. Accuracy of the FAMACHA system for on-farm use by sheep and goat producers in the southeastern United States. *Vet. Parasitol.* 147, 89–95. <https://doi.org/10.1016/j.vetpar.2007.03.033>.
- Byers, S.R., Kramer, J.W., 2010. Normal hematology of sheep and goats. In: Weiss, D.J.,

- Wardrop, K.J. (Eds.), Schalm's Veterinary Hematology, 6th edn. Blackwell Publishing Ltd., Ames, IA, USA, pp. 836–842.
- Coop, R.L., Holmes, P.H., 1996. Nutrition and parasite interaction. *Int. J. Parasitol.* 26, 951–962. [https://doi.org/10.1016/S0020-7519\(96\)80070-1](https://doi.org/10.1016/S0020-7519(96)80070-1).
- Courtney, C.H., Parker, C.F., McClure, K.E., Herd, R.P., 1985. Resistance of exotic and domestic lambs to experimental infection with *Haemonchus contortus*. *Int. J. Parasitol.* 15, 101–109. [https://doi.org/10.1016/0020-7519\(85\)90107-9](https://doi.org/10.1016/0020-7519(85)90107-9).
- Hoste, H., Chartier, C., 1998. Response to challenge infection with *Haemonchus contortus* and *Trichostrongylus colubriformis* in dairy goats. Consequences on milk production. *Vet. Parasitol.* 74, 43–54. [https://doi.org/10.1016/S0304-4017\(97\)00130-1](https://doi.org/10.1016/S0304-4017(97)00130-1).
- Hoste, H., Torres-Acosta, J.F.J., Quijada, J., Chan-Perez, L., Dakheel, M.M., Kommuru, D.S., Mueller-Harvey, I., Terrill, T.H., 2016. Interactions between nutrition and infections with *Haemonchus contortus* and related gastrointestinal nematodes in small ruminants. *Adv. Parasitol.* 93, 239–351. <https://doi.org/10.1016/bs.apar.2016.02.025>.
- Hu, W., Gipson, T.A., Hart, S.P., Dawson, L.J., Sahl, T., Goetsch, A.L., 2012. Optimum duration of performance testing for growth, feed intake, and feed efficiency in growing Boer bucks. *Small Rumin. Res.* 104, 114–121. <https://doi.org/10.1016/j.smallrumres.2011.09.047>.
- Kaplan, R.M., Burke, J.M., Terrill, T.H., Miller, J.E., Getz, W.R., Mobini, S., Valencia, E., Williams, M.J., Williamson, L.H., Larsen, M., Vatta, A.F., 2004. Validation of the FAMACHA® eye color chart for detecting clinical anemia in sheep and goats on farms in the southern United States. *Vet. Parasitol.* 123, 105–120. <https://doi.org/10.1016/j.vetpar.2004.06.005>.
- Le Jambre, L.F., 1995. Relationship of blood loss to worm numbers biomass and egg production in *Haemonchus* infected sheep. *Int. J. Parasitol.* 25, 269–273. [https://doi.org/10.1016/0020-7519\(94\)00118-8](https://doi.org/10.1016/0020-7519(94)00118-8).
- Mederos, A., Kelton, D., Peregrine, A.S., VanLeeuwen, J., Fernández, S., LeBoeuf, A., Menzies, P., Martin, R., 2014. Evaluation of the utility of subjective clinical parameters for estimating fecal egg counts and packed cell volume in Canadian sheep flocks. *Vet. Parasitol.* 205, 568–574. <https://doi.org/10.1016/j.vetpar.2014.08.030>.
- Mengistu, U.L., Puchala, R., Sahl, T., Gipson, T.A., Dawson, L.J., Goetsch, A.L., 2017. Conditions to evaluate differences among individual sheep and goats in resilience to high heat load index. *Small Rumin. Res.* 147, 89–95. <https://doi.org/10.1016/j.smallrumres.2016.12.039>.
- Miller, J.E., Bishop, S.C., Cockett, N.E., McGraw, R.A., 2006. Segregation of natural and experimental gastrointestinal nematode infection in F2 progeny of susceptible Suffolk and resistant Gulf Coast native sheep and its usefulness in assessment of genetic variation. *Vet. Parasitol.* 140, 83–89. <https://doi.org/10.1016/j.vetpar.2006.02.043>.
- Moors, E., Gauly, M., 2009. Is the FAMACHA® chart suitable for every breed? Correlations between FAMACHA® scores and different traits of mucosa color in naturally parasite infected sheep breeds. *Vet. Parasitol.* 166, 108–111. <https://doi.org/10.1016/j.vetpar.2009.07.040>.
- Ngere, L., Burke, J.M., Morgan, J.L.M., Miller, J.E., Notter, D.R., 2018. Genetic parameters for fecal egg counts and their relationship with body weights in Katahdin lambs. *J. Anim. Sci.* 96, 1590–1599. <https://doi.org/10.1093/jas/sky064>.
- Notter, D.R., Andrew, S.A., Zajac, A.M., 2003. Response of hair and wool sheep to a single fixed dose of infective larvae of *Haemonchus contortus*. *Small Rumin. Res.* 47, 221–225. [https://doi.org/10.1016/S0921-4488\(02\)00279-1](https://doi.org/10.1016/S0921-4488(02)00279-1).
- NRC, 2000. Nutrient Requirements of Beef Cattle (Update 2000). National Academy Press, Washington, DC, USA.
- Paolini, V., Bergeaud, J.P., Grisez, C., Prevot, F., Dorchie, Ph., Hoste, H., 2003. Effects of condensed tannins on goats experimentally infected with *Haemonchus contortus*. *Vet. Parasitol.* 113, 253–261. [https://doi.org/10.1016/S0304-4017\(03\)00064-5](https://doi.org/10.1016/S0304-4017(03)00064-5).
- Preston, R.L., 2015. 2015 feed composition table. 51(7). Beef Magazine, Penton, New York, NY, USA, pp. 14–29.
- SAS (Ed.), 2013. Base SAS® 9.4 Procedures Guide: Statistical Procedures, 2nd ed. SAS Institute Inc., Cary, NC, USA.
- SAS, 2013b. Introduction to Mixed Modeling Procedures. In: SAS/STAT® 13.1 User's Guide. SAS Institute Inc., Cary, NC, USA, pp. 115–128.
- Scheuerle, M., Mahling, M., Muntwyler, J., Pfister, K., 2010. The accuracy of the FAMACHA®-method in detection anaemia and haemonchosis in goat flocks in Switzerland under field conditions. *Vet. Parasitol.* 170, 71–77. <https://doi.org/10.1016/j.vetpar.2010.01.035>.
- Shakya, K.P., Miller, J.E., Lomax, L.G., Burnett, D.D., 2011. Evaluation of immune response to artificial infections of *Haemonchus contortus* in Gulf Coast native compared with Suffolk lambs. *Vet. Parasitol.* 181, 239–247. <https://doi.org/10.1016/j.vetpar.2011.03.051>.
- Smith, M., Sherman, D., 2009. Goat Medicine, 2nd edn. Blackwell Publishing Ltd., Ames, IA, USA.
- Sotomaior, C.S., Rosalinski-Moraes, F., da Costa, A.R.B., Maia, D., Monteiro, A.L.G., van Wyk, J.A., 2012. Sensitivity and specificity of the FAMACHA® system in Suffolk sheep and crossbred Boer goats. *Vet. Parasitol.* 190, 114–119. <https://doi.org/10.1016/j.vetpar.2012.06.006>.
- Stafford, K.J., West, D.M., Pomroy, W.E., 1994. Nematode worm egg output by ewes. *NZ Vet. J.* 42, 30–42. <https://doi.org/10.1080/00480169.1994.35778>.
- Tsukahara, Y., Gipson, T.A., Hart, S.P., Dawson, L.J., Wang, Z., Puchala, R., Sahl, T., Goetsch, A.L., 2015a. Effects of breed and resistance classification of sire on progeny growth performance and response to artificial infection with *Haemonchus contortus* in a central performance test. *J. Anim. Sci.* 93, 493–494 Suppl.s3.
- Tsukahara, Y., Gipson, T.A., Hart, S.P., Dawson, L.J., Wang, Z., Puchala, R., Sahl, T., Goetsch, A.L., 2015b. Growth performance and resistance to internal parasitism of small ruminant males from the south-central US in a centralized test. *J. Anim. Sci.* 95 (Suppl. 4), 494.
- Tsukahara, Y., Gipson, T.A., Hart, S.P., Dawson, L.J., Wang, Z., Puchala, R., Sahl, T., Goetsch, A.L., 2016. Species and breed differences of small ruminant in response to experimental infection with *Haemonchus contortus* and growth performance in a centralized performance test. *J. Anim. Sci.* 94 (E-Suppl. 5), 817–818. <https://doi.org/10.2527/jam2016-1706>.
- Vatta, A.F., Letty, B.A., van der Linde, M.J., van Wijk, E.F., Hansen, J.W., Krecek, R.C., 2001. Testing for clinical anaemia caused by *Haemonchus* spp. in goats farmed under resource-poor conditions in South Africa using an eye color chart developed for sheep. *Vet. Parasitol.* 99, 1–14. [https://doi.org/10.1016/S0304-4017\(01\)00446-0](https://doi.org/10.1016/S0304-4017(01)00446-0).
- Zajac, A.M., Conboy, G.A., 2006. Fecal examination for the diagnosis of parasitism. In: Zajac, Z.M., Conboy, G.A. (Eds.), *Veterinary Clinical Parasitology*, 7th edn. Blackwell Publishing Ltd., Ames, IA, USA, pp. 3–148.
- Zajac, A.M., Krakowka, S., Herd, R.P., McClure, K.E., 1990. Experimental *Haemonchus contortus* infection in three breeds of sheep. *Vet. Parasitol.* 36, 221–235. [https://doi.org/10.1016/0304-4017\(90\)90034-9](https://doi.org/10.1016/0304-4017(90)90034-9).