Is visceral organ size related to feed efficiency in tropical hair sheep?

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ABSTRACT
The residual feed intake (RFI) and residual intake and gain (RIG) are indices that measure ruminant feed efficiency. Their application has become alternatives to improve the profitability of intensive lamb production systems. This study aimed to evaluate the accuracy of RFI and RIG to measure the non-carcase organ size and cavitary fat of lambs. Thirty non-castrated male lambs were fed for 92 days and slaughtered, and non-carcase organs were weighed. RFI and RIG were classified in low, medium and high efficiency groups, and correlated to carcase and non-carcase organ size. The average RFI values were 0.07, 0.00, and 0.07 kg DM/d and the RIG values were 1.86, 0.20, and 1.91, for high, medium and low, respectively. Low-RFI lambs had lower \( p < .05 \) dry matter intake (DMI) and percentage of DMI standardised by metabolic weight. High-RIG lambs had a higher feed conversion ratio \( p < .05 \) and tended \( p < .10 \) towards higher average dairy gain. The efficient lambs (low-RFI and high-RIG) had higher heart weight \( p < .05 \). Trends \( p < .10 \) towards higher blood volume and lower relative weight in omental and total cavitary fat deposits were found in lambs with low RFI. Lambs classified as low-RFI and high-RIG had larger hearts, which could be related to improved cardiovascular performance and feed efficiency.

HIGHLIGHTS
- Heart size is related to feed efficiency.
- Lambs with improved feed efficiency have larger hearts.
- High-RIG lambs have higher intestinal mass.

Introduction
The residual feed intake (RFI) and residual intake and gain (RIG) are two indices to measure the feed efficiency of livestock. They have become popular in recent decades because they are independent of body size and productivity (Koch et al. 1963; Berry and Crowley 2012). Both indices have become alternative measures applied to improve the profitability of intensive sheep meat production systems, where feed represents more than 70% of total production costs (Lima et al. 2017).

The RFI, proposed by Koch et al. (1963), is estimated by the difference between the actual feed intake and the expected feed intake for a given live weight and productive level during a period of time, and its objective is to identify the most efficient individuals in the use of feed, to enable selective breeding for genetic improvement (Arthur and Herd 2008). In turn, RIG aims to identify individuals with higher growth rates, to allow reducing confinement and slaughter times because commercial weights are reached at younger ages, in addition to having the advantage of improving feeding efficiency (Berry and Crowley 2012; Carneiro et al. 2019).

Among the biological mechanisms that contribute to the variation in feeding efficiency, non-carcase components have been reported to contribute 5% (Richardson and Herd 2004). The variation in the size and functionality of the liver and organs of the gastrointestinal tract is associated with a high metabolic cost, affecting the energy requirements of basal
metabolism (Kenny et al. 2018). In addition, there is a relationship between feed intake and energy used to digest it, whereby higher intake is associated with greater the energy expenditure, due to an increase in the size of the digestive organs and the energy expended within the tissues of these organs (Herd and Arthur 2009). In this regard, it has been reported that greater feed efficiency of lambs is related to lower dry matter intake (DMI), higher feed conversion ratio (FCR) and smaller size of organs other than the carcase. For example, Zhang et al. (2017) reported that low-RFI lambs had a difference of 240 g/d of DMI compared to inefficient ones, smaller size of liver, lungs, kidneys and total stomach weight, and greater length of the duodenum and ileum. In turn, Carneiro et al. (2019) reported that high-RIG lambs had higher average daily gain (ADG, 0.31 versus 0.26 kg/d), improved FCR (3.91 versus 4.99 kg), larger size of skin and hooves, and smaller size of testicles and cavitary fat deposits (omental, mesenteric and total fat). Montelli et al. (2021) reported smaller size of lungs and diaphragm in high-RFI lambs.

High feed efficiency of animals is very important to increase the profitability of production systems and reduce the environmental impacts of livestock breeding, since animals with low-RFI have lower DMI and produce less enteric methane per unit of dry matter consumed (Nkrumah et al. 2006; Fitzsimons et al. 2013).

In Mexico, sheep production is one of the largest livestock activities, with an inventory of 8,708,246 head according to the most recent census (SIAP 2020), and Pelibuey is the most numerous tropical breed because of its maternal ability, high prolificacy, rusticity, resistance to parasites and good adaptation to tropical climates in Mexico (Chay-Canul et al. 2016).

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### Methodology

The lambs included in this study were managed according to the guidelines for the use and care of animals destined for research in the tropics, and this study was approved by the Committee on the Use and Care of Animals of Colegio de Postgraduados, Mexico (SUBINVTAB.CP. -105/18).

#### Location, management and diet

The study was carried out at the Centro Integral de Ovinos del Sureste (CIOS), located in Villahermosa, Tabasco, Mexico (17°78’N, 92°96’W; 10 m altitude); with humid tropical climate. Thirty non-castrated male Pelibuey lambs with age of 123 ± 36 d and initial body weight (BWi) of 21 ± 5 kg were used. Lambs were housed in individual pens (2 x 2 m). The fattening period lasted 92 days after previous adaptation of 15 days. The diet provided contained 80% concentrated feed and 20% hay on a dry basis (Table 1). Fresh water was always available. The lambs were fed ad libitum at two times (08:00 and 15:00 h), and the feed was offered in excess to obtain a minimum feed rejected daily of 10%. The diet was formulated based on the energy (11 MJ/kg DM) and protein (85 g/d) requirements for a lamb weighing 20 kg with an ADG of 250 g, according to the AFRC (1993).

### Lamb performance

The individual DMI was calculated daily by the difference between the feed offered and rejected on a dry...
basis. Body weight (BW) was recorded weekly, initial BW (BW1) was determined after the adaptation period, and final BW (BWf) was recorded 92 days after measuring feed efficiency. The mean body weight (MBW) was calculated as the difference between BW and ADG. The BW was modelled over time by linear regression to determine ADG using the REG procedure (SAS 2012). FCR was calculated as the ratio between DMI and ADG.

**Feed efficiency**

The residual feed intake (RFI) and residual gain (RG) indices were modelled by multiple linear regression using the REG procedure (SAS 2012). The independent variables were ADG, DMI, and BW0.75 (Koch et al. 1963), resulting in following equations:

\[
\text{RFI} = -0.39(\pm 0.13) + 2.03(\pm 0.31) \times \text{ADG} \\
\times 0.08(\pm 0.01) \times \text{BW}^{0.75}(r^2 = 0.82) \\
\text{RG} = 0.19(\pm 0.04) + 0.29(\pm 0.05) \\
\times \text{DMI} - 0.02(\pm 0.005) \times \text{BW}^{0.75}(r^2 = 0.61)
\]

Subsequently, the equation RFI was used to determine the expected DMI (DMIe) and the equation RG for expected ADG (ADGe). The residuals of the RFI index were calculated as the difference between the DMI and DMIe. Likewise, the residuals of the RG index were calculated as the difference between ADG and ADGe. Residual intake and gain (RIG) was calculated using the formula RIG = ADGe - ADG. Residual intake and gain (RIG) were calculated as the difference between ADG and DMI. Likewise, the residuals of the RG index were calculated as the difference between expected DMI (DMIe) and equation RG. The residuals of the RFI and RG indices were standardised (mean 0 and standard error 1) using the STANDARD routine (SAS 2012). Lambs were classified as low-RFI (efficient), 30% of lambs had negative RFI values and were grouped in the low-RFI class (inefficient); and the remaining 70% of lambs had positive RFI values and were classified as low-RFI (efficient); 30% of lambs had a positive value and were classified as high-RFI and RG indices, as described by Berry and Crowley (2012). Previously, the residuals of the RFI and RG indices were standardised (mean = 0 and standard error = 1) using the STANDARD routine (SAS 2012). Lambs were classified as low-RFI and low-RIG (<0.5 SE below mean), medium-RFI and medium-RIG (±0.5 SE from mean), and high-RFI and high-RIG (>0.5 SE above mean).

**Weights of visceral organs, gastrointestinal tract, fat deposits and non-carcass components**

Lambs were slaughtered according to the Mexican Standard NOM-033-SAG/ZOO-2014 after fasting for 18 h, and the slaughter weight (SBW) recorded. After slaughter, the blood was collected in plastic bags and the weight recorded. The weights of the visceral organs (spleen, heart, liver, lungs and trachea, pancreas, kidneys), gastrointestinal tract (empty stomach and intestines), cavitary fat deposits (total, mesenteric, omental and perirenal fat) and non-carcass external components (head, hooves, skin, and testicles) were immediately recorded. Empty body weight (EBW) was calculated by the difference between the SBW and the content of the gastrointestinal tract. The proportional weight of each organ, fat deposits and non-carcass external components was calculated in relation to EBW.

**Statistical analysis**

A completely randomised design was used, where each lamb was an experimental unit. For the statistical analysis, the GLM procedure (SAS 2012) was used. Least mean squares were calculated and compared using the Tukey test at significance of p < .05.

**Results**

In this study, 30% of the lambs presented negative RFI values and were classified as low-RFI (efficient); 30% of lambs had positive RFI values and were grouped in the high-RFI class (inefficient); and the remaining 40% were classified as medium-RFI (Table 2). In the RIG index, 40% of the lambs had a positive value and were classified as high-RIG (efficient), 37% had negative RIG and were grouped in the low-RIG class (inefficient), and the remaining 23% were medium-RIG

| Table 2. Least square means and standard errors of the mean (SEM) for empty body weight (EBW) and feed efficiency traits of Pelibuey lambs classified using residual feed intake (RFI) and residual intake and gain (RIG). |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                             | Residual feed intake        |                             | Residual intake and gain     |                             |
|                             | Low            | Medium     | High         | p-value | Low          | Medium     | High         | p-value | SEM |
| EBW (kg)                    | 36.58a         | 36.30b     | 35.21c       | .753    | 35.07a       | 35.36b     | 37.38c       | .347    | .729          |
| DMI (kg DM/d)               | 1.15           | 1.24       | 1.26         | .340    | 1.24         | 1.21       | 1.22         | .930    | .031          |
| DMI (g/Kg/d of BW0.75)      | 83.90ab        | 91.27a     | 94.23b       | .006    | 91.43        | 90.04      | 88.31        | .618    | 1.735         |
| DMI (% of BW0.75)           | 8.39b          | 9.13a      | 9.42c        | .006    | 9.1418       | 9.0429     | 8.83         | .616    | 1.137         |
| ADG (kg)                    | 0.230          | 0.239      | 0.226        | .759    | 0.213        | 0.231      | 0.252        | .668    | 0.007         |
| FCR (kg of DMI/kg of ADG)   | 4.993          | 5.424      | 5.569        | .352    | 5.904a       | 5.27ab     | 4.86b        | .010    | 0.159         |
| RFI (kg DM/d)               | -0.075c        | 0.002b     | 0.071a       | <.001   | 0.059a       | 0.006b     | -0.058c      | <.001   | 0.012         |
| RG (kg BW/d)                | 0.021a         | 0.001b     | -0.023c      | <.001   | -0.025c      | -0.002a    | 0.024a       | <.001   | 0.004         |
| RIG                         | 1.990a         | 0.028b     | -2.028c      | <.001   | -1.910c      | 0.200b     | 1.688a       | <.001   | 0.344         |

DMI: dry matter intake; ADG: average daily gain; FCR: feed conversion ratio; RG: residual gain; BW: Body weight. **abc**Different letters indicate significant differences (p < .05, Tukey test).
Table 3. Least square means and standard errors of the mean (SEM) for carcase and visceral organ size in Pelibuey lambs classified using residual feed intake (RFI) and residual intake and gain (RIG).

| Organs          | Weight   | Residual feed intake | Residual intake and gain | p-value | SEM   |
|-----------------|----------|----------------------|--------------------------|---------|-------|
| Carcase         |          | Low      | Medium | High   |        |        |
| Absolute, kg    | 20.69    | 20.58    | 19.96  | .715    | 19.93  | 20.11  | 21.07  | .372    | 0.368  |
| Relative, %     | 56.60    | 56.78    | 56.90  | .948    | 57.02  | 56.90  | 56.45  | .768    | 0.350  |
| Heart           |          | Low      | Medium | High   |        |        |
| Absolute, kg    | 0.18\(^a\) | 0.16\(^b\) | 0.15\(^b\) | .037    | 0.15\(^b\) | 0.16\(^b\) | 0.18\(^a\) | .016    | 0.004  |
| Relative, %     | \(0.49^a\) | \(0.44^b\) | \(0.43^b\) | .007    | \(0.43^b\) | 0.44\(^b\) | 0.48\(^a\) | .050    | 0.008  |
| Blood           |          | Low      | Medium | High   |        |        |
| Absolute, kg    | 1.66     | 1.45     | 1.40   | .096    | 1.41   | 1.48   | 1.58   | .319    | 0.057  |
| Relative, %     | 4.53     | 4.02     | 3.97   | .084    | 4.02   | 4.18   | 4.27   | .651    | 0.112  |
| Spleen          |          | Low      | Medium | High   |        |        |
| Absolute, kg    | 0.07     | 0.07     | 0.07   | .555    | 0.07   | 0.08   | 0.07   | .568    | 0.002  |
| Relative, %     | 0.20     | 0.21     | 0.20   | .725    | 0.21   | 0.22   | 0.19   | .227    | 0.006  |
| Liver           |          | Low      | Medium | High   |        |        |
| Absolute, kg    | 0.69     | 0.73     | 0.67   | .265    | 0.68   | 0.71   | 0.72   | .475    | 0.015  |
| Relative, %     | 1.90     | 2.03     | 1.92   | .112    | 1.95   | 2.02   | 1.93   | .461    | 0.028  |
| Lungs and trachea|          | Low     | Medium | High   |        |        |
| Absolute, kg    | 0.70     | 0.68     | 0.62   | .393    | 0.64   | 0.64   | 0.72   | .290    | 0.025  |
| Relative, %     | 1.91     | 1.88     | 1.77   | .599    | 1.83   | 1.80   | 1.91   | .738    | 0.057  |
| Kidneys         |          | Low      | Medium | High   |        |        |
| Absolute, kg    | 0.11     | 0.12     | 0.11   | .219    | 0.11   | 0.12   | 0.12   | .643    | 0.002  |
| Relative, %     | 0.31     | 0.34     | 0.33   | .439    | 0.33   | 0.34   | 0.32   | .444    | 0.007  |
| Stomach         |          | Low      | Medium | High   |        |        |
| Absolute, kg    | 1.00     | 1.01     | 0.98   | .791    | 0.98   | 0.97   | 1.04   | .416    | 0.022  |
| Relative, %     | 2.75     | 2.90     | 2.80   | .915    | 2.82   | 2.75   | 2.78   | .900    | 0.055  |
| Intestine       |          | Low      | Medium | High   |        |        |
| Absolute, kg    | 1.13     | 0.96     | 0.98   | .163    | 0.95\(^b\) | 0.90\(^b\) | 1.14\(^a\) | .026    | 0.039  |
| Relative, %     | 3.08     | 2.64     | 2.79   | .153    | 2.72   | 2.58   | 3.05   | .118    | 0.094  |

\(^{a,b}\)Different letters indicate significant differences \(p < .05\), Tukey test.

(Table 2). Low-RFI lambs had lower DMI and DMI percentage expressed in g/kg of BW\(^{0.75}\) compared to high-RFI animals (Table 2), while high-RIG lambs had improved FCR \(p < .05\) compared to low-RIG lambs. The EBW was not significant \(p > .05\) for both feed efficiency indices (RFI and RIG, Table 2).

The carcase yield was not significant \(p > .05\) for both feed efficiency indices (RFI and RIG, Table 3), but it had a significant effect on absolute \(p \leq .05\) and relative \(p \leq .01\) and \(p \leq .05\), respectively) heart weights. The efficient lambs (low-RFI and high-RIG) had heavier hearts than the inefficient lambs (high-RFI and low-RIG), without differences with the intermediate groups (except for relative weight in the RFI index, Table 3). Low-RFI and high-RIG lambs had hearts with greater relative weight (0.05 and 0.06%, respectively) compared to high-RFI and low-RIG lambs. The RIG index had a significant effect \(p \leq .05\) on absolute intestine weight. Lambs with high RIG had 240 g heavier intestine weight than those with medium RIG, and non-significant differences of 190 g higher in the absolute weight of intestines in high-RIG lambs compared to low-RIG animals were found (Table 3). Except for the heart and intestines, no significant differences \(p > .05\) were found in the weights of the other visceral organs evaluated by both feed efficiency indices (Table 3). However, trends \(p < .1\) to higher weight (absolute and relative) of blood were observed in lambs with low RFI compared to lambs with high RFI (Table 3).

The amounts of total, omental, perirenal and mesenteric cavity fat were not related to either feed efficiency index (Table 4). However, trends \(p < .1\) to lower relative weight of total and omental cavity fat deposits were observed in lambs with low RFI compared to lambs with high RFI (Table 4).

Significant differences \(p < .05\) were observed in absolute hooves weight for the RIG index (Table 5). Lambs classified with high-RIG had larger hooves weights than low-RIG lambs, and no difference was observed with medium-RIG lambs (Table 5). The weight of head, skin, and testicles did not differ \(p > .05\) according to both feed efficiency indices (Table 5).

Discussion

As expected, the EBW and the size of the carcase did not differ when using both indices. This is explained because the residual feed intake (RFI) and residual intake and gain (RIG) are estimated independently of body size (Koch et al. 1963; Berry and Crowley 2012). In this study, the low-RFI lambs had lower DMI, with a difference of 10.33 g/kg of BW\(^{0.75}\) compared to high-RFI lambs, without affecting the growth rate. This agrees with the results of other hair breed lambs (Lima et al., 2017; Montelli et al., 2019). High-RIG lambs had improved FCR, with a difference of 1.04 kg, and similar DMI in comparison with low-RIG lambs, which also agrees with the results for other hair breed lambs (Lima et al., 2017; Carneiro et al., 2019; Montelli et al., 2019). Efficient animals may have lower energy requirements for maintenance (Castro-Bulle et al. 2007; Gomes et al. 2012), which allows more ingested nutrients to be distributed towards growth (Redden et al. 2013). The results reported by Montelli et al.
(2021) showed that efficient lambs (low-RFI and high-RIG) have higher concentrations of the IGF-1 hormone compared to inefficient lambs (99.5 versus 79.7 for RFI, and 88.8 versus 73.9 for RIG). Therefore, efficient lambs have increasing muscle mass, since this hormone is involved in the regulation of metabolism and growth (Rechler and Nissley 1991). In this sense, efficient lambs (low-RFI and high-RIG) have more efficient metabolism, since they require less feed.

On the other hand, the size of the visceral organs and gastrointestinal tract has a high metabolic cost, so it is likely that the variation between animals in the size and functionality of these organs can impact the energy requirements (Fitzsimons et al. 2017). Although the gastrointestinal tract and liver account for a small proportion of body weight (6–13%), they utilise 38–50% of the maintenance energy required to absorb and metabolise digested nutrients (Burrin et al. 1990; Seal and Reynolds 1993). It has been reported that efficient beef cattle have smaller organs, such as liver (Basarab et al. 2003; Bonilha et al. 2009, Nascimento et al. 2016), gastrointestinal tract (Basarab et al. 2003; Bonilha et al. 2009) and empty reticulum-rumen (Fitzsimons et al. 2014). Additionally, efficient individuals have lower DMI, so there is a relationship between feed intake and the energy used to digest it (the higher the intake, the greater the energy expenditure), due to an increase in size of the digestive organs and the energy expended within the tissues of these organs (Herd and Arthur 2009).

In this study, we did not observe differences in liver and stomach weight between efficient and inefficient lambs. Differences in the absolute weight of intestines between medium-RIG and high-RIG lambs were found. Although the low-RIG group presented an absolute weight similar to that of efficient lambs, numerical differences were appreciated. These differences numerical and statistical were 190 and 240 g greater in efficient lambs, respectively, which suggests that greater gut mass improves nutrient absorption in high-RIG lambs, resulting in higher feed efficiency (Zhang et al. 2017, Fitzsimons et al. 2017). Zhang et al. (2017) reported that low-RFI lambs had greater duodenum and ileum length than high-RFI lambs. Montanholi et al. (2013) reported that bulls with low RFI had a greater number of cell nuclei in the duodenum and ileum compared to high-RFI animals, indicating that efficient bulls have a more metabolically active small intestine, a trait that improves absorption of nutrients and energy efficiency.

Regarding the size of visceral organs, our results showed that lambs with low RFI and high RIG had larger hearts, which could be due to greater cardiovascular efficiency and improved feed efficiency. The data reported by Munro et al. (2015) indicated greater relative weight of the right ventricle (22.0 versus 21.3%, \( p = 0.04 \)) and of the total ventricular weight (86.6 versus 85.9%, \( p = 0.05 \)) in relation to the whole heart weight, in cattle with low RFI. In addition, a positive correlation (0.29, \( p = 0.005 \)) of thickness of the right ventricle

### Table 4. Least square means and standard errors of the mean (SEM) for visceral fat deposit weight in Pelibuey lambs classified using residual feed intake (RFI) and residual intake and gain (RIG).

| Fat deposit       | Weight | Residual feed intake | Residual intake and gain |
|-------------------|--------|----------------------|--------------------------|
|                   | Low    | Medium | High  | \( p \)-value | Low    | Medium | High  | \( p \)-value | SEM  |
| Total fat         |        |        |       |             |        |        |       |             |      |
| Absolute, kg      | 2.71   | 3.32   | 3.10  | .264        | 3.10   | 3.15   | 3.00  | .930        | .154 |
| Relative, %       |        |        |       |             | 8.73   | 8.86   | 7.94  | .441        | .317 |
| Omental           |        |        |       |             |        |        |       |             |      |
| Absolute, kg      | 1.26   | 1.56   | 1.43  | .250        | 1.47   | 1.43   | 1.40  | .928        | .075 |
| Relative, %       |        | 4.26   | 4.02  | .096        | 4.14   | 4.03   | 3.70  | .480        | .160 |
| Perirenal         |        |        |       |             |        |        |       |             |      |
| Absolute, kg      | 0.74   | 0.93   | 0.93  | .328        | 0.89   | 0.93   | 0.82  | .725        | .057 |
| Relative, %       |        |        | 2.04  | .200        | 2.52   | 2.61   | 2.17  | .374        | .135 |
| Mesenteric        |        |        |       |             |        |        |       |             |      |
| Absolute, kg      | 0.71   | 0.83   | 0.73  | .314        | 0.73   | 0.79   | 0.78  | .802        | .037 |
| Relative, %       |        | 1.94   | 2.18  | .128        | 2.07   | 2.22   | 2.07  | .666        | .071 |

### Table 5. Least square means and standard errors of the mean (SEM) for non-carcase external component size in Pelibuey lambs classified using residual feed intake (RFI) and residual intake and gain (RIG).

| Organs          | Weight | Residual feed intake | Residual intake and gain |
|-----------------|--------|----------------------|--------------------------|
|                 | Low    | Medium | High | \( p \)-value | Low    | Medium | High | \( p \)-value | SEM  |
| Hooves          | Absolute, kg | 1.03 | 0.95 | 0.96 | .214 | 0.93b  | 0.94ab  | 1.04*  | .045  | .021 |
| Relative, %     |        | 2.83   | 2.62 | 2.74 | .180 | 2.66   | 2.69   | 2.79  | .460  | .047 |
| Skin            | Absolute, kg | 3.82 | 3.61 | 3.64 | .736 | 3.54   | 3.54   | 3.88  | .340  | .112 |
| Relative, %     |        | 10.50  | 9.90 | 10.26 | .384 | 10.03  | 9.99   | 10.39 | .544  | .160 |
| Head            | Absolute, kg | 2.25 | 2.12 | 2.04 | .497 | 2.03   | 2.04   | 2.28  | .211  | .068 |
| Relative, %     |        | 6.14   | 5.82 | 5.73 | .341 | 5.73   | 5.76   | 6.11  | .316  | .115 |
| Testicles       | Absolute, kg | 0.51 | 0.53 | 0.53 | .907 | 0.54   | 0.51   | 0.52  | .840  | .017 |
| Relative, %     |        | 1.40   | 1.46 | 1.50 | .548 | 1.52   | 1.44   | 1.40  | .361  | .034 |

*Different letters indicate significant differences (\( p < .05 \), Tukey test).
with the RFI index was reported, indicating that cattle with high RFI have increased cardiovascular rate by spending less time resting, increasing DM intake with higher digestibility. The increased cardiovascular flow raises the heart rate and blood volume, and it is assumed that the pressure of the right atrium also increases, which can result in hypertrophy of the right ventricle. Therefore, cattle with high RFI have a higher workload of the right ventricle of the heart, and the selection of cattle with low RFI does not have a negative impact on cardiovascular structure and function (Munro et al. 2019). In this sense, a heavier heart and improved cardiovascular rate could explain why lambs with low RFI tend to have greater blood weight.

The difference in heart size found in this study differs from that reported in temperate and tropical sheep breeds, since no difference was reported in the heart weight among the classes using the RFI (Meyer et al. 2015; Zhang et al. 2017; Montelli et al. 2021), and RIG (Carneiro et al. 2019; Montelli et al. 2021). Likewise, it differs from that reported in cattle classified by RFI index (Basarab et al. 2003; Gomes et al. 2012; Fitzsimons et al. 2014; Nascimento et al. 2016) and RIG index (Nascimento et al. 2016).

On the other hand, Herd and Arthur (2009) reported a difference in the efficiency of the deposition of lean tissue (40–50%) and cavitary fat (70–95%), and this variation in muscle was due to protein turnover. Lambs with low RFI tend to deposit less cavitary fat (total and omental fat) compared to lambs with high RFI. These results can be explained because lambs with low RFI have lower feed intake (146 g DM/d less compared to high-RFI), and therefore lower energy intake. In this regard, Carneiro et al. (2019) reported that the lambs with high-RIG level had lower relative weight of total cavitary fat (4.95 versus 5.91%), omental fat (1.89 versus 2.30%) and mesenteric fat (1.20 versus 1.48%) compared to lambs with low-RIG values. Montelli et al. (2021) also reported a trend towards lower omental fat deposition in efficient lambs (low-RFI and high-RIG animals) compared to inefficient lambs (0.748 versus 0.876 kg for RFI and 0.786 versus 1.041 kg for RIG, respectively). However, several authors have reported that lambs classified by the RFI index do not differ in the amount of cavitary fat deposited (Meyer et al. 2015; Zhang et al. 2017; Rocha et al. 2018).

Regarding the non-carcase external components, high-RIG lambs showed higher hooves weight. This result agrees with that reported by Carneiro et al. (2019), who found higher relative weight of hooves in crossbred Texel × Pantaneira lambs classified by the RIG index. Likewise, no difference in hooves size has been reported using the RFI index (Zhang et al. 2017; Rocha et al. 2018), which agrees with our results.

**Conclusions**

Low-RFI and high-RIG lambs had improved feed efficiency and larger hearts, which could be related to improved cardiovascular performance. In addition, low-RFI lambs tended to have higher blood volume and deposited less cavitary fat, while that high-RIG have higher intestinal mass, which could be related to improved feed efficiency. More experimental studies are required to determine the relationship of feed efficiency with non-carcase organ size in tropical hair sheep. Finally, anatomy and physiology of the heart in tropical hair sheep are topics that need to be further evaluated.

**Acknowledgements**

The first author is grateful for the research grant provided by the National Council for Science and Technology of Mexico (CONACYT) for his PhD studies at the Colegio de Postgraduados. The authors are grateful for the assistance of Walter Lanz-Villegas, who granted access to the facilities of the Centro de Integracion Ovina del Sureste (CIOS).

**Ethics approval**

The animals included in the present study were managed in compliance with the regulations for the use and care of animals intended for research and, the study was approved by the Ethics Committee on Animal Use and Animal Care of Colegio de Postgraduados (SUBINVTAB.CP. -105/18).

**Disclosure statement**

The authors declare they have no conflicts of interest.

**Funding**

The first author received a grant from the National Council for Science and Technology of Mexico (CONACYT) for his postgraduate studies. The other expenses were financed by the authors.

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Data availability statement

Data are available from Carlos Arce-Recinos, e-mail: carlos.arce@colpos.mx upon reasonable request.

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