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RESEARCH ARTICLE

Relationships between the incidence and degree of medullation with the diameter of alpaca fibers evaluated using a novel device based on artificial intelligence

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ABSTRACT

The presence of medullated fibers affects the textile processing, comfort and appeal of alpaca apparel. Measuring the incidence of medullated fibers is slow and expensive. Previous reports of the incidence of medullated fibers are often based on small test samples. The objectives of this work were to: (1) evaluate the Fiber Med device which uses artificial intelligence technology to rapidly and accurately identify the incidence of alpaca fibers according to their type of medullation and determines average fiber diameter (AFD); and (2) to relate the incidence of medullated fibers to a range of animal and fiber characteristics including age of alpaca at shearing, sex of alpaca, breed (Huacaya, Suri), location, and AFD. This study examined fiber from two locations, using 302 alpacas from two breeds and six age groups. Over 630,000 fibers were assessed (average per sample 2112) with AFD 22.1 μm (range 15.5–33.3 μm). Fiber medullation was categorized as either not present (58.6%; AFD 19.6 μm), fragmented (17.1%; 23.0 μm), discontinuous (7.6%; 25.6 μm), continuous (15.4%; 28.6 μm) or strongly medullated (1.3%; 37.8 μm). After appropriate data transformation, analysis of variance, linear and multiple regression analyses were performed to determine relationships between total medullation, AFD, location, breed, sex and age at shearing. There were significant differences in total medullation between location, breed and age at shearing but not sex of alpaca. However, in multiple regression analyses, once AFD was included in models, neither sex nor age at shearing was significant. AFD alone explained over 70% of the variation in total medullation. Differences in the incidence of the degree of medullation between age groups and marketing categories determined using AFD, were associated with differences in AFD. The differences due to location were explained by genetic selection programs to reduce AFD at one location. There was a persistent small incidence of strongly medullated fibers at all age groups (mean range 0.33–1.14%), locations, breeds and sexes and a higher incidence in fiber with AFD $>$ 26.5 μm (mean range 2.87–6.50%). Suri alpaca had a lower incidence of medullation than Huacaya alpaca. Since the Fiber Med device provided a direct, fast and low-cost measurement of the incidence of medullation it appears to be a practical option for use in programs to improve fiber quality, marketing and processing of white alpaca fiber. To reduce strongly medullated fibers in all categories of alpaca fiber, the measurement of the incidence of medullation should become a routine assessment in alpaca breeding programs.

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South American Camelids; objectionable fibers; wool; medullation type; fiber diameter

Introduction

Alpaca fiber is considered a luxury or specialty fiber with special softness qualities and different physical properties compared with sheep wool and it is produced in limited amounts. It has a thinner cuticle (McGregor & Quispe, 2018) and contains less grease compared with sheep wool (Wang, Wang, & Liu, 2003). Alpaca fiber has a lower specific weight (Czaplicki, 2012) compared with apparel wool, in part, as a consequence of having a high incidence of fibers with medulla. These medullated fibers have a central channel containing residual cells or pockets of continuous or interrupted air along the fibers (Villarroel, 1963; Carpio, 1991; McGregor, 2006; Radzik et al., 2018).

Alpaca fleeces are composed of fibers that have no medulla, or with fragmented, discontinuous, or continuous medulla. Those fibers that are strongly medullated can also be called objectionable fibers. These objectional fibers are especially important because the medulla occupies more than 60% of the total diameter of the fiber and are exaggeratedly thick and with little flexibility (Villarroel, 1963; Carpio, 1991; Lupton, Pfeiffer, & Blakeman, 1991). The presence of medullation in the alpaca fibers is considered advantageous, because they give a greater thermoregulatory

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Table 1. Incidence of medullated fibers and average fiber diameter in alpaca of different ages reported in different studies with s.d. and range shown in parentheses.

Authors	Quantity of animals	Alpaca breed	Age of animals (years)	Fiber diameter (μm)	Medullated fibers by number (%)	Location
Carpio (1991)	NR	Suri	NR	NR	(44.5–43.6)	Perú
McGregor (2006)	1100	Suri and Huacaya	1 to 10	28.9 ± 5.3 (18–47)	31.9 ± 20.7 (1.0–95.0)	Australia
Cruz et al. (2019)	2283	Suri and Huacaya	1 to 20	18 to 36	32.7–37.3	Perú
Guillén and Leyva (2000)	186	Huacaya	1.5 to >4	19.9 ± 4.7	47.0	Perú
Pinares et al. (2019)	36	Huacaya	1 to 10	19.1 to 27.6	67.4 ± 18.3	Perú
Contreras (2010)	248	Huacaya	1 to 8	22.7 ± 0.2	71.14	Perú
Córdova (2015)	35	Huacaya	>1	28.7 ± 0.2	68.0	Ecuador
Radizik and Wiercinska (2021)	36	Huacaya	NR	25.3 ± 0.8	68.9 ± 2.8	Poland
Aruquipa (2015)	320	Huacaya	1 to 8	22.8 ± 2.27	26.1 ± 4.5	Bolivia
Torres (2020)*	200	Huacaya and Suri	0.5 to 8	21.5 ± 0.2	28.7 ± 1.37	Perú
Lupton et al. (2006)	267	Huacaya	1 to >3	27.9 ± 5.6	17.5 ± 11.0	USA
Villarroel (1963)	11	Suri and Huacaya	NR	22.4 – 38.4	33 – 97	Perú

NR: Not reported.
*Torres (2020) determined % of Continuous + Strongly medullated fiber only.

capacity and the garments based on them are lighter (Czaplicki, 2012). However, for the textile industry, medullated fibers, especially those with continuous medullation and those which are strongly medullated are considered defects and attract a considerable market discount as shown with mohair (McGregor & Butler, 2004). The main reason for the market discount is that medullated fibers affect the transmission of light through the fiber resulting in uneven heterogeneous dappling appearance in fabrics following dyeing, thus precluding such fiber from high value apparel textiles (Hunter, 1993).

During early-stage textile processing medullated fibers break quickly increasing the proportion of short fibers which are removed as low value waste (Gupta, Arora, & Verma, 1981). The breakage of medullated fibers is due to their low tensile strength and high deformation with lower tension force (Rao & Chopra, 1985). This reduces the yield of alpaca tops and increases the unit cost of production.

The incidence of medullated fibers increases in association with increases in the mean fiber diameter of raw alpaca and mohair (Lupton et al., 1991; McGregor, 2006; McGregor et al., 2012). Increasing mean fiber diameter of apparel textiles is associated with reduced comfort as a result of increasing prickle sensations (McGregor et al., 2013). Thus, increasing fiber medullation (continuously and strongly medullation categories) in alpaca textiles is associated with the negative prickle sensations (Frank et al., 2014).

Given these negative impacts of medullated fibers there is a marked interest in eliminating them or strongly reducing their incidence in alpaca fibers. In this sense, the incidences of these types of fibers have been proposed as new selection criteria (Gupta et al., 1981; Cruz et al., 2019; Pinares et al., 2018; Torres, 2020; Radzick-Rant & Wierckinska, 2021), in order to improve the quality of alpaca fibers through genetic selection. However, there is little information about the incidence of strongly medullated and continuously medullated fibers and tolerance limits for the presence of strongly medullated fibers have not yet been determined, as in the case of Merino wool and mohair fibers. In high quality mohair fibers, the general requirement in good quality fibers is an incidence of strongly medullated fiber below 1%, (Hunter, Smuts, & Botha, 2013; Sacchero, 2019) which after processing the value must be less than 0.3% (Hunter, 1993; SGS, 2003) although by animal selection this value can be reduced to less than 0.1%. High-quality dehaired cashmere textiles have no more than 0.2% objectionable fibers (McGregor & Postle, 2004).

Some results about the incidence of alpaca fiber medullation are shown at Table 1. There is little detailed data on the incidence of different types of medullation in raw and processed alpaca fiber. This is related to the laboriousness and cost involved in their determination, and also to the lack of equipment with high precision, accuracy, speed and at a low cost. Studies on types of medullation in alpaca fibers, using the projection microscope, have generally been performed with relatively few samples (Villarroel, 1963; Carpio, 1991; Radzik et al., 2018; Pinares et al., 2019; Radzick-Rant & Wierckinska, 2021; Checalla, 2021), or with few fibers read per sample (Villarroel, 1963; Carpio, 1991; Contreras, 2010; Cordero et al., 2011; Aruquipa, 2015). Other studies with a larger number of samples have been carried out using the OFDA100 (Aylan-Parker & McGregor, 2002; Wang, Wang, & Liu, 2003; McGregor, 2006; Lupton, McColl, & Stobart, 2006; Cruz et al., 2019) which evaluates the incidence of medullated and unmedullated fibers based on opacity (Turpie & Steenkamp, 1995; Balasingam, 2005). However, the OFDA100 may underestimate the incidences of medullation in alpaca fibers. One report of using the OFDA100 found that medullation values of mohair fibers were underestimated by up to 8% (Lee, Maher, Frampton, & Ranford, 1996) while another report with alpaca found wide differences with medullation values obtained compared with the projection microscope (Pinares, et al., 2018; Torres, 2020).

The objectives of the present study were to: (1) evaluate a novel piece of equipment which uses artificial intelligence technology to rapidly and accurately identify the incidence of alpaca fibers according to their type of medullation; and (2) to relate the incidence of medullated fibers to a range of animal and fiber characteristics including age of alpaca at shearing, sex of alpaca, breed (Huacaya, Suri), location, and average fiber diameter

Materials and methods

Location and duration

Samples of white alpaca fibers ($n = 302$) were obtained from two locations: Lachocc Production and Research Center, National University of Huancavelica, Huancavelica ($n = 106$ Huacaya); Pacomarca Scientific Station, belonging to the Inca Group, Puno ($n = 196$ Huacaya and Suri alpacas). The analysis of the medullation and diameter of fiber was carried out in the Textile Fibers Laboratory of the Center for Scientific Research and Technological Development, Natural Fiber's Tech SAC, located in Lima, Peru. Work began in February, culminating in November 2021.

The geographical coordinates of Lachocc are: −12.7869 South latitude, and −74.9731 West longitude, of Pacomarca are: −14.9478 and −70.8803, respectively, and of Lima are: −12.0436 and −76.9714, respectively.

Animal source and sampling

The alpacas were born between January and March of each year and the shearing was done between November and December. The fiber samples were taken from the mid-side site, located over the third last rib, half-way between the mid-line of the belly and the mid-line of the back (Aylan-Parker & McGregor, 2002). Sampling location (Lachocc, Pacomarca), the breed (Huacaya, Suri), sex (male, female) and age (in months) were recorded along with animal identification. Data from 25 animals from Lachocc had missing details of sex and age. All the alpacas at Lachocc were Huacaya. The age of Lachocc alpacas, ranged between 2 and 12 years, while those of Pacomarca ranged between 0.5 and 9 years.

Measurement equipment

The Fiber Med (Figure 1) comprises of a hardware and AI-based software, whose development is based on the recognition of the different types of fiber medullation by artificial intelligence (AI) (Quispe, Quispe, & Quispe, 2020; NFT, 2021). The device is made up of 4 parts: Mechanical; electronic; optical; and programming. These interact as a system allowing the determination of the incidence of medullation in fibers, according the medullation category, expressed in absolute and relative data (Quispe, Quispe, & Quispe, 2020). The operation is based on the scanning of fiber fragments prepared on a slide, by millimeter movements provided by belts and toothed pulleys driven by 2 motors, and then by a proprietary software based on artificial intelligence which recognizes the fibers by medullation type, and at the same time measures the diameter of each of them (Figure 1). They interact scanning the sample of fiber snippets prepared on a glass slide, and covered with a coverslip. Hundreds of photographed fibers are captured, analyzed, and identified during the scanning using AI-based software. The results of the evaluation of each sample are saved in a excel file (numeric data), and the images of the fibers identified (according medullation type) within each photograph with their respective diameter are stored in files within a folder (Figure 2). Additionally, the descriptive statistics of AFD, incidence of medullation fibers, graphic on AFD distribution by medullated and non-medullated fibers are shown on the graphical user interface (GUI). For the automatic recognition of the type of fibers according to their medullation by Fiber Med, it is necessary that the medulla of the fiber is clearly distinguished. Thus, the fiber med evaluates only white or light-colored fibers.

Measurement of average diameter and medullated fibers

Prior to their evaluation, the samples were washed for 3 min in an ultrasonic washing device with a mixed solution of 7 parts of 96% alcohol and 3 parts of benzine. The drying was done by placing the samples on an absorbent towel and covering with paper towel that was pressed repeatedly with a small roller.

The measurement of average diameter and medullation of fibers was carried out with Fiber Med. Fiber Med evaluated an average of 2112 fibers per sample in 40 s, with medullation being classified as: non-medullated (NoMed); fragmented medullation (FragMed); discontinuous medullation (DiscMed); continuous medullation (ContMed); strongly medullated (StrMed); and total medullated (TMed) = (FragMed + DiscMed + ContMed + StrMed). NoMed, FragMed, DiscMed, ContMed, StrMed and MedT fibers, expressed in absolute and relative units (quantity and percentage, respectively). Additionally, it obtains the average fiber diameter (AFD) by medullation category (AFD_NoMed, AFD_FragMed, AFD_DiscMed, AFD_ContMed, AFD_StrMed, AFD_TMed) and an overall average (AFD_G). In addition, it provides images of fibers before and after being automatically identified (input and output images, respectively), which can be saved in a specific directory (Figure 2).

Before the use of the Fiber Med, tests were carried out on the proper functioning and identification of the fiber medullation. Output images were obtained (Figure 2) of 4810 fibers that were automatically recognized by the device with information on the percentage of fibers (%F) with NoMed, FragMed, DiscMed, ContMed, StrMed and MedT (%F_NoMed, %F_FragMed, %F_DiscMed, %F_ContMed, %F_StrMed and %F_TMed, respectively). The same images of fibers, but without identification (input images) were counted directly by an operator (4816), also obtaining the percentages of the different types of fibers according to the category of medullation. Comparison made by z tests of proportions, found no evidence of any difference between methods, so it was considered that the Fiber Med correctly identifies the different types of medullation of the fibers. For the measurement of the AFD, the device was previously calibrated and then validated with 8 samples of standard wool tops (SWTop) with known diameter. The procedure was similar at the calibration and validation of the optical fibre diameter analyzer (OFDA100) indicated at IWTO-47-07 (IWTO, 2015a), finding that the AFD obtained with the Fiber Med had values similar to the samples of standard wool, because all deviations between average values of each sample of SWTop obtained by Fiber Med and known diameter of SWTop were within the tolerance limits of the OFDA100, demonstrating that the Fiber Med has the ability to measure the fiber diameter with acceptable accuracy.

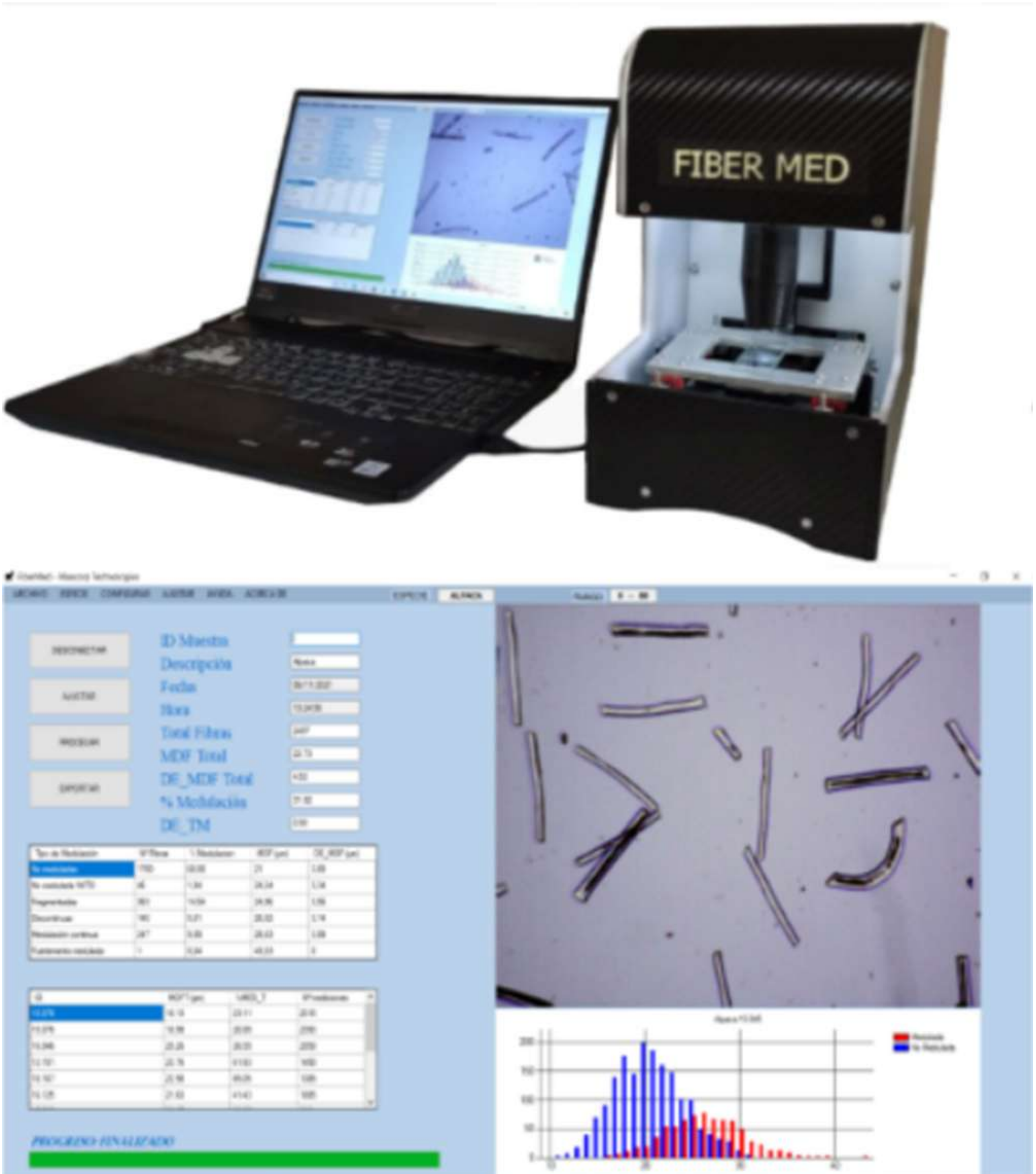

Figure 1. Top: Intelligent electronic medullator of animal fibers (Fiber Med) that was used for the analysis of white alpaca fibers. Down: Graphical user interface (GUI) of the device.

The procedure indicated by IWTO-8-04 was considered (IWTO, 2015b) for preparation of the fiber samples. Fiber snippets (between 0.2 and 0.4 mm length) were obtained by Hardy's microtome and a razor blade. These snippets were carefully placed in the middle of a glass slide, and a drop of immersion oil (with refractive index very similar to that of alpaca fiber) was placed on top. Then, the fiber snippets and immersion oil were scattered through slow circular movements using a glass rod. Finally, a cover was placed on top, preventing the formation of air bubbles. Subsequently, the sample was placed on the "X" coordinate table of the Fiber Med, and after entering the identification, the evaluation of the samples began.

Data preparation

Prior to the statistical analysis, the database obtained with the Fiber Med, went through a series of preliminary evaluations, transformations and categorizations. Shapiro and

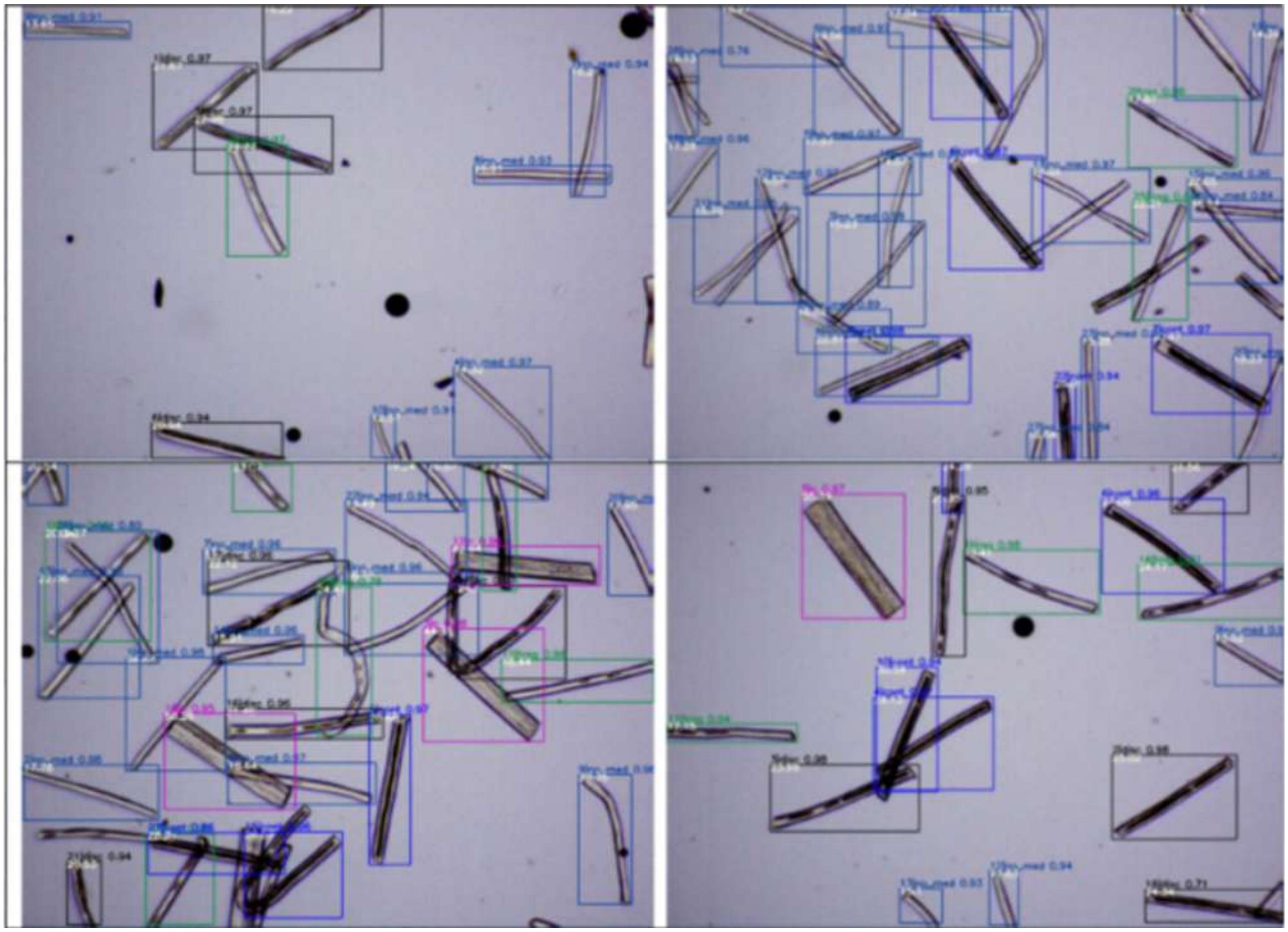

Figure 2. Automatic identification of alpaca fibers with different types of medullation. In white numbers the diameter of each of them is indicated. See fragmented medullated fibers with a diameter of less than 18 μm. Strongly medullated fibers with diameters greater than 42 μm are also observed. Fibers without medullation (framed in celestial lines) are those that exhibit the smallest diameter.

Barlett tests were used to evaluate the normality and homoscedasticity compliance of the AFD and %F with various types of medullations, finding evidence that the %F_NoMed, %F_FragMed, %F_DiscMed, %F_ContMed, %F_StrMed and %F_TMed had no normal distribution or homoscedastity. For this reason, the quadratic transformation of proportion of these data was performed, using the following Arcsine function $[(\%F/100)^{1/2}]$, obtaining %F_NoMedTrans, %F_FragMedTrans, %F_DiscMedTrans, %F_ContMedTrans, %F_StrMedTrans and %F_TMedTrans.

A new variable "Fiber quality" was created, based on the AFD and accepted industry classifications, considering 6 levels: Imperial ($\leq$ 18 μm); Super Baby ($>$ 18 and $\leq$ 20 μm); Baby ($>$ 20 and $\leq$ 23 μm); Fleece ($>$ 23 and $\leq$ 26.5 μm); Medium Fleece ($>$ 26.5 and $\leq$ 29 μm); Huarizo-Gruesa ($>$ 29 μm). This classification was based on the Peruvian technical standard 231-301 (INDECOPI, 2014) with slight modifications. Another categorical variable "Shearing" was created based on age (because shearing is carried out annually) considering 6 levels: 1st. shearing ($\leq$ 11 months old); 2nd. shearing ($>$ 11 and $\leq$ 23 months old); 3rd. shearing ($>$ 23 and $\leq$ 35 months old); 4th. shearing ($>$ 35 and $\leq$ 47 months old); 5th. shearing ($>$ 47 and $\leq$ 59 months old); 6th. shearing and greater ($>$ to 59 months old). Additionally, taking into account the %F_TMed, the variable "Degree of Total Medullation" (D_TMed) was created, in 6 levels: "Very low" ($\leq$ 10%); "low" ($>$ 10 and $\leq$ 20%); "regular" ($>$ 20 and $\leq$ 40%); "medium" ($>$ 40 and $\leq$ 60%); "high" ($>$ 60 and $\leq$ 80%); "very high" ($>$ 80%). Finally, based on the %F_StrMed, the categorical variable called "Degree of incidence of StrMed fibers" (DI_FStrMed) was also created with 6 levels: Nil (0%); very low ($>$ 0 and $\leq$ 0.2%); low ($>$ 0.2 and $\leq$ 0.5%); medium ($>$ 0.5 and $\leq$ 1.0%); high ($>$ 1.0 and $\leq$ 3.0%); very high ($>$ 3.0%).

Statistical analysis

For the general summary of %F and AFD by category medullation, descriptive statistics were used. Duncan's test was used for multiple comparisons of AFD from different medullation categories, and pairwise comparisons of Wilcoxon rank test was used to compare medullation category percentages. To evaluate the effect of breed (B), sex, shearing (Shear) and AFD_G on %F_FragMedTrans, %F_DiscMedTrans, %F_ContMedTrans, %F_StrMedTrans and %F_TMedTrans an analysis of variance was obtained from a linear additive model with covariable and interactions ($\%F_{ijklmn} = \mu + B_j + sex_k + Shear_l + AFD\_G_m + L_i{*}Sex_k + B_j{*}Sex_k{+}B_j{*}Shear_l + e_{ijklmn}$) using data of Pacomarca alpacas only, but to evaluate effect of location a randomized complete model was used with Pacomarca and Lachocc data. In addition, in order to evaluate the effect of fiber quality corrected by shearing, a linear additive model was also used. Duncan's test was used for comparisons of means. Subsequently, a multiple linear regression was used to evaluate the relationship of age (in months), AFD (μm), R, S and interaction S*R (dummy variable was created for R and S) with %F_FragMedTrans, %F_DiscMedTrans, %F_ContMedTrans, %F_StrMedTrans and %F_TMedTrans. Scatter graphics including lines of best fit (polynomic, and exponential) were elaborated to evaluate the relationship among fiber quality with %F_FragMed, %F_DiscMed, %F_ContMed, and %F_StrMed. Density graphs, bars, points and dispersion matrix were also developed to visualize the performance and relationships of the %F (with different medullation categories) and their respective AFDs.

The free software RStudio Version 4.0.3 was used for statistical processing (R Core Team, 2020).

Results

The average number of fibers tested per sample was 2112 with a range of 336 to 5353. Of the 302 mid-side samples, 330 fibers were measured and identified in one sample (0.3%); between 601 and 999 fibers in 22 samples (7.3%), while in 279 samples (92.4%) more than 1000 fibers per sample were measured and identified. The AFD of the samples tested was 22.1 μm with a range of 15.5–33.3 μm. In total almost 638,000 fibers were tested and 58.6% of the fibers had no medullation and 41.4% had some type of medullation (Table 2). The average fiber diameter of non-medullated fibers was 19.6 μm and as the degree of medullation increased the AFD of the fibers also increased with strongly medullated fibers averaging 37.8 μm (Table 2).

The %F_FragMed and %F_ContMed have almost similar incidences (17.1 and 15.3%) and that %F_StrMed was around 1.3%. Likewise, AFD was lower in NoMed fibers, and increased as the medullation became more pronounced (Table 2), clearly observing that StrMed fibers are quite thick, but that there was an overlap in the distribution between medullation categories (Figure 3).

Also, there were 16.2% of alpacas with high %F_StrMed, and animals without StrMed fibers. The %F_TMed ranged from 4.8 to 98.1%.

Table 3 shows means and effects of L, B, sex, Shear, fibre quality and interactions on fiber medullation percentages. There were no interactions detected for any effect on TMed. Breed by Shearing interactions on some parameters are considered marginal at p-value = 0.02 and are not discussed.

For main effects there were significant effects of location, breed, shearing and fiber quality on the incidence of FragMed, DiscMed, ContMed, StrMed and TMed fibers (p-value $\leq$ 0.001), except for the effect of the location on %F_StrMed (p-value = 0.862) and breed on %F_ContMed (p-value = 0.106). Sex had no main effect on the incidence of any medullation category when AFD was included in the model.

Alpacas from Lachocc had higher %F_TMed, %F_FragMed, %F_DiscMed and %F_ContMed, but similar %F_StrMed compared with alpacas from Pacomarca. Huacaya alpacas exhibited higher %F_FragMed, %F_DiscMed and %F_TMed, but lower %F_StrMed compared with the Suri alpacas. Also, increasing the shearing age from the first to the fifth (which correspond to animals under 60 months) all categories of medullation increased. Between the fifth and sixth shearing there was a decrease in %F_FragMed, and a similarity of %F_DiscMed, %F_ContMed, %F_StrMed, and %F_TMed.

When the fiber quality (determined on the basis of AFD) was taken into account, the fibers of the best quality ("Imperial", with AFD < 18 μm) had the lowest incidence (%F) in each of the medullation categories. In general, the %F that are medullated increased as the fiber quality decreased, with the exception of %F_FragMed, which increased to Fleece quality, and then decreased in the subsequent quality (Medium Fleece to Huarizo_Gruesa) with a third degree polynomial curve behavior, while the %F_ContMed and %F_StrMed increased strongly and

Table 2. Descriptive statistics of incidence of medullation and average fiber diameter by medullation category, in 302 white alpaca fiber samples.

Variables	*n*	Average	Standard deviation	Median	Minimum value	Maximum value
Fibres measured (*n*)	302	2112	880.2	1955	336	5353
Average fiber diameter (μm)	302	22.1	3.19	22.1	15.5	33.3
Lachocc	106	23.6	3.2	23.5	16.2	33.3
Pacomarca Huacaya	96	21.4	3.1	21.3	15.5	28.7
Pacomarca Suri	100	21.1	2.7	21.2	16.2	28.6
Incidence of medullation by medullation category[(1)]						
None (%)	302	58.6[a]	23.7	60.1	1.9	95.2
Fragmented (%)	302	17.1[b]	8.7	17.3	2.8	39.3
Discontinuous (%)	302	7.6[c]	6.4	5.7	0.2	36.0
Continuous (%)	302	15.4[b]	11.2	11.2	0.7	69.3
Strong (%)	302	1.3[d]	2.2	0.4	0.0	16.2
Total medullation (%)	302	41.4	23.7	38.0	4.8	98.1
Average fiber diameter by medullation category[(2)]						
None (μm)	302	19.6[e]	2.26	19.4	15.0	25.7
Fragmented (μm)	302	23.0[d]	2.06	22.8	18.6	28.9
Discontinuous (μm)	302	25.6[c]	1.86	25.5	21.0	31.7
Continuous (μm)	302	28.6[b]	1.70	28.4	24.0	34.2
Strong (μm)	281	37.8[a]	4.96	38.0	24.2	57.6
Total medullation (μm)	302	25.8	2.16	25.6	20.5	33.4

[1]Incidence of medullation: Different letter indicate significative difference, by pairwise comparison using Wilcoxon rank sum test
[2]Average fiber diameter: Different letters indicate significant difference, using the Duncan-test

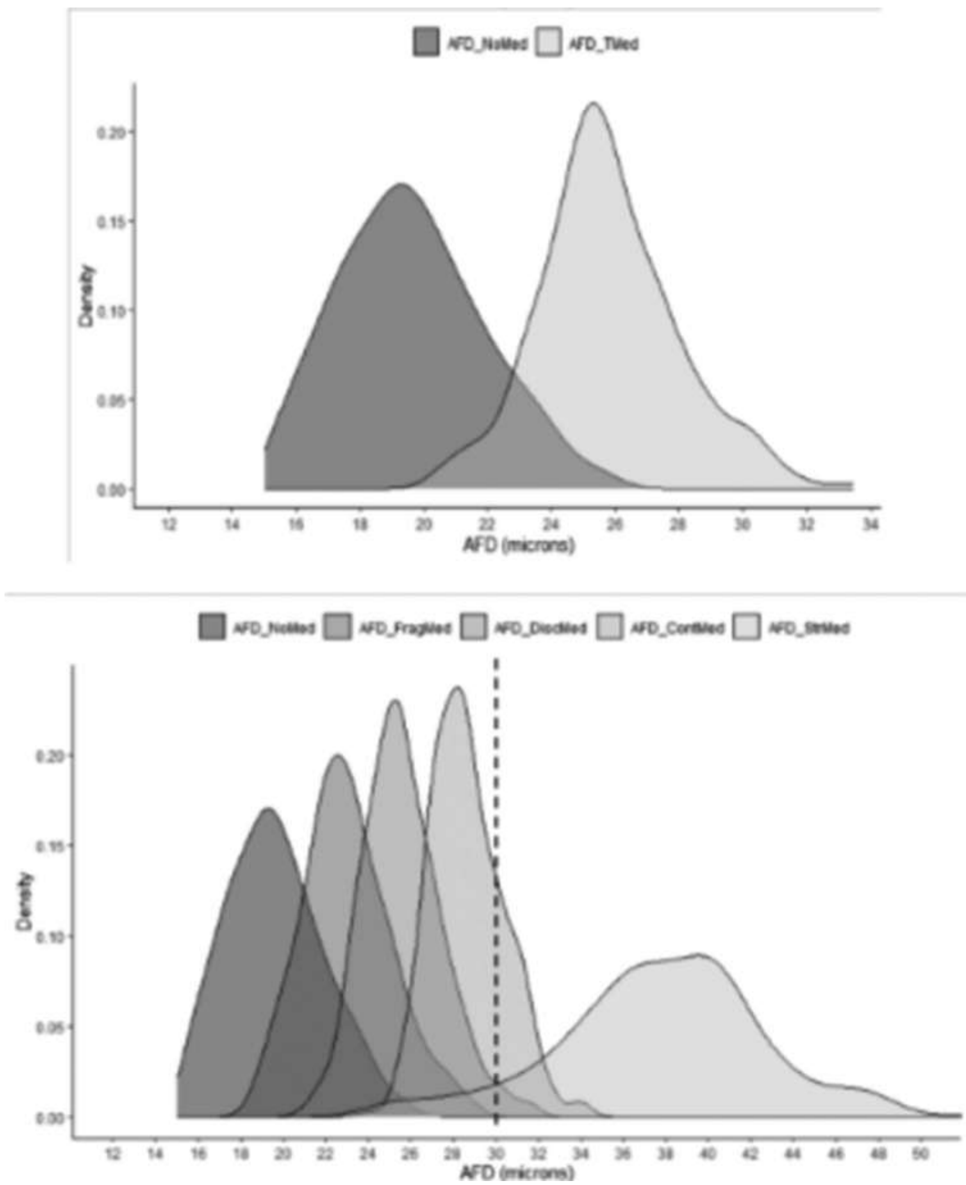

Figure 3. Density graph, showing the distribution of fiber diameter by type of medullation ($n = 302$). Above: AFD density of non medullated and medullated fibers. Below: AFD density of non medullated, fragmented, discontinuous, continuous and strongly medullated fibers.

exponentially from Imperial to Huarizo_Gruesa quality whose exponential equations are $\%F_{ContMed} = 2.2499e^{0.546*\text{Fiber quality}}$ and $\%F_{StrMed} = 0.0.547e^{0.785*\text{Fiber quality}}$, respectively.

Likewise, when %F_FragMed, %F_DiscMed, %F_ContMed, %F_StrMed were evaluated, proportionally with respect to %F_TMed, it was found that the %F_FragMed is higher in fibers of Imperial, Super Baby and Baby quality, but in other fiber qualities %F_ContMed is higher than another medullation categories. Thus, in the Imperial quality, %F_FragMed incidence is about 60% of %F_TMed, and %F_StrMed only reach 1%. The %F_ContMed increase as quality decreases, because at Imperial quality the incidence of these fibers is almost 30%, but in Huarizo-Grueso quality the incidence is more than 60%. The %F_DiscMed range between 10 and 20% of %F_TMed in the different qualities, while %F_StrMed range between 1 and 2% in Imperial, Super Baby and Baby qualities, but have a greater incidence in Medium Fleece and Huarizo-Gruesa fibers (3.9 and 7.1%).

The "very low", "low", "regular", "medium", "high" and "very high" D_TMed (Figure 4a) were found in proportions of 0.08 (25/302), 0.15 (44/302), 0.30 (90/302), 0.23 (70/302), 0.17 (50/302) and 0.07 (22/302) respectively. Therefore, the highest proportion of alpaca fibers (0.77) have GMedT between "regular" to "very high" (with %F_TMed $>$ 20%), but also almost a fifth have "very low" and "low" D_TMed (with %FTMed $\leq$ 20%). The "null", "very low", "low", "medium", "high" and "very high" DI_FStrMed (Figure 4b) were found in proportions of 0. 07 (21/302), 0.30 (91/302), 0.19 (56/302), 0.13 (40/302), 0. 20 (60/302) and 0.11 (34/302) respectively. Thus, a proportion close to 0.45 of the fiber samples have "null" or "very low" ($\leq$ 0.2% of %F_StrMed), but also a proportion greater than 0.30, have "high" and "very high" DI_StrMed (wth %F_StrMed $>$ 1.0%).

The D_TMed and DI_FStrMed according to the shearing and fiber quality factors, can be seen in Figure 4c, d. The "very low" D_TMed ($\leq$ 10% TMed) was only found in the 1st and 2nd shearing, and D_TMed from "low" to "high"

Table 3. Effect of location, breed, sex, shearing, fiber quality and interactions on %F_FragMed, %F_DiscMed, %F_ContMed, %F_StrMed and %F_TMed (with inverse and quadratic trigonometric transformation) of white alpaca fiber.

Variables	n	FragMed (%)	DiscMed (%)	ContMed (%)	StrMed (%)	Tmed (%)
Location		*<0.001*	*<0.001*	*<0.001*	*0.862*	*<0.001*
• Lachocc	81	21.27[a]	10.34[a]	18.17[a]	0.72[a]	55.52[a]
• Pacomarca	196	13.85[b]	4.76[b]	11.42[b]	0.74[a]	33.49[b]
Breed[1]		*<0.001*	*<0.001*	*0.106*	*<0.001*	*<0.001*
• Huacaya	96	17.05[a]	6.14[a]	11.29[a]	0.38[b]	37.81[a]
• Suri	100	11.05[b]	3.59[b]	11.55[a]	1.23[a]	29.46[b]
Sex[1]		*0.486*	*0.434*	*0.095*	*0.321*	*0.517*
• Female	99	13.98[a]	4.95[a]	12.59[a]	0.75[a]	34.70[a]
• Male	97	13.72[a]	4.57[a]	10.28[a]	0.76[a]	32.26[a]
Shearing[1]		*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
• 1st. shearing	55	6.73[d]	1.63[d]	5.54[c]	0.33[c]	15.14[d]
• 2nd. Shearing	48	15.50[c]	4.73[c]	11.81[b]	0.76[ab]	34.93[c]
• 3rd. shearing	27	19.17[b]	7.40[b]	13.11[b]	0.44[bc]	43.41[b]
• 4th. Shearing	21	19.45[b]	9.36[a]	18.99[a]	1.09[a]	53.76[a]
• 5th. Shearing	9	23.95[a]	11.19[a]	18.35[a]	1.12[a]	57.56[a]
• 6th. Shearing or more	36	19.13[b]	9.08[ab]	18.48[a]	1.14[a]	52.28[a]
Interactions						
• Breed * Sex		*0.332*	*0.006*	*0.616*	*0.492*	*0.080*
• Breed*Shearing		*0.020*	*0.024*	*0.474*	*0.196*	*0.056*
Covariable						
• Fiber diameter	196	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Fiber quality		*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
• Imperial	31	6.74[c]	1.21[d]	3.30[f]	0.12[d]	11.88[f]
• Super Baby	51	9.07[c]	2.42[d]	6.79[e]	0.32[d]	19.41[e]
• Baby	112	18.03[a]	6.25[c]	15.05[d]	0.46[d]	37.85[d]
• Fleece	81	22.16[a]	10.45[b]	20.22[c]	1.18[c]	56.97[c]
• Medium Fleece	20	21.68[a]	15.30[a]	33.35[b]	2.87[b]	77.67[b]
• Huarizo_Gruesa	7	13.37[b]	16.17[a]	54.84[a]	6.50[a]	93.93[a]

[1]Comparisons made only at Pacomarca.

are found from the 1st to the 6th shearing ages. First shearing fibers do not have "very high" D_Tmed (see Figure 4c). Also, the "very low" G_TMed are found in Imperial, Super Baby and Baby qualities fiber, and "very high" G_TMed are found only in Huarizo-Gruesa quality (see Figure 4c). In the general form, it is observed that, as the G_TMed increases, the fiber quality decreases.

Some samples of 1st, 2nd, 3rd, 4th, and 6th shearing ages (6.5%) did not have StrMed fibers; however, fiber from 1st to 5th shearing had from "very low" to "high" DI_FStrMed. In 1st shearing fibers, no "very high" DI_FStrMed was found, but in 6th shearing fibers, DI_FstrMed were found from "null" to "very high" (see Figure 4d).

The multiple regression relationships of %F_FragMedTrans, %F_DiscMedTrans, %F_ContMedTrans, %F_StrMedTrans and %F_TMedTrans with age, and AFD_G controlled by breed, sex and interactions are shown in Table 4. The variance accounted for by the statistical models ranged from 48 to 70%. The intercepts (all negative) and regression coefficients (all positive) of the AFD were highly significant (p-value $\leq$ 0.001), while the regression coefficients of age, breed, sex and interactions were not significant with exception breed for %F_FragMedTrans, and breed*sex interaction for %F_DiscMedTrans.

The relationship among age with %F_FragMedTrans, %F_DiscMedTrans, %F_ContMedTrans, %F_StrMedTrans, and %F_TMedTrans varies between low and medium, when they were analyzed independently. The correlation coefficient between age and %F_StrMedTrans was the lowest (0.25), and the highest was between age and %F_TMedTrans (0.52, Figure 5). It was possible to find samples with %F_TMed greater than 80% originating from animals of different ages, and animals older than 50 months with %F_TMed less than 25%.

Also, the AFD_G had a relationship between medium and strong with the %F_FragMedTrans, %F_DiscMedTrans, %F_ContMedTrans, %F_StrMedTrans, and %F_TMedTrans (The r-Pearson coefficients were 0.55, 0.72, 0.77, 0.57, and 0.84, respectively). The relationship between AFD_G and %F_TMedTrans were the strongest, with a positive linear association, reinforcing the results from the multiple linear regression analysis (Table 4) of the existence of a high and strong relationship between %F_TMed and AFD_G. (Figure 6a), but the relationship between AFD_G with age was moderate (p-Pearson= 0.57, Figure 6b)

The relationships between the AFDs and the incidence of different medullation categories, the direct and linear relationships between the AFD_NoMed, AFD_FragMed, AFD_DiscMed, AFD_ContMed, AFD_TMed, and AFD_G were found, whose Pearson correlation coefficients (r_P) vary between 0.57 and 0.86; however, the relationships between AFD_StrMed with AFD_FragMed, AFD_DiscMed, AFD_ContMed, AFD_NoMed, AFD_TMedT and AFD_G are not significant or very low, as r_P varied between 0.08 and 0.31 (Figure 7).

Discussion

The main findings of this work were that the incidence of medullation and the more serious types of medullation in alpaca fiber increased rapidly as both fiber diameter and age at shearing increased. However, the effect of shearing age was not significant once fiber diameter was taken into account. These observations are discussed in the context of industry classifications of fiber quality, and normal development of the fleece as alpacas grow and the potential for

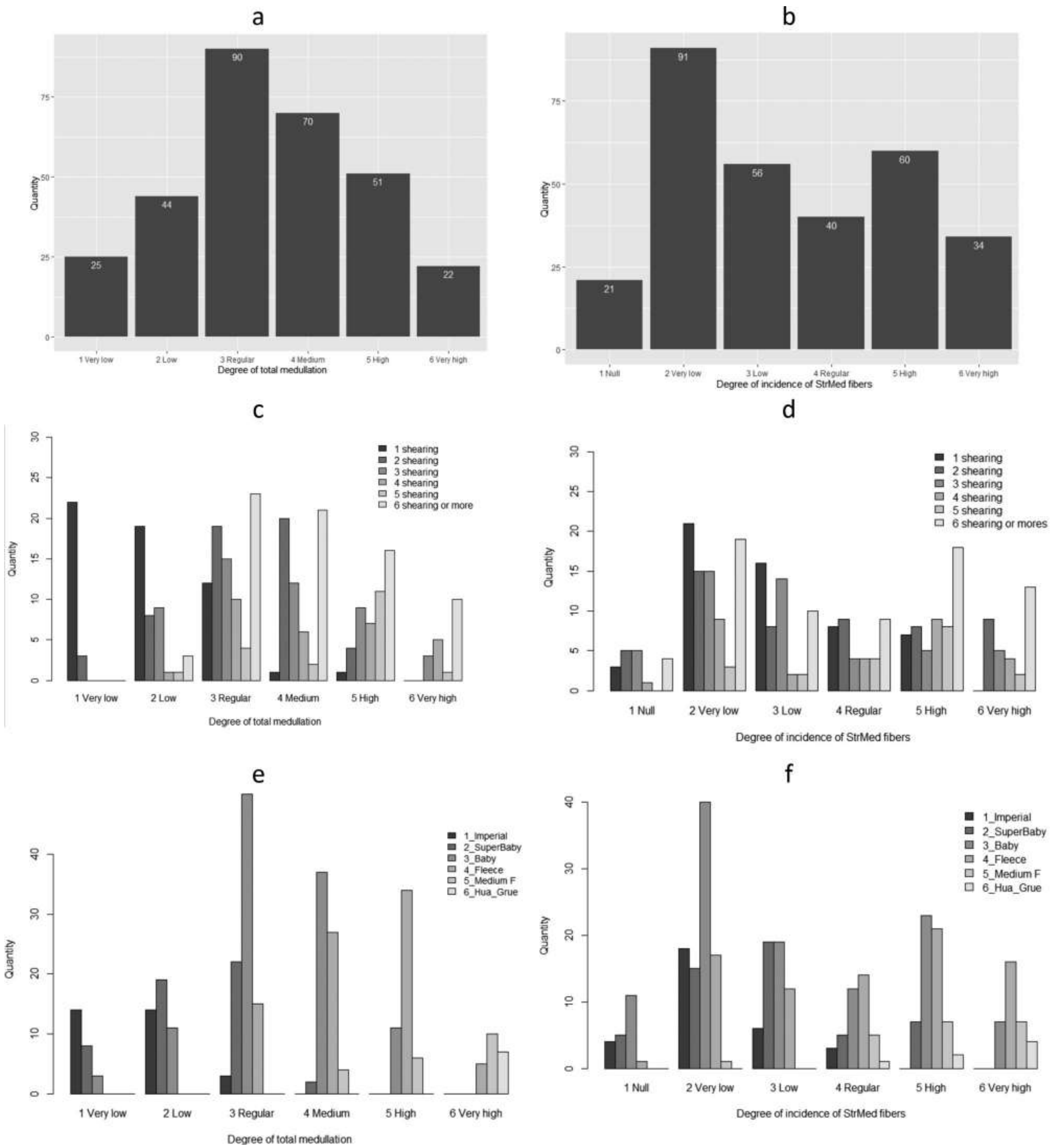

Figure 4. Bar diagrams of quantity of fiber samples found by: (a) Degrees of total medullation; (b) Degrees of total medullation and shearing number; (c) Degrees of total medullation, and fiber quality (Down); (d) Degrees of incidence of strongly medullary fibers; (e) Degrees of incidence of strongly medullary fiber, and number shearing; (f) Degrees of incidence of strongly medullary fiber, and fiber quality.

genetic selection. The use of the Fiber Med device enabled a large number of samples and fibers to be simultaneously tested to determine both fiber diameter and the incidence and degree of medullation.

Main effects on the incidence of medullated fibers

The main factor associated with the increasing incidence and degree of medullation was the increase in average diameter of the fiber. The age at shearing, breed and sex had little or no additional effect on medullation but location of the source alpaca did have an effect. The relationship between the incidence and degree of medullation with increasing age is discussed in a following section.

Fiber diameter

The correlation between AFD_G with %F_TMed (0.68) was lower than the 0.77 and 0.80 reported by McGregor (2006) and Pinares et al. (2019), respectively; however, it is close to

Table 4. Relationships between the percentages of fibers with fragmented, discontinuous, continuous and strongly medullated fibers (with inverse and quadratic trigonometric transformation) with age and average fiber diameter, controlled by sex, breed and sex interaction*breed.

Variables	FragMed $r^2 = 0.56$	DiscMed $r^2 = 0.60$	ContMed $r^2 = 0.54$	StrMed $r^2 = 0.48$	TMed $r^2 = 0.70$
Intercept	*−0.121*	*−0.317*	*−0.512*	*−0.257*	*−0.832*
	0.0496	0.0437	0.0661	0.0313	0.0835
	0.016	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Age (months)	*0.0005*	*0.0003*	*−0.0003*	*−0.0002*	*−0.00003*
	0.00028	0.00025	0.00037	0.00018	0.00047
	0.099	**0.17**	**0.41**	**0.34**	**0.96**
AFD (µm)	*0.0244*	*0.0254*	*0.0410*	*0.0150*	*0.6847*
	0.00246	0.00217	0.00328	0.00155	0.00414
	<0.001	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Breed (Suri = 1)	*−0.062*	*−0.021*	*0.022*	*0.057*	*−0.033*
	0.0160	0.0142	0.0214	0.0101	0.0270
	<0.001	**0.13**	**0.23**	**<0.001**	**0.22**
Sex (Male = 1)	*0.014*	*0.022*	*−0.028*	*0.0005*	*0.0133*
	0.01626	0.0144	0.0217	0.0103	0.0273
	0.40	**0.12**	**0.20**	**0.62**	**0.62**
Breed * Sex	*−0.031*	*−0.058*	*−0.014*	*−0.008*	*−0.069*
Suri = 1; Male = 1					
	0.0228	0.0201	0.0304	0.0144	0.0384
	0.18	**0.0041**	**0.66**	**0.57**	**0.073**

Only data from Pacomarca were analyzed where all these parameters were available ($n = 196$).
Regression coefficient estimated: Italic type.
Standard error: Grey.
p-value: Bold.

0.62, 0.64 and 0.65 reported by Cordero et al. (2011), Córdova (2015) and Berolatti et al. (2021); and higher than 0.44 reported by Aruquipa (2015). These comparisons show our results are within normal ranges. Also, given the evidence of a high and positive genetic correlation (0.93) between AFD and the presence of medullation reported by Pinares et al. (2019), as well as a positive correlation found by Cruz et al. (2019), if it were selected against %F_TMed, a reduction in AFD_G could be obtained, because the regression coefficient is high (0.68). Selection against %F_Tmed would not necessarily lead to a reduction in %F_StrMed or %F_ContMed, since the regression coefficient for these measurements with AFD are very low (0.02 and 0.04, respectively—see Table 4).

The decrease in AFD achieved by the effect of artificial selection has been extremely successful with significant genetic progress, which according to our results could have also led to a decrease in the AFD_FragMed, AFD_DiscMed and probably also of AFD_ContMed, however, very little would have been achieved to reduce the AFD_StrMed, because it has low phenotypic relationship and probably also very low genotypic correlation. Therefore, it would be a priority to consider the %F_StrMed as a selection criterion, since in this way the quality of the alpaca fiber is improved, and fiber diameter variability reduced, as StrMed fibers have a high fiber diameter (Table 1; Gutiérrez et al., 2009; Cervantes et al., 2010; Cruz et al., 2019).

In case of animal selection to reduce or eliminate StrMed fibers, the results obtained indicate that there was good variability with 44% of animals that have very low ($\leq$ 0.2%) or null (0%) %F_StrMed. Retaining these animals and eliminating older animals that have a high or very high incidence of StrMed fibers, would provide the first steps in active selection for lowering the incidence of StrMed.

Location

In relation to the effect of location on the medullation incidence, the high difference in %F_TMed found between the Lachocc and Pacomarca (55.5 and 33.5%, respectively), is primarily due to the fact that in Pacomarca an intensive genetic improvement program has been carried over many years. This program selects on fineness and other textile traits (Cruz, et al., 2019). The program should also have acted indirectly on the decrease of %F_TMed, %F_FragMed, %F_DiscMed, %F_ContMed. One modifying aspect of the effect of location is that there was a different breed structure in the samples taken from the two locations, with Pacomarca having half the samples taken from Suris whereas Lachocc only had Huacayas. As the Suris had an 8% lower incidence of TMed (Table 3), the difference between the locations adjusted for Huacayas would be about 4.2% less TMed, that being 55.5 vs 37.7%. This difference between the locations is still substantial.

The similarity of %F_StrMed found in both locations, allows us to deduce that although there is a lower incidence of %F_Tmed at Pacomarca, it does not necessarily lead to low incidences of StrMed fibers. Thus to reduce the %F_StrMed, a direct pressure should be exerted against this variable that negatively affects processing and consumer assessment (Merrick, 1998; Frank et al., 2014; Pinares et al., 2019).

Breed

The effect of the breed was a higher %F_TMed in the Huacaya than in Suri alpaca fiber. This result is similar to that reported by McGregor (2006), Cruz et al. (2019) and Torres (2020). This higher %F_TMed in Huacaya alpaca fibers is observed despite the fact that they would have lower AFD (Cruz, et al., 2019; Torres, 2020) and that they have been subjected with greater emphasis to different

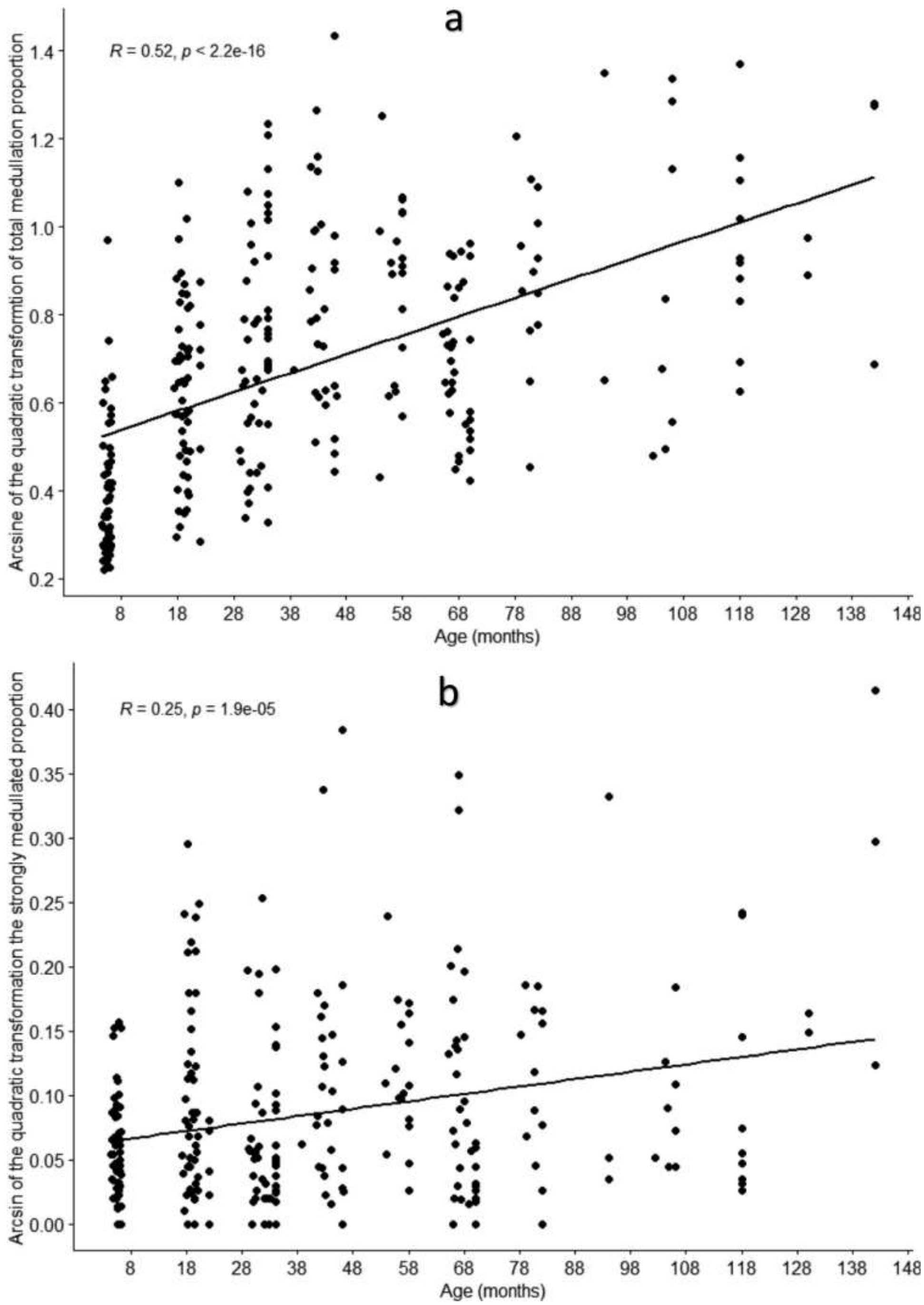

Figure 5. Top: Scatter plot showing relationships of age (in months) with arcsine of the quadratic transformation of the total medullation proportion %F_TMedTrans. Down: Scatter plot of relationship between age (in months) with arcsine of the quadratic transformation the strongly medullated proportion (%F_StrMedTrans) of white alpaca fibers. The Pearson correlation coefficient and *p*-value are shown, also.

selection processes in favor of refining the fiber. Similarly, McGregor (2006) determined with Australian alpaca, that once AFD was taken into account that Suri alpaca had a 6.4% lower incidence of medullated fibers compared with Huacaya alpaca. Consequently, we could deduce that alpacas of the Suri breed may have genes and/or fleece characteristics that result in the reduced incidence of medullation, and based on the present work, specifically the %F_FragMed and %F_DiscMed fibers.

There was no or little meaningful difference in %F_ContMed and %F_StrMed fibers between the breeds. While the measurement of %F_StrMed in Suris was 3 times higher than in Huacaya, this only translates to a difference of 0.85%, equivalent to 18 more strongly medullated fibers in the average count of 2112. Such a small but consistent difference between the breeds suggests that further investigation is needed to ensure that differences in fiber curvature or lustre are not associated with small errors in the assessment of the degree of medullation. These results are novel, as there is no other information about it.

Sex

The similarity of the %F_TMed in males and females found in the present work is consistent with that reported by other

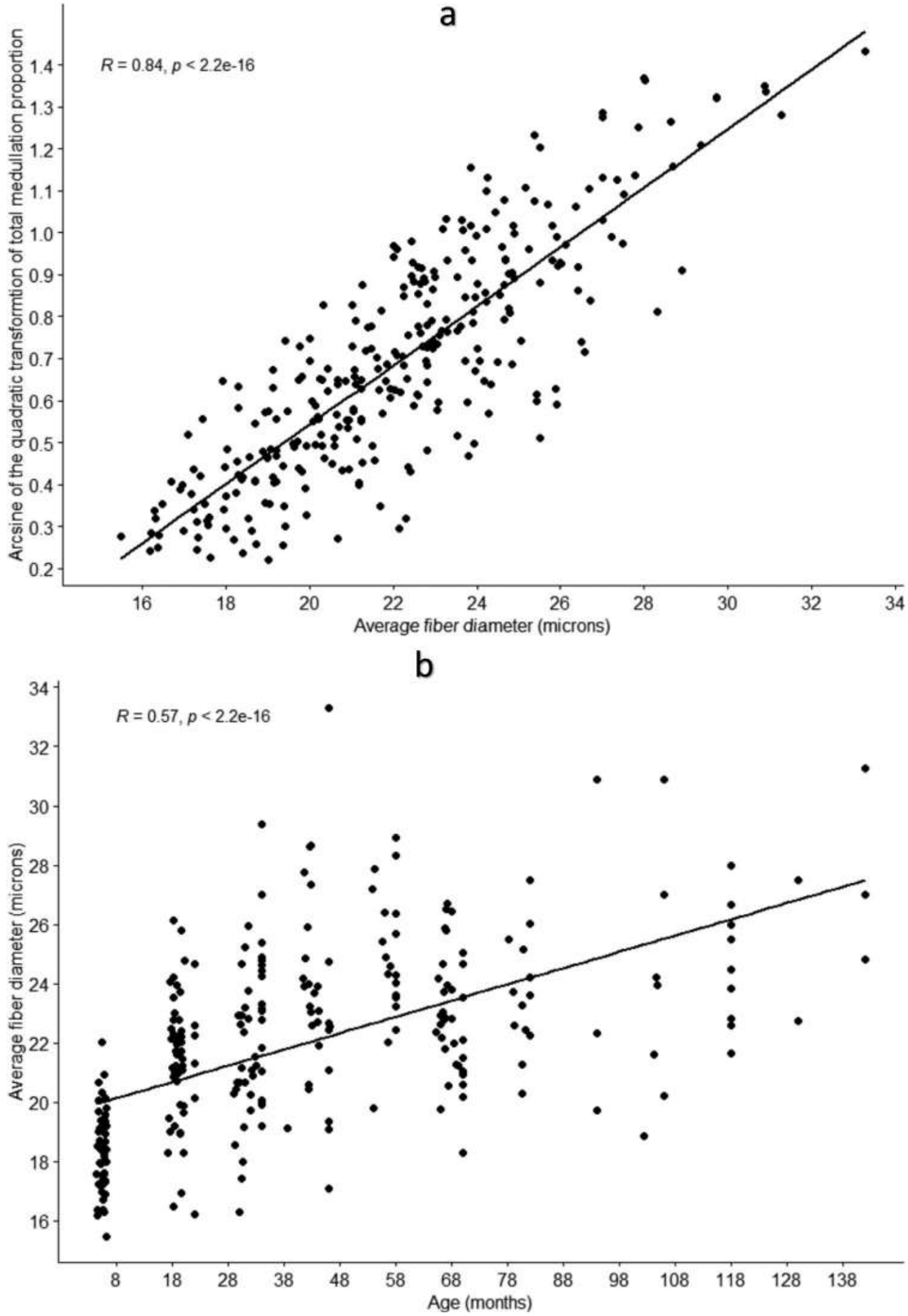

Figure 6. Top: Scatter plot showing the relationship between average fiber diameter (μm) with arcsine of the quadratic transformation of total medullation proportion (%F_TMedTrans). Down: Scatter plot showing the relationship between age with average fiber of white alpaca fibers. The Pearson correlation coefficient and *p*-value are shown, also.

researchers (Aruquipa, 2015; Córdova, 2015; Radzik, Pofelska, & Rant, 2018), which gives solidity to our results. However, it is different from what was found by Contreras (2010) who refers to greater %F_TMed for males, although other scholars (Torres, 2020; Radzick-Rant & Wierckinska, 2021) found more %F_TMed in females than in males. These differences could be due to the methodology used, the number of samples, sampling site, differences in the AFD between the sexes, any selection pressure or other bias in the sample of animals available for the studies.

Fiber quality classification

There were significant effects of fiber quality classification on the incidence and degree of medullation. This result was to be expected as the assignment of fiber quality was determined based on the measured AFD and given that AFD was the best predictor of degree of medullation it is to be expected that medullation incidence reflects the AFD of the fiber quality classification.

These findings are consistent with the results obtained by Guillén and Leyva (2020) who found that as the fiber

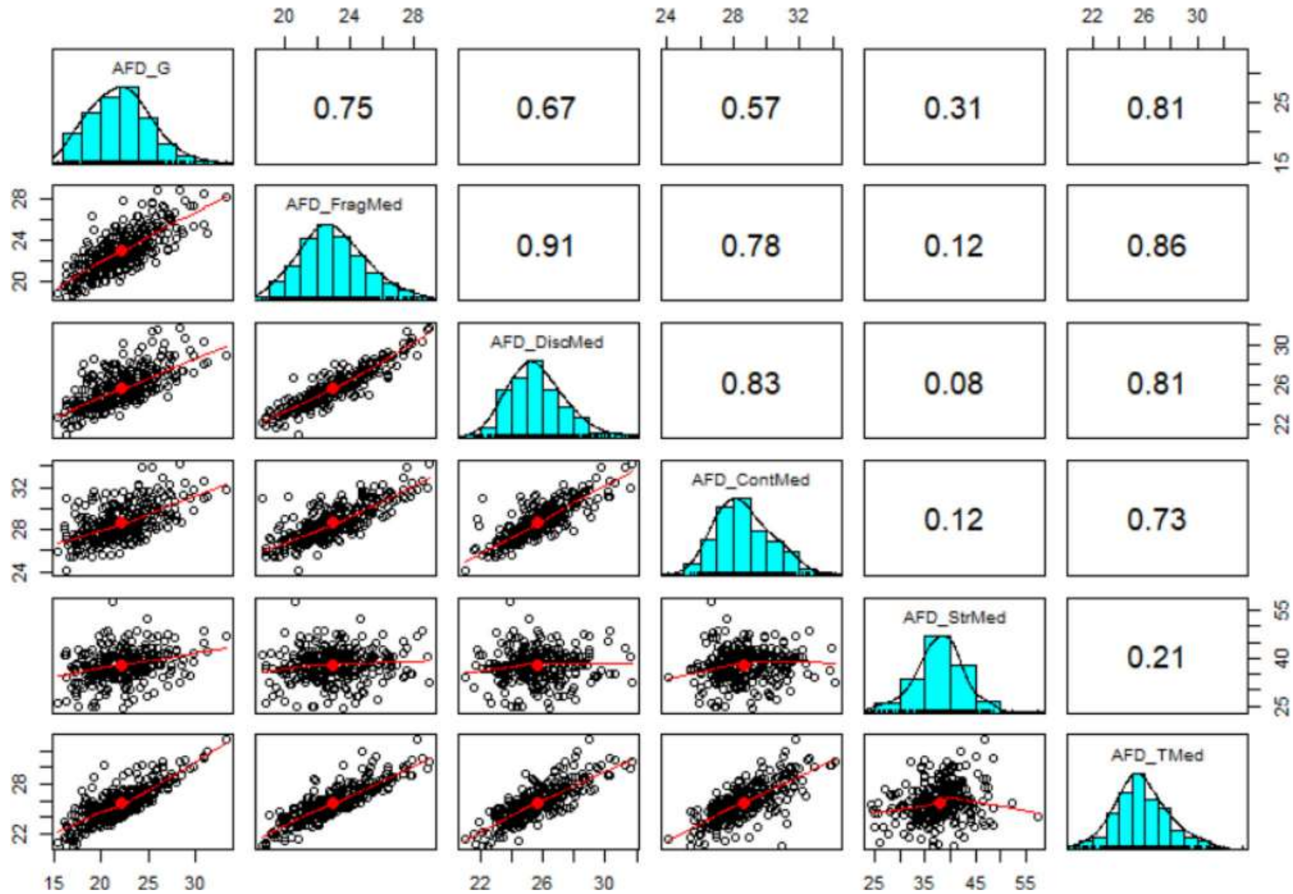

Figure 7. Matrix of dispersion, histogram and correlation between AFD of the different types of medullation of alpaca fibers. On the diagonal the distribution of the AFDs are observed, at the bottom the scatter plots are shown, and at the top the Pearson correlation coefficients are shown.

category decreases, the %F_TMed increases. Also, Córdova (2015), found greater medullation in lower and posterior anatomical regions of alpacas, where fibers with lower quality are found. For the first three shearings the incidence of StrMed fibers (0.33-0.76%), was higher than that required for mohair and cashmere fibers of high quality (SGS, 2003; McGregor B. , 2012).

At an industry level, these results suggest that medullation assessment obtained with the use of the Fiber Med device may assist in the assignment of raw fiber or processed tops for the potential end use of the fiber in textiles. This may be particularly so for next to skin applications for the Imperial and Super Baby classifications.

Development of the fleece and the incidence of medullation with increasing age at shearing

As the alpacas aged there was a sequence of fiber development which resulted in an increasing proportion of the fibers which were medullation and the degree of medullation increased in magnitude. This is in agreement with previous studies with llamas (Martinez, Iñiguez, & Rodríguez, 1997) and alpacas (Lupton, McColl, & Stobart, 2006; McGregor B. , 2006; Contreras, 2010; Pinares, Gutiérrez, Cruz, Burgos, & Gutiérrez, 2019; Aruquipa, 2015). As discussed in the previous section, this change in the incidence and degree of medullated fibres is explained by the increase in AFD. The explanation of this process in alpacas is similar with that observed in Merino sheep and Angora goats. Essentially, there are two stages of development of the fleece, the first is the evolution of the skin follicle population which is complete early in post-natal life, followed by the second stage which is the allometric maturation of the follicle population as the animals grow and their skin surface area increases. The process of medullation formation is not fully understood but appears dependent upon both AFD and biosynthesis of keratin. None of these mechanisms are 100% predictive, as is usual in biology, providing room for individual variation. At the time of maturation of the alpaca skin follicle population there are both primary and secondary skin follicles (Antonini, Gonzales, & Valbonesi, 2004), with the primary follicles producing hair type fibers many of which are medullated as they are relatively coarse. As these fiber animals grow the density of skin follicles declines as the skin area increases with a consequential proportional increase in the cross-sectional diameter of the skin follicles leading to the growth of fibers of greater fiber diameter. This allometric response in fiber diameter has been shown clearly with Merino sheep (McGregor & Butler, 2016), and Angora goats (McGregor, Butler, & Ferguson, 2012). Thus, heavier alpacas, sheep and goats produce coarser fiber compared with when they were lighter and smaller. It is usual for animals to keep growing as they age so harvesting the fiber at increasing ages is usually associated with increasing AFD. This response depends upon the seasonal nutrition of the animal as live weight loss leads to the production of finer fiber as the skin surface area reduces and skin follicle density increases. Such fiber diameter responses to changes in seasonal live weight, both increases and decreases, have been detected in alpacas (McGregor B. , 2002).

In the present study even in first-shearing animals, the incidence of ContMed fibers was greater than 5.0%. This is in line with the knowledge that the primary to secondary follicle ratio is about 1:9, meaning that 10% of the skin follicles are primary follicles. Thus, about half of the primary follicles of first-shearing animals are growing fibers with continuous medullation. When age increases there appears to be another process whereby the number of actively growing skin follicles decreases, sometimes in a cyclic seasonal pattern (Khan, et al., 2012) which further decreases skin follicle density. The net result of these changes in skin follicle density and the increase in AFD is that fibers develop medulla and the medulla becomes more prominent along the fibers (Villarroel, 1963; Carpio M. , 1991).

Formation of the medulla, which is essentially empty cells along the centre of the fiber shaft is not fully understood. It is believed to be related to disturbed keratinization in the follicular bulb (and is discussed in further detail elsewhere; McGregor et al., 2012) which occurs when the skin follicle diameter increases greater than about 20 µm related to insufficient synthesis of protein. Such a relationship was shown in mohair with increasing degree of medullation as fiber diameter increased (Lupton & Pfeiffer, 1998).

Comparisons of these results with previous reports

The present results can be compared with previous reports about the incidence of medullation in alpaca fiber as summarized in Table 1. Our results of the %F_TMed (41.36%±23.75) are similar compared with those in Table 1. Differences are most likely can be attributed to differences in the sampling and testing methodology (where most investigations only measured 100–200 fibers per sample), to the age and live weight of the animals, and to any genetic selection exerted on the sampled population. Detailed comparisons of the degree of medullation in alpaca between the present work and other studies are meaningless without details of the AFD of samples tested.

These results obtained demonstrate the presence of animals with good fiber fineness, which would be found in the Alpaca baby quality, however the demerit of quality would be reflected by the existence of fibers with %F_StrMed of 1.25 ± 1.25%. Likewise, the wide range found of the %F_StrMed found (between 0 and 16.24%), indicates the existence of alpacas with poor and good quality of their fleeces, not only for the fineness of their fibers, but also for their low or no incidence of StrMed fibers. Finally, the AFD_NoMed found (19.6 µm), was also similar or close to 19.1, 17.6, 21.7, 19.6 µm reported respectively by Aruquipa (2015), Pinares et al. (2019), Radzik and Wierckinska (2021) and Radzik et al. (2021). This similarity of results indicates that the different categories of medullated fibers are very defined around their AFD, but with overlap in relation to their variation (Figure 3) most likely related to differences in the AFD of the fiber samples. Radzik and Wierckinska (2021) graphed AFD by fiber category, showing total overlap of the AFD_DiscMed and AFD_ContMed. Radzik et al. (2021) found histograms of AFD_NoMed, AFD_DiscMed and AFD_ContMed that did not show normal distribution, and also showed high overlaps, which is different from the histograms of the present work. The results from Berolatti et al. (2021) also show normal distribution of the AFD of each of the fiber categories according to their medullation. The differences could be due to the low number of fibers evaluated per sample considered by Radzik and Wierckinska (2021) and Radzik et al. (2021), probably due to the laborious work that involves working under the projection microscope methodology.

Fiber med measurement

The Fiber Med device was able to quickly measure the incidence and fiber diameter of medullation fibers and categorize the medullation status of white alpaca fibers. This substantially reduced the time and cost of measurement. For Fiber Med to recognize the type of medullation in the fibers, it is necessary for the medulla of the fiber to be clearly distinguished. It is not possible to measure dark-colored fibers (black, brown, among others). In these cases, the bleaching of colored fibers is necessary. However, there are no procedures that allow colored wool fibers to be bleached without greatly affecting their structures (Liu, Hurren, & Wang, 2003)

The number of fibers evaluated per sample is important to achieve a reliable result (Lupton & Pfeiffer, 1998). The IWTO-8-04 procedure recommends at least 600 fiber per sample. The Fiber Med meets this requirement, since in 99.7% of samples in the present study more than 600 fiber per sample were measured. Only in one sample did it no meet this requirement, which was due to the small number of fiber snippets that the operator placed on the coverslip. This problem can be avoided through practice, recommending that there be between 8 and 15 fibers per field of view of the Fiber Med.

Conclusions

This investigation was able to efficiently use the Fiber Med device, which uses artificial intelligence, to automatically recognize fibers with different types of medullation and to determine the average diameter of each fiber. This provided over 630,000 measurements of alpaca fiber originating from 302 alpacas of varying ages and from two locations.

The mean %F_Tmed was 41.36 with a standard deviation of 23.75, which indicates a high variability, with a high incidence of FragMed and ContMed fibers (17.12 and 15.36%) respectively, and with 1.25% of StrMed fibers.

The incidence of medullation was primarily affected by the AFD and origin of the alpacas. Any effect of age at shearing and fiber quality was not significant when AFD was initially accounted for, and the sex of the alpacas was not a significant determinant of medullation. There was a difference between breed of alpaca and the total incidence of medullation, primarily related to a higher incidence of fragmented and discontinuous medullation in Huacaya alpaca.

Differences between the results of published investigations into the incidence of various categories of medullation are most likely related to differences in the AFD of the samples measured. There is clear evidence that genetic selection can reduce the incidence of medullation as the fiber from the selected population at Pacomarca had significantly less medullation compared with the unselected population at Lachocc.

There appears to be a small incidence of strongly medullated fibers in alpaca harvested at all ages and in the finest three qualities of fiber classification. This incidence is well above those tolerable for mohair and cashmere fibers of high quality. It appears that direct selection pressure will be required specifically on strongly medullated fibers if this characteristic is to be minimized.

Implications

Since to the Fiber Med device provided a direct, fast and low-cost measurement of the incidence of medullation in alpaca fibers it is therefore has a practical application to help improve fiber quality, sorting, marketing and processing of white alpaca fiber.

Given the strong association between AFD and the incidence of medullation the focus for improving alpaca fiber quality should remain on reducing AFD given that AFD is the primary determinant of price and reductions in AFD lead to reductions in the incidence of medullation. However, to reduce other sources of variation contributing to the incidence of medullation and particularly strongly medullated fibers in all categories of alpaca fiber, the measurement of the incidence of medullation should become a routine assessment in alpaca breeding programs. The use of Fiber Med measurements of medullation will help determine the genetic parameters related to medullation which are required as the first step in establishing selection criteria and breeding indices.

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