CSIRO PUBLISHING
www.publish.csiro.au/journals/ajar *Australian Journal of Agricultural Research*, 2004, **55**, 433–442

Sources of variation in fibre diameter attributes of Australian alpacas and implications for fleece evaluation and animal selection

B. A. McGregor[A] *and K. L. Butler*[B]

[A]Primary Industries Research Victoria, Attwood, Vic. 3049, Australia; email: bruce.mcgregor@dpi.vic.gov.au
[B]Primary Industries Research Victoria, Werribee, Vic. 3030, Australia.

Abstract. Sources of variation in fibre diameter attributes of Australian alpacas and implications for fleece evaluation and animal selection were investigated using data collected in the years 1994–97, from 6 properties in southern Australia. Data were analysed using REML (multiple regression analysis) to determine the effect on mean fibre diameter (MFD) and coefficient of variation of MFD (CV(FD)) of age, origin (property), sex (entire male, female), breed (Huacaya, Suri), liveweight, fibre colour, individual, and interactions of these effects. The mean (n = 100) age (range) was 4.2 years (0.1–11.9), liveweight 72.0 kg (12.0–134 kg), MFD 29.1 μm (17.7–46.6 μm), CV(FD) 24.33% (15.0–36.7%).

A number of variables affected MFD and CV(FD). MFD increased to 7.5 years of age, and correlations between MFD at 1.5 and 2 years of age with the MFD at older ages were much higher than correlations at younger ages. Fibre diameter 'blowout' (increase with age) was positively correlated with the actual MFD at ages 2 years and older. There were important effects of farm, and these effects differed with year and shearing age. Suris were coarser than Huacayas with the effect reducing with increased liveweight; there was no effect of sex. Fleeces of light shade were 1 μm finer than dark fleeces. CV(FD) declined rapidly between birth and 2 years of age, reaching a minimum at about 4 years of age and then increasing; however, CV(FD) measurements on young animals were very poor predictors of CV(FD) at older ages, and the response of CV(FD) to age differed with farm and year. Suris had a higher CV(FD) than Huacayas on most properties, and MFD, liveweight, and sex did not affect CV(FD). Fleeces of dark shade had higher CV(FD) than fleeces of light shade in 2 of the years. It is concluded that there are large opportunities to improve the MFD and CV(FD) of alpaca fibre through selection and breeding. The potential benefit is greatest from reducing the MFD and CV(FD) of fibre from older alpacas, through reducing the between-animal variation in MFD and CV(FD). Sampling alpacas at ages <2 years is likely to substantially decrease selection efficiency for lifetime fibre diameter attributes.

Additional keywords: camelid, age, origin, breed, fleece colour, repeatability.

Introduction

In Australia, fibre production from alpacas began in 1858 (Carter 1996) but the industry failed to establish. In the 1980s, alpacas were imported from Chile and more recently from Peru (Hack *et al*. 1999). Husbandry and veterinary practices for alpacas have been described by Calle-Escobar (1984) and Fowler (1989). As with wool, the physical fibre attribute of greatest economic importance in alpaca fibre is mean fibre diameter (McGregor 1997). In Merino wool, the variation in fibre diameter affects 'ends-down' in spinning, yarn strength, bending rigidity of yarn, and levels of skin comfort associated with prickle to the extent that a change of 5% units in coefficient of variation of mean fibre diameter is the same as a change of about 1 μm in mean fibre diameter (Martindale 1945; Roberts 1961; Ly 1983; Naylor *et al*. 1995; Lamb 1997; Butler 2001). This is likely to be the case for alpaca fibre, since both the processing machinery and the textile end products are similar to those for apparel wool.

The productivity of Australian alpacas has been investigated on commerical properties in southern Australia (Tuckwell *et al*. 1995; Hack *et al*. 1999). This work revealed a large variation in the mean fibre diameter and in the variation in fibre diameter of alpaca fleeces (McGregor 1999). Aylan-Parker and McGregor (2002) described the most appropriate sampling methods and the sampling variance in determining the mean fibre diameter (MFD) and variation in fibre diameter of alpaca fleeces. The inheritance of alpaca fibre attributes has been described in young Australian alpaca (Ponzoni *et al*. 1999) as well as in South American (Calle-Escobar 1984) and New Zealand (Wuliji *et al*. 2000) alpaca.

 10.1071/AR03073 0004-9409/04/040433

There is limited information about the sources of variation in alpaca fibre diameter attributes. Wuliji *et al.* (2000) reported year effects on the mean fibre diameter of alpaca fibre but was unable to detect any effect of sex, fleece colour, or other variable. Wuliji and co-workers did not investigate any environmental effects on alpaca mean fibre diameter coefficient of variation (CV(FD)). Alpaca breeders need to understand the sources of variation in the attributes of alpaca fibre for effective fibre testing, genetic and phenotypic improvement programs, live animal assessment, purchasing decisions, and alpaca fibre classing and selling systems.

This paper reports the analysis of sources of variation in fibre diameter attributes of Australian alpacas. The objectives of this work were to determine the effects on alpaca MFD and CV(FD) of age, property, sex, breed, fibre colour, liveweight, and individual, and interactions of these effects.

Materials and methods

Animals and measurements

Data were collected in the years 1994–97, from 5 alpaca producers in southern Australia (Hack *et al.* 1999). As one producer moved from an unimproved hilly location with skeletal soils to a property with improved perennial pasture on deep basaltic soils, we have treated the data as coming from 6 separate properties. All animals from each particular flock studied were measured and used in the analysis. Data included animal identity, age at shearing, breed (Huacaya, Suri), sex, origin (property), year, liveweight at shearing (for 1000 of 1100 records), fleece colour, and fleece weight. Midside saddle fleece samples (Aylan-Parker and McGregor 2002) were collected at shearing (281 males, 836 females). Suris were found on 4 properties (n = 228). The samples were tested using the optical fibre diameter analyser (OFDA100) at the Victorian Institute of Animal Science following international standards for fibre testing (Baxter *et al.* 1992; IWTO 1988, 1995). Summary information for this study has previously been presented (McGregor 1999).

Table 1. Definitions of abbreviations used in model formula

Abbreviation	Definition
MFD	Mean fibre diameter
CV(FD)	Coefficient of variation of fibre diameter
Animal	Individual animal identifier
FARM	Farm origin
YEAR	Year of shearing
BREED	Breed of alpaca (Huacaya, Suri)
SHADE	Alpaca fibre colour base, (dark or light)
Natural colour	The 6 natural colours of the fleece (black with dark and medium brown, grey, other dark mixtures, light brown, fawn and white)
SEX	Sex of animal (entire male, female)
LWT	Liveweight at shearing (kg)
Age	Age at shearing (years)
Lage	$\text{Log}_{10}(\text{Age} + 0.5)$
$(\text{Lage})^2$	Lage × Lage
Tage	Lage if Lage ≤0.9 and 0.9 if Lage >0.9
$(\text{Tage})^2$	Tage × Tage

Statistical analyses

Data were analysed by a multiple regression approach, using a restricted maximum likelihood (REML) algorithm, to determine the relationships between MFD and CV(FD) and the other factors and variables (GenStat Committee 2000). The best predictive model was developed with terms being added or rejected on the basis of Wald tests for fixed effects and change in deviance tests for random effects. Some of the terms were transformed and interactions between terms calculated. Terms used in the model are presented in Table 1; the statistical significance of rejected and included terms are presented in Tables 2 and 3. Rearing status was not included as all cria were single-born and single-reared.

Responses to the major effects were calculated and graphed. Some graphs have been simplified by excluding similar overlaying curves. Standard errors of difference between means (s.e.d.), standard errors (s.e.) and standard deviations (s.d.) are presented as appropriate.

We calculated, using the model parameters, the ‘specific age repeatability ratio’ (SARR) (Butler and McGregor 2002) as follows:

$$\text{SARR} = \sigma_a^2/(\sigma_a^2 + \sigma_e^2)$$

Table 2. Statistical significance of rejected and included terms in the REML model for mean fibre diameter

All those terms marginal to those listed as terms retained are included in the model. A point indicates the interaction between the terms

Adjustment to model	Type of test	χ^2 value	d.f.	*P*-value
		Terms rejected		
Natural colour	Wald	1.3	5	0.94
SEX	Wald	2.3	1	0.13
FARM.SHADE	Wald	7.1	5	0.21
YEAR.SHADE	Wald	0.6	3	0.90
BREED.SHADE	Wald	0.8	1	0.37
SHADE.Tage	Wald	3.5	1	0.06
$(\text{Tage})^3$	Wald	0.6	1	0.56
Lage[A]	Wald	0.0	1	1.00
FARM.(Tage)^2	Wald	4.4	5	0.49
YEAR.Tage	Wald	6.1	3	0.11
BREED.Tage	Wald	0.0	1	1.00
LWT.Tage	Wald	1.6	1	0.21
FARM.BREED	Wald	1.9	4	0.75
YEAR.BREED	Wald	3.2	3	0.36
YEAR.LWT	Wald	5.8	3	0.12
FARM.LWT	Wald	4.1	5	0.54
$(\text{LWT})^2$	Wald	0.7	1	0.40
Animal.LWT	Wald	462.6	460	0.46
		Terms retained		
Animal.Tage[B]	Change in deviance	126.4	2	$<10^{-12}$
Correlation between Animal and Animal.Tage	Change in deviance	111.9	1	$<10^{-12}$
FARM.YEAR	Wald	54.6	9	1.5×10^{-8}
$(\text{Tage})^2$	Wald	19.1	1	1.2×10^{-5}
FARM.Tage	Wald	19.5	5	0.0016
SHADE	Wald	8.9	1	0.0029
BREED.LWT	Wald	4.0	1	0.046

[A]For testing if there is any change above $\log_{10}$(shearing age + 0.5) = 0.9 (i.e. 7.5 years of age).
[B]Including correlation with Animal (i.e. random animal slope and its covariance with random animal main effect).

Table 3. Statistical significance of rejected and included terms in the REML model for coefficient of variation of fibre diameter
All those terms marginal to those listed as terms retained are included in the model. A point indicates the interaction between the terms

Adjustment to model	Type of test	χ^2 value	d.f.	*P*-value
Terms rejected				
Natural colour	Wald	2.9	5	0.72
SEX	Wald	0.0	1	1.00
MFD	Wald	0.0	1	1.00
LWT	Wald	2.9	1	0.089
YEAR.BREED	Wald	6.3	3	0.098
BREED.Lage	Wald	0.7	1	0.40
BREED.SHADE	Wald	0.6	1	0.44
SHADE.Lage	Wald	3.3	1	0.069
$(\text{Lage})^3$	Wald	0.4	1	0.53
Tage	Wald	1.1	1	0.29
FARM.$(\text{Lage})^2$	Wald	2.4	4	0.66
YEAR.$(\text{Lage})^2$	Wald	1.9	3	0.59
FARM.SHADE	Wald	5.3	4	0.26
Terms retained				
Animal.Lage[A]	Change in deviance	63.2	2	$<10^{-12}$
Correlation between Animal and Animal.Lage	Change in deviance	28.6	1	9.0×10^{-8}
$(\text{Lage})^2$	Wald	65.3	1	$<10^{-12}$
YEAR.SHADE	Wald	16.2	3	0.0010
FARM.BREED	Wald	11.1	3	0.011
FARM.YEAR[B]	Wald	33.4	8	5.2×10^{-5}
YEAR.Lage[B]	Wald	13.3	3	0.0040
FARM.Lage[B]	Wald	12.6	4	0.013
FARM.YEAR.Lage	Wald	12.0	8	0.151

[A]Including correlation with Animal (i.e. random animal slope and its covariance with random animal main effect).
[B]Compared with model excluding 3-factor interaction FARM.YEAR.Lage.

where σ_a^2 is variance of all random factors pertinent to an individual animal at a specific age, and σ_e^2 is residual error variance.

SARR includes genetic factors, all environmental factors that persist over a lifetime (e.g. any prenatal nutritional factors on follicle development), and the interaction of these genetic and environmental factors. SARR differs from heritability only in that σ_a^2 includes the inherent lifetime environmental factors. SARR can have a different value for each alpaca age.

We also calculated, using the model parameters, 'repeatable within-animal correlations' (RAC) (Butler and McGregor 2002) between 2 ages as the correlation between the inherent lifetime animal factors at those 2 ages. This is defined as the correlation between the sum of all random factors pertinent to an individual animal, at 2 specific ages. An RAC between specific ages and a slope parameter associated with individual animal responses to age was also calculated (Butler and McGregor 2002).

Over 15% of the data comprised measurements of cria (<12 months of age) and tui (12–24 months of age) that were not shorn at the time of sampling. It became clear that to exclude these measurements in order to include fleece weight would considerably reduce the potential value of the results. In commercial practical terms, the value of a fleece weight measurement for purchasing decisions is limited by a prospective purchaser's inability to control shearing interval. For these reasons, fleece weight was excluded from further analyses.

Results

The mean and range in age was 4.2 years (0.1–11.9 years) and in liveweight was 72.0 kg (12.0–134 kg).

Mean fibre diameter

Mean fibre diameter averaged 29.1 μm (range 17.7–46.6 μm). The final REML model had both fixed and random terms, which could be symbolically represented (GenStat Committee 2000) as as follows.

Fixed model: MFD = FARM*(YEAR+ Tage) + $(\text{Tage})^2$ + BREED*LWT +SHADE

Random model: Animal + Animal.Tage

allowing correlation between these 2 terms within an individual animal. This implies that the random factors pertinent to the *i*th individual animal can be written as:

$$a_i + b_i \times \text{Tage}$$

where :

$$\text{Tage} = \begin{cases} \log_{10}(\text{Age}+0.5) & \text{if } \log_{10}(\text{Age}+0.5) \leq 0.9 \\ 0.9 & \text{if } \log_{10}(\text{Age}+0.5) > 0.9 \end{cases}$$

and (a_i,b_i) pairs are independent bivariate normal random variables. This implies that a_i is independent of a_j and b_j, and b_i is independent of a_j and b_j, for different animals *i* and *j*. However, a_i and b_i are correlated for the same animal *i*. The parameter b_i is the slope parameter.

Effect of age

The form of Tage in the model implies that MFD responded to age until the alpacas reached an age of about 7.5 years, corresponding to $\log_{10}$(age + 0.5) equalling about 0.9. There was no further systematic response to age for animals older than 7.5 years. This response to age differed with origin of animal (ie. FARM), and also varied in a random fashion between individual animals in any one flock.

Between-animal variation in response to age. The variation between animals increased as age at shearing increased (Table 4). The estimates for between-animal variation were precise as the s.e. for each animal s.d. was very low. The specific age repeatability ratio of MFD increased with age of shearing (Table 4).

The RAC of MFD at one age with the next older age increased as shearing age increased (bold diagonal in Table 5). At shearing ages of 0.5 and 1 years the RAC correlation between MFD and MFD at an older age declined substantially as the latter age increased. At shearing ages of 1.5 and 2 years the RAC of MFD and MFD at an older age declined marginally, at shearing ages 3–5 the change was negligible, and for 6 years and older was essentially 1. The RAC of age and slope (Table 6) increased with age.

Table 4. Between-animal variation (animal standard deviation, s.d.), accuracy in estimation of animal s.d. (s.e.(s.d.)), and specific age repeatability ratio (SARR) estimates at different ages for mean fibre diameter of midside alpaca fibre

Age (years)	Animal s.d.	s.e.(s.d.)	SARR	s.e. (SARR)
0.5	1.24	0.15	0.606	0.058
1	1.52	0.12	0.697	0.032
1.5	1.79	0.11	0.761	0.023
2	2.02	0.12	0.803	0.018
3	2.40	0.13	0.852	0.014
4	2.69	0.15	0.879	0.012
5	2.93	0.17	0.896	0.011
6	3.13	0.19	0.908	0.010
7	3.31	0.20	0.916	0.009
8	3.38	0.21	0.919	0.009
Residual error	1.42	0.05		

Age and origin interaction. The increase in MFD with age was affected by the origin of animals; that is, farm property management (in all its variations) affected the increase with age (Fig. 1).

Effect of breed and liveweight

The effect of breed varied with liveweight. The mean difference between the breeds was 1.5 µm, with Suris being coarser than Huacayas up to liveweights of 110 kg (Fig. 2). For every 10 kg increase in liveweight, MFD increased 0.64 µm (s.e. 0.085) for Huacayas and 0.36 µm (s.e. 0.139) for Suri (s.e.d. between these values was 0.137, $P = 0.046$ for interaction of breed and linear liveweight response). As liveweight increased, MFD increased.

Effect of sex

There was no effect of sex on MFD (males 28.4 µm, females 28.8 µm, s.e.d. 0.3 µm).

Effect of fleece colour

Fleeces classified as dark shade were 1.0 µm coarser than those classified as light shade (dark 29.2 µm, light 28.2 µm, s.e.d. 0.32). Dark shade fleeces included those with natural colour described as black and dark and medium brown (29.2 µm), grey (29.2 µm), and combinations of these colours (29.1 µm). Light shade fleeces were fawn (28.3 µm), light brown (27.7 µm), and white and combinations of these

Table 5. REML estimates for repeatable within-animal correlations between mean fibre diameter at one shearing age and mean fibre diameter at another shearing age, assuming the fitted model
Correlation for ages >8 are the same as for age 8

Age (years)	0.5	1	1.5	2	3	4	5	6	7
1	**0.945**								
1.5	0.880	**0.987**							
2	0.831	0.967	**0.996**						
3	0.767	0.935	0.980	**0.994**					
4	0.728	0.913	0.967	0.986	**0.998**				
5	0.701	0.896	0.956	0.979	0.995	**0.999**			
6	0.681	0.883	0.947	0.973	0.992	0.998	**1.000**		
7	0.666	0.873	0.941	0.968	0.989	0.996	0.999	**1.000**	
8	0.660	0.870	0.938	0.966	0.988	0.995	0.998	1.000	**1.000**

Table 6. Estimated variances and covariances of animal slope and age means and the repeatable within-animal correlation (RAC) between mean fibre diameter at a given age and slope parameter for change in mean fibre diameter

Age	Slope[A] variance	s.e.	Age[A] variance	s.e.	Covariance of slope and age[A]	s.e.	RAC of age and slope
0.5	9.179	2.147	1.536	0.373	1.363	0.650	0.363
1	9.179	2.147	2.301	0.352	2.979	0.503	0.648
1.5	9.179	2.147	3.188	0.400	4.126	0.553	0.763
2	9.179	2.147	4.074	0.467	5.015	0.668	0.820
3	9.179	2.147	4.926	0.545	5.742	0.790	0.854
4	9.179	2.147	5.736	0.630	6.357	0.906	0.876
5	9.179	2.147	7.233	0.807	7.359	1.109	0.903
6	9.179	2.147	8.585	0.986	8.159	1.278	0.919
7	9.179	2.147	9.817	1.160	8.825	1.423	0.930
8	9.179	2.147	10.95	1.330	9.395	1.548	0.937
9	9.179	2.147	11.42	1.400	9.624	2.146	0.940

[A]Variance divided by residual variance of 2.015.

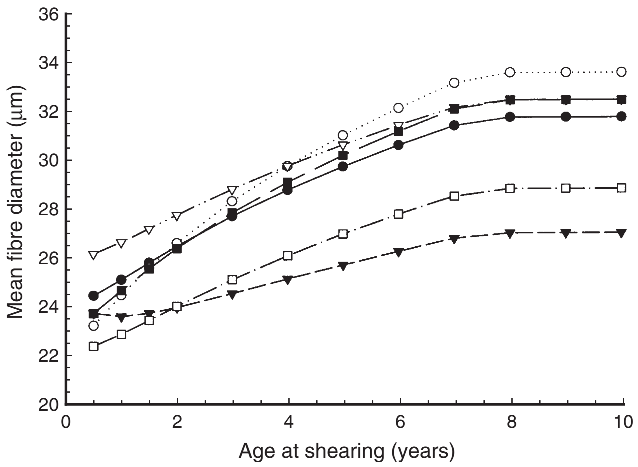

Fig. 1. Responses of mean fibre diameter to shearing age after adjustment for year, liveweight, shade, and breed on 6 different farms (origin of animal).

natural colours (28.2 µm). Other than the differences between dark and light shade fleeces, there was no evidence of difference in MFD within natural colour groups.

Effect of origin and management

There were important effects of origin and interactions between origin and year, indicating that management affects the measured result in any one year. The presentation of the graphs (Fig. 3) has been standardised by making the average MFD for each property the same. One property reduced MFD over time by 2 µm, while another recorded an increase of 3 µm during 4 years.

Coefficient of variation of fibre diameter

The mean CV(FD) was 24.33% (range 15.0–36.7%). The final REML model had different terms to the MFD model.

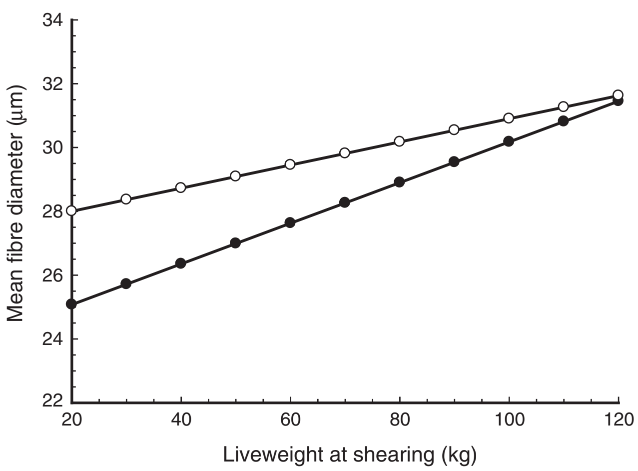

Fig. 2. Effect on mean fibre diameter of breed (Suri ○, Huacaya ●) and liveweight adjusted for shearing age, farm, shade, and year.

The model for CV(FD) can be represented (GenStat Committee 2000) as follows.

$$\text{Fixed model: CV(FD)} = \text{FARM*BREED} + \text{YEAR*SHADE} + \text{FARM*YEAR*Lage} + (\text{Lage})^2$$

$$\text{Random model: Animal} + \text{Animal.Lage}$$

allowing correlation between these 2 terms within an individual animal. This implies that the random factors pertinent to the *i*th individual animal can be written as:

$$a_i + b_i \times \text{Lage}$$

where :

$$\text{Lage} = \log_{10}\left(\text{Age} + 0.5\right)$$

and (a_i, b_i) pairs are independent bivariate normal random variables. The parameter b_i is the slope parameter.

Effect of age

There were strong effects of age at shearing that differed with origin and year.

Between-animal variation. The variation between animals increased with age of shearing from 1.5 years (Table 7). Estimates for between-animal variation were precise as the s.e. of the animal s.d. for each age was very low.

The specific age repeatability ratio of CV(FD) was relatively high and increased with age of shearing from 1.5 years of age (Table 7).

The RAC of CV(FD) at one age with the next age was very high at all ages (bold diagonal in Table 8). At all shearing ages the RAC of CV(FD) and CV(FD) at later older ages declined substantially as the difference between the 2

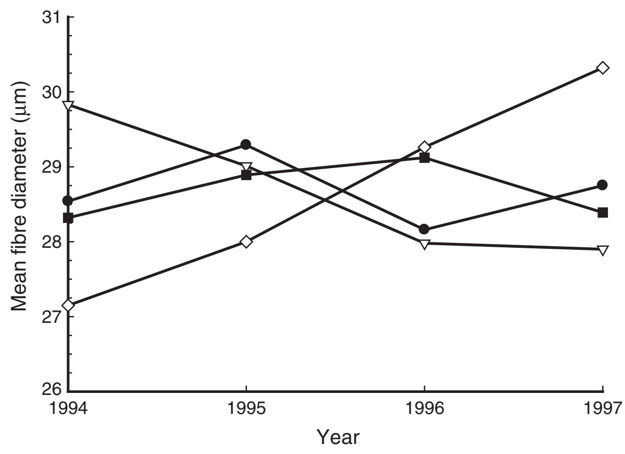

Fig. 3. Changes in mean fibre diameter with year at various properties after adjustment for liveweight, shearing age, shade, and breed. For clarity, only properties that had measurements taken in all 4 years are presented. Mean fibre diameter has been standardised to make the average mean fibre diameter over the 4 years the same for each property.

Table 7. Between-animal variation (animal standard deviation, s.d.), accuracy in estimation of animal s.d. (s.e.(s.d.)), and specific age repeatability ratio (SARR) estimates at different ages for coefficient of variation of fibre diameter of midside alpaca fibre

Age (years)	Animal s.d.	s.e.(s.d.)	SARR	s.e. (SARR)
0.5	1.83	0.21	0.769	0.031
1	1.64	0.19	0.729	0.030
1.5	1.61	0.18	0.721	0.027
2	1.64	0.18	0.729	0.025
3	1.79	0.17	0.761	0.022
4	1.95	0.18	0.793	0.020
5	2.12	0.18	0.818	0.019
6	2.27	0.18	0.837	0.018
7	2.40	0.19	0.853	0.017
8	2.53	0.19	0.865	0.017
9	2.64	0.19	0.875	0.016
10	2.75	0.19	0.883	0.015
Residual error	1.5553	0.05		

ages increased. At shearing ages of 0.5 and 1 the decline was very large and the decline at 1.5, 2 and 3 years of age was still important, while changes at later ages were less.

The RAC of age and slope (Table 9) shows that measurements of CV(FD) on young animals were very poor predictors of CV(FD) at older ages.

Age, origin, and year interaction. The age and origin of animals and the year of measurement all affected CV(FD). CV(FD) declined with age rapidly until about 2 years of age. CV(FD) minimum was reached at about 2–4 years of age followed by a slower increase in CV(FD) with age. The response to age differed substantially between origins and years (Fig. 4).

Effect of breed

Differences between Huacaya and Suri breeds differed with origin (Table 10). There was no difference on Property 1 but differences were detected on 3 other farms. (Farms with only one breed have been excluded from Table 10.)

Effect of liveweight

The change in CV(FD) was –0.1555% (s.e. 0.09085) per 10 kg increase in liveweight ($P = 0.089$, Table 3). This was equivalent to a decline in CV(FD) of 1% with an increase in liveweight of 65 kg.

Effect of sex

There was no evidence of an effect of sex on CV(FD) (males 25.31%, females 25.35%, s.e.d. 0.323%, Table 3).

Effect of fleece colour

There was evidence that dark shade fleeces had higher CV(FD) values in 2 of the 4 years but not in the other 2 years compared with light-shaded fleeces (Table 11). Within the 2 fleece SHADE groups there was no significant difference ($P > 0.1$, Table 3) between natural colours.

Effect of mean fibre diameter

There was no evidence of an effect of MFD on CV(FD). The change in CV(FD) as MFD increased was –0.00681% per μm (s.e. 0.03183, $P > 0.1$).

Discussion

This analysis has shown that a number of variables affect mean fibre diameter and the coefficient of variation of fibre diameter.

Between-animal variation in repeatable mean fibre diameter increase with age

A major feature of the data was the large, repeatable animal-to-animal variation in the responses of MFD and CV(FD) to age. In the present work we investigated this issue using a statistical model that was sufficiently rich to allow lifelong effect differences between animals in the rate of increase of MFD and CV(FD) with age. These lifelong effect differences are sometimes referred to as permanent environmental variation. This is achieved by using a random coefficient regression model approach (Butler and

Table 8. REML estimates for repeatable within-animal correlation between coefficient of variation of fibre diameter at one shearing age and coefficient of variation of fibre diameter at another shearing age, assuming the fitted model

Age (years)	0.5	1	1.5	2	3	4	5	6	7	8	9
1	**0.958**										
1.5	0.865	**0.973**									
2	0.761	0.915	**0.984**								
3	0.580	0.790	0.910	**0.970**							
4	0.449	0.687	0.836	0.921	**0.988**						
5	0.355	0.608	0.776	0.876	0.967	**0.995**					
6	0.285	0.548	0.727	0.839	0.946	0.984	**0.997**				
7	0.231	0.501	0.688	0.807	0.926	0.973	0.992	**0.998**			
8	0.189	0.462	0.655	0.780	0.909	0.962	0.985	0.995	**0.999**		
9	0.154	0.431	0.628	0.758	0.894	0.952	0.978	0.991	0.997	**0.999**	
10	0.125	0.404	0.605	0.738	0.880	0.943	0.972	0.987	0.994	0.998	**1.000**

Table 9. Estimated variances and covariances of animal slope and age means and repeatable within-animal correlation (RAC) between coefficient of variation of diameter at a given age and slope parameter for change in coefficient of variation of fibre diameter

Age (years)	Slope[A] variance	s.e.	Age[A] variance	s.e.	Covariance of slope and age[A]	s.e.	RAC of age and slope
0.5	9.255	2.114	3.337	0.585	–2.653	0.920	–0.477
1	9.255	2.114	2.690	0.403	–1.021	0.621	–0.205
1.5	9.255	2.114	2.579	0.352	0.134	0.474	0.027
2	9.255	2.114	2.692	0.347	1.030	0.444	0.206
3	9.255	2.114	3.190	0.390	2.382	0.560	0.438
4	9.255	2.114	3.821	0.472	3.392	0.725	0.570
5	9.255	2.114	4.482	0.572	4.198	0.879	0.652
6	9.255	2.114	5.140	0.682	4.869	1.014	0.706
7	9.255	2.114	5.781	0.795	5.444	1.134	0.744
8	9.255	2.114	6.400	0.909	5.947	1.241	0.773
9	9.255	2.114	6.996	1.021	6.394	1.337	0.795
10	9.255	2.114	7.569	1.131	6.796	1.424	0.812

[A]Variance divided by residual variance of 2.419.

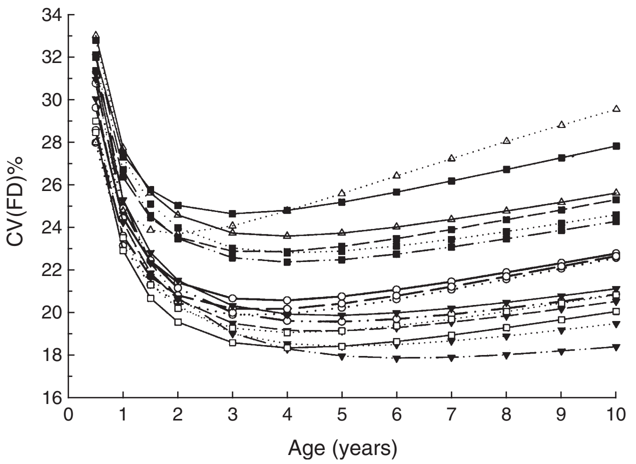

Fig. 4. Responses of coefficient of variation of fibre diameter (CV(FD)) to shearing age after adjustment for shade and breed on different farms (origin of animal) and in different years. Some data have been deleted to simplify the graph. Years have different line styles. Each farm has a different symbol.

Table 10. Effect of breed at different farms on the coefficient of variation of fibre diameter after adjustment for differences in shearing age, year, and shade

Farm	Suri	Huacaya	s.e.d.
1	26.62	26.36	0.636
2	28.24	24.52	1.959
3	24.88	21.66	1.185
4	28.23	23.80	1.477

Table 11. Effect of fleece shade in different years on the coefficient of variation of fibre diameter (%) after adjustment for differences in shearing age, property, and breed

Year	Dark	Light	s.e.d.[A]
1994	25.18	23.99	0.436
1995	24.81	23.79	0.369
1996	23.81	24.06	0.393
1997	24.77	24.31	0.408

[A]These s.e.d.s are only for comparisons within years.

McGregor 2002). In this approach a SARR is derived for each age from the parameters of the model. This implies that there is a separate SARR for each age. Similarly, separate RAC can be calculated between each pair of ages (Butler and McGregor 2002).

The traditional method of investigating heritable and repeatable changes in fibre diameter with age has been to calculate genetic and repeatable parameters, such as heritabilities, on contrasts of MFD measured at various ages (Cottle *et al.* 1995; Hickson *et al.* 1995). As pointed out by other authors (James 1998; Hill *et al.* 1999), this approach can lead to the detection of spurious changes in repeatable and heritable MFD with age that have no basis in reality. The statistical method used in this paper does not suffer from this limitation (Butler and McGregor 2002). In fact, this paper appears to be the first study to examine repeatable (or heritable) increases in MFD with age for alpacas/sheep/goats using a statistical technique that does not suffer from this deficiency.

The term 'micron blowout' is commonly used in the wool industry to describe the increase in MFD with age that is not due to short-lived environmental influences. According to Cottle *et al.* (1995), 'There is a common belief in industry that sheep (and bloodlines) vary in their ability to maintain, or increase less than average, average fibre diameter throughout their lifetime or when feed is plentiful, i.e. express lower "micron blowout"'. The repeatable animal-to-animal variation in responses of MFD to age of the animal can be reasonably referred to as between-animal variation in 'micron blowout'. The following simple calculations illustrate the size of this effect for mean fibre diameter.

Depending on the property, the average increase in MFD between ages 0.5 and 7.5 years (7.5 years being the approximate age before the response plateaus) is around 7.5 µm (Fig. 1). Thus, for our model, the increase for an individual animal at a typical property equals:

$$7.5 + (\text{deviation of the slope for the individual animal}) \times (\log_{10}(7.5 + 0.5) - \log_{10}(0.5 + 0.5))\ \mu\text{m}$$

Therefore an estimate of the 95% probability range for the increase in mean fibre diameter from 0.5 to 7.5years of age is:

$$7.5 \pm 1.96 \times \log_{10}(8) \times \sqrt{\text{var(individual animal slope)}}\ \mu\text{m}$$

$$= 7.5 \pm 1.96 \times \log_{10}(8) \times \sqrt{9.179 \times 2.015}$$ (see second column and footnote Table 6) µm

$$\approx 7.5 \pm 7.5\ \mu\text{m}.$$

It should be noted that this calculation cannot validly be calculated from the best linear unbiased predictors of the individual animal slopes because these predictors are shrunk (GenStat Committee 2000, p. 436), and hence their variance will be less than the variance of the true individual animal slopes.

Thus, it is estimated that 95% of the repeatable increases in MFD from 0.5 to 7.5 years of age will be between 0 and 15 µm. This implies that repeatable animal-to-animal variation is such that some alpacas will not increase their fibre diameter at all from a young to an old age, while some other alpacas will increase their fibre diameters about 15 µm.

Furthermore, the increase in fibre diameter with age is only weakly correlated with the inherent animal fibre diameter at a young age, as indicated by the RAC of 0.5 years age and slope being only 0.363 (Table 6). It would appear that the issue of finding the cause of differences in 'micron blowout', whether genetic or environmental, is crucial in being able to control fibre diameter of Australian alpacas through their lifetime.

The existence and possible cause of substantial 'micron blowout' in Merino sheep is highly controversial within the stud Merino breeding industry. However, the existence of huge differences in 'micron blowout' is confirmed, beyond any reasonable doubt, by our results for Australian alpacas. This is clearly one of the most important issues that needs addressing within the Australian alpaca industry.

The between-animal standard deviation, as reported in Table 4, is the combined effect of genetic variation and permanent environmental variation which has a lifelong effect. An example of such a lifelong environmental effect could be pre- and post-natal nutrition that affects follicle development. Thus, the between-animal standard deviation in this study will be at least as large as the between-animal genetic variation, and they will only be equal when there is no permanent environmental variation that has a lifelong effect.

Pre-natal skin follicle development in alpacas is similar to the development of fibre follicles in sheep (Yi 1995). It may therefore be reasonably assumed that the type of environmental effects that affect the pre-natal development of fibre follicles in sheep (Turner and Young 1969) also affect the fibre follicle development of alpacas.

Between-animal variation in repeatable CV(FD) increase with age

Similar calculation can be done for CV(FD). Depending on the property, the average decrease in CV(FD) between ages 0.5 and 7.5 years is around 8% (Fig. 4). Thus, for our model, the change for an individual animal at a typical property equals:

$$-8 + (\text{deviation of the slope for the individual animal}) \times (\log_{10}(7.5 + 0.5) - \log_{10}(0.5 + 0.5))\%$$

Therefore, an estimate of the 95% probability range for the change in CV(FD) from 0.5 to 7.5years of age is:

$$-8 \pm 1.96 \times \log_{10}(8) \times \sqrt{\text{var(individual animal slope)}}\ \%$$

$$= -8 \pm 1.96 \times \log_{10}(8) \times \sqrt{9.255 \times 2.419}$$ (see second column and footnote Table 9) %

$$\approx -8 \pm 8\%$$

Thus, it is estimated that 95% of the repeatable decreases in CV(FD) from 0.5 to 7.5 years of age will be between 0 and 16%. This implies that repeatable animal-to-animal variation is such that some alpacas will not decrease their CV(FD) at all from a young to an old age, while some other alpacas will decrease their CV(FD) about 16%. This decrease in CV(FD) is equivalent to a decrease of about 3 µm in MFD (Butler and Dolling 1995).

Genetic estimates

Ponzoni *et al.* (1999) have reported genetic parameters on tuis alpacas, used in this study. From their reported results the between-animal genetic standard deviation can be calculated (using $\sigma_G = h.\sigma_P$) as 2.4 and 3.1 for MFD and CV(FD), respectively. These are greater than the between-animal standard deviations, for similar aged alpacas, reported in Tables 4 and 7. Although the genetic parameters in the study of Ponzoni *et al.* have relatively low precision, as indicated by the standard errors reported by them, this is *prima facie* evidence that the repeatable parameters at young ages that are reported in the present study are largely genetic. It would be reasonable to suggest that the lifelong between-animal variation, specific age repeatabilities, and repeatable within-animal correlations at older ages are largely genetic. This would imply that the inherent between-animal standard deviations, the specific age repeatability ratios, and the repeatable between-animal correlations are indicative of genetic standard deviations, heritabilities, and genetic correlations, respectively.

Optimum age for alpaca selection and fleece sampling

The implementation of these findings will impact on the effectiveness of alpaca genetic selection programmes aiming to improve alpaca fibre characteristics. There is clearly higher risk attached with alpaca selection using samples taken at earlier than 2 years of age. Fleece sampling and genetic selection of alpacas at ages >3 years of age will produce an opportunity cost of delaying the potential benefits from earlier selection of alpacas.

Measurement errors

Although the present work was not designed to separate errors due to sampling and laboratory measurement, it does provide relevant information on the subject. The analyses indicated that the residual variance of MFD was 2.015 (Table 6) and the residual variance of CV(FD) was 2.419 (Table 9), indicating that the residual s.d. of MFD was 1.42 and the residual s.d. of CV(FD) was 1.56. This residual variation contains components due to sampling error, measurement error, and short-lived environmental variation. As the residual s.d. is small it can be concluded that only a small part of the total variation was due to sampling and measurement error. However when buying or selling alpacas, it would be prudent to allow for measurement errors of 1–2 μm MFD or 1–2% CV(FD). Further information on the measurement errors inherent in measuring the fleeces of Suri and Huacaya alpaca is provided elsewhere (Aylan-Parker and McGregor 2002).

Effect of property and year

It is likely that effects of property and year are largely due to seasonal and management variations in nutrition. McGregor (2002) demonstrated that when alpacas and Merino sheep grazed together, the effect of years on fleece attributes, including MDF and variation in fibre diameter were similar in both species. This was associated with differences between years in pasture availability and liveweight change.

Effect of breed

At typical commercial liveweights, Suri alpacas in this study had a MFD 2–3 μm greater than Huacaya alpacas. In alpacas, the density of secondary skin follicles is the main determinant of MFD, as the ratio of secondary to primary follicles is about 7:1 (Calle-Escobar 1984; McGregor 1995; M. B. Ferguson, B. A. McGregor, R. Behrendt, unpublished data). Hoffman and Fowler (1995) suggest that the skin follicle density in the Suri is less than in the Huacaya, which, if true, may provide the explanation for the increase in MFD and CV(FD) of Suris compared with Huacayas observed in the present work. However, M. B. Ferguson, B. A. McGregor, and R. Behrendt (unpublished data 1998), who studied 24 Suri and 12 Huacaya alpacas, found the opposite, with the secondary follicle density and secondary follicle : primary follicle ratio of a sample of Suri alpacas significantly greater than a sample of Huacaya alpacas. The differences may not be true for all alpacas, since the observed differences could be due in part to differences in skin surface area (this was not measured in either study), due to incomplete sampling of the total breed population or to environmental influences.

Effect of fleece colour

To our knowledge this is the first time a report has shown that light-shaded alpaca fleeces are finer and have less variation in fibre diameter than dark-shaded alpaca fleeces. This finding may be explained by the observations made on piebald lambs that were mostly crosses between the Jacob and Polled Dorset breeds (Ryder and Adalsteinsson 1987) which produce a fleece that also has a significant proportion of medullated primary fibres. Ryder and Adalsteisson found that in 9 of 31 lambs, black wool areas on piebald lambs were longer (and they inferred the wool was also coarser) than the white spot areas and had a different array of fibre types. In 2 out of the 31 lambs the white wool was longer than the black wool and on the remaining 20 lambs, the black and the white wool was the same length. As the recessive piebald gene in sheep prevents melanoblasts from migrating into certain areas of the skin, Ryder and Adalsteisson suggest that the absence of melanocytes affects the growth of wool and that there might be different types of spotting gene. However, these differences are small compared with repeatable differences between individual alpacas and are of a similar magnitude to measurement errors. In the scheme of things, both alpaca breed and fleece colour differences are minor issues, since they are likely to be much smaller than the responses that are likely to be obtained through alpaca selection and breeding.

Effect of sex

Given the small differences in estimated means for males and females, together with a low s.e.d., it can be concluded that there was little difference in MFD or CV(FD) between sexes.

Conclusions

There are large opportunities to improve the MFD and CV(FD) of alpaca fibre through selection and breeding. The potential benefit is greatest from reducing the fibre diameter and CV(FD) of fibre from older alpacas, through reducing micron and CV(FD) blowout. The data indicate that the optimal time for alpaca fleece sampling is at about 2 years of age. In particular, sampling alpacas at younger ages is likely to substantially decrease selection efficiency for lifetime fibre diameter attributes.

Acknowledgments

The data were collected with the willing co-operation of the property owners, who are gratefully thanked. The initial project was financed by the Rural Industries Research and Development Corporation, Department of Primary Industries (Victoria), and Primary Industries South Australia. The Australian Alpaca Association is thanked for financial support enabling the present analyses to be completed. We thank our former colleagues, in particular Ms Andrea Howse, Mr David Hubbard, and Mr Chris Tuckwell for their assistance.

References

Aylan-Parker J, McGregor BA (2002) Optimising sampling techniques and estimating sampling variance of fleece quality attributes in Alpacas. *Small Ruminant Research* **44**, 53–64. doi:10.1016/S0921-4488(02)00038-X

Baxter BP, Brims MA, Teasdale DC (1992) The optical fibre diameter analyser (OFDA). New technology for the wool industry. *Wool Technology and Sheep Breeding* **40**, 131–134.

Butler KL (2001) Counting precision for spinning fineness. *Journal of the Textile Institute* **92**(Part 1), 360–364.

Butler KL, Dolling M (1995) Spinning fineness for wool. *Journal of the Textile Institute* **86**(Part 1), 164–166.

Butler KL, McGregor BA (2002) A statistical approach for evaluating micron blowout, with Australian Alpacas as an example. *Wool Technology and Sheep Breeding* **50**, 383–389.

Calle-Escobar R (1984) 'Animal breeding and production of American camelids.' (Ron Hennig-Patience: Lima)

Carter B (1996) 'Lama down under.' (AgMedia: Melbourne)

Cottle DJ, Russell BC, Atkins KD (1995) Do Merino hoggets with 'positive micron' wool have a propensity for 'micron blowout'. *Proceedings of the Australian Association Animal Breeding Genetics* **11**, 525–528.

Fowler ME (1989) 'Medicine and surgery of South American camelids.' (Iowa State University Press: Ames, IA)

GenStat Committee (2000). 'The Guide to GenStat®. Part 2: Statistics.' (Lawes Agricultural Trust: Rothamsted, UK)

Hack W, McGregor B, Ponzoni R, Judson G, Carmicheal I, Hubbard D (1999) 'Australian alpaca fibre: improving productivity and marketing.' Rural Industries Research and Development Corporation Research Paper Series No. 99/140. (RIRDC: Barton, ACT)

Hickson JD, Kinghorn BP, Piper LR, Swan AA (1995) Micron blowout —using available genetic variation. *Proceedings of the Australian Association Animal Breeding Genetics* **11**, 529–533.

Hill AJ, Ponzoni RW, James JW (1999) Micron blowout: heritability and genetic correlations with fibre diameter and secondary follicle diameter. *Australian Journal of Agricultural Research* **50**, 1375–1379. doi:10.1071/AR98192

Hoffman E, Fowler ME (1995). 'The alpaca book: management, medicine, biology and fiber.' (Clay Press Inc.: CA)

IWTO (1988) Method for the determination of oven-dry mass and calculated invoice mass of scoured or carbonised wool. IWTO-33-88. International Wool Textile Organisation, Ilkley, Yorkshire, UK.

IWTO (1995) Measurement of the mean and distribution of fibre diameter of wool using an optical fibre diameter analyser (OFDA). IWTO-47-95. International Wool Textile Organisation, Ilkley, Yorkshire, UK.

James JW (1998). Aspects of the inheritance of age changes. *Proceedings 6th World Congress Genetics Applied to Livestock Production* **24**, 35–38.

Lamb PR (1997) Wool quality for spinners (Report No. WT97.05), CSIRO Division of Wool Technology, Geelong, Victoria, Australia.

Ly NG (1983) The contribution of the fibre-diameter distribution to the bending rigidity of yarns. *Journal of the Textile Institute* **74**, 228–230.

Martindale JG (1945) A new method of measuring the irregularity of yarns with some observations on the origin of irregularities in worsted slivers and yarns. *Journal of the Textile Institute* **36**, T35–T47.

McGregor BA (1995) Alpaca fleece development and methods of assessing fibre quality. In 'Proceedings International Alpaca Industry Conference'. Geelong, pp. 55–78. (Australian Alpaca Association: Forest Hill, Vic.)

McGregor BA (1997) The quality of fibre grown by Australian alpacas: 1. The commercial quality attributes and value of alpaca fibre. In 'Proceedings International Alpaca Industry Conference'. Sydney. pp. 43–48. (Australian Alpaca Association: Forest Hill, Vic.)

McGregor BA (1999) Fleece production, fibre quality and fibre assessment. In 'Australian alpaca fibre: improving productivity and marketing'. pp. 6–46. Rural Industries Research and Development Corporation Research Paper Series No. 99/140. (RIRDC: Barton, ACT)

McGregor BA (2002) Comparative productivity and grazing behaviour of Huacaya alpacas and Peppin Merino sheep grazed on annual pastures. *Small Ruminant Research* **44**, 219–232. doi:10.1016/S0921-4488(02)00050-0

Naylor GRS, Phillips DG, Veitch CJ (1995) The relative importance of mean fibre diameter and coefficient of variation of sale lots in determining the potential skin comfort of wool fabrics. *Wool Technology and Sheep Breeding* **43**, 69–82.

Ponzoni RW, Grimson RJ, Hill JA, Hubbard DJ, McGregor BA, Howse A, Carmichael I, Judson GJ (1999) The inheritance of and associations among some production traits in young Australian alpacas. *Proceedings of the Australian Association Advancement of Animal Breeding and Genetics* **13**, 468–471.

Roberts NF (1961) The effects of fibre thickness, length, and crimp on worsted spinning limits, yarn irregularity, and handle. *Wool Technology and Sheep Breeding* **9**, 27–36.

Ryder ML, Adalsteinsson S (1987) A note on the differences in coat structure between the black and white areas of piebald lambs. *Journal of Agricultural Science, Cambridge* **108**, 379–382.

Tuckwell CD, Ponzoni RW, McGregor BA, Carmichael I, Judson GJ, Keynon R (1995) A brief account of South American Camelids in Australia, with a description of an alpaca research project and a summary of preliminary data. In 'Proceeding European Association of Camelids'. Camerino, Italy, pp. 153–162.

Turner HN, Young SSY (1969) 'Quantitative genetics in sheep breeding.' (Macmillan: Melbourne)

Wuliji T, Davis GH, Dodds KG, Turner PR, Andrews RN, Bruce GD (2000) Production performance, repeatability and heritability estimates for liveweight, fleece weight and fiber characteristics of alpaca in New Zealand. *Small Ruminant Research* **37**, 189–201. doi:10.1016/S0921-4488(00)00127-9

Yi PJ (1995) The pre-natal development of the fibre follicle in alpaca (*Lama pacos*). *Fine Fibre News* **5**, 27–32.

Manuscript received 3 April 2003, accepted 21 January 2004