Methods for estimating fibre length and diameter in wool staples

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Summary: Present techniques to measure the fibre diameter and fibre length of individual fibres are both time consuming and expensive. This has effectively restricted the use of fibre length measurements in wool growth studies. This paper describes and evaluates a number of techniques to measure fibre diameter and fibre length. Sixteen fine wool Merino wethers at pasture were intra-dermally injected with ^{35}S-cysteine and dye-banded on two occasions, 28 days apart. Fibre diameter was measured using image analysis and the Optical Fibre Diameter Analyser (OFDA). Fibre length was measured using a dyeband and a snippet technique, which both utilised image analysis. Mean fibre length and fibre length variations were also predicted using three prediction equations based on staple characteristics including crimp frequency and OFDA fibre curvature measurements. Techniques that were developed to measure fibre length growth rate and fibre diameter between dyebands were highly correlated (r=0.81, P<0.05) with the ^{35}S estimates of fibre length. Fibre diameter estimated by the snippet and the dyeband techniques were correlated (r=0.96, P<0.001) and the means did not differ (P>0.05). Mean fibre length was not significantly different (P>0.05) between the snippet and dyeband techniques. The estimates of fibre length variation and fibre diameter variation were very different (r<0.47 and r<0.40 respectively) between the three techniques. Fibre length predicted from staple characteristics was not significantly different (P>0.05) from, and highly correlated with, fibre length measured from the ^{35}S technique (r=0.85, P < 0.001). Dyeband fibre length was best predicted by greasy staple length (r=0.91, P=0.0001) and snippet fibre length using prediction method three (r=0.69, =0.0042) which was estimated using a combination of the length of each crimp curve and the number of crimps between dyebands. Fibre length variation was not accurately measured nor predicted by the methods described in this paper. These results all indicate that mean fibre length growth of the fibres can be accurately measured and predicted without using the traditional autoradiographic techniques.

Keywords: Wool growth measurement, fibre length, dyeband, Image analysis.

Introduction

The quantity and quality of wool produced by sheep is primarily a function of fibre growth and density. While fibre specific gravity and follicle density remains relatively constant (Lyne 1964; Reis *et al.* 1990) the physical dimensions of individual fibres vary markedly throughout the year (Downes 1971; Woods and Orwin 1988; Schlink *et al.* 1999). Changes in individual fibre growth can be due to both changes in fibre diameter (cross sectional area) and rate of fibre elongation (Downes 1971; Reis *et al.* 1990; Reis 1992).

The rate of fibre length growth to fibre diameter during a period of time (L/D) varies widely between sheep, ranging between approximately 10 to 20 (Hynd 1992; Reis *et al.* 1990; Schlink *et al.* 1996; Schlink *et al.* 1999). The ratio also remains relatively constant when wool growth changes (Downes 1971; Reis *et al.* 1990), although, this assumption has been challenged with recent studies with grazing sheep (Woods and Orwin 1988; Schlink *et al.* 1996: Schlink *et al.* 1999). The current method of measuring short-term changes in fibre diameter, rate of fibre elongation and L/D ratio relies on the use of either intra-venous or intra-dermal injections of radioactive isotopes (Downes *et al.* 1967). The process is time consuming and expensive. As a consequence the number of sheep and fibres per sheep that are normally examined is limited, restricting the use of the technique in the field. Staples are comprised of thousands of individual fibres (Schlink *et al.* 1996; Peterson and Gherardi 1996), between which there is significant variation in fibre diameter (Quinnell *et al.* 1973; McKinley *et al.* 1976), and hand sampling a small number of individual fibres can introduce significant sampling errors. Samples for ^{35}S have been shown to skew the fibre sample selected towards the coarser wool fibres in the fibre population (Schlink *et al.* 1998; Schlink *et al.* 1999). As a result the traditional ^{35}S technique may have some inherent disadvantages.

An alternative technique to the isotope procedure was proposed by Schlink *et al.* (1998) to estimate fibre length and fibre diameter parameters in dyebanded wool samples using image analysis and measurements obtained from the Optical Fibre Diameter Analyser System (OFDA, BSC Electronics Pty Ltd., Myaree Western Australia). While they did not measure fibre diameter and fibre length using the isotope technique for the same period, the average L/D was 17.7, which falls within the range of L/D ratios reported for Merino sheep. McKinley *et al.* (1976) had previously investigated the use of dyebands to measure the components of fibre variation using the base of dyebands as the time point reference on individual wool fibres.

Fibre length variation has been shown to influence staple strength by influencing peak force but not work to break (de Jong *et al.* 1985; Peterson 1997). Selection for measured staple strength has been shown to reduce fibre length variation (Bray *et al.* 1995; Peterson 1997). The influence of fibre length variation within a staple on processing performance has not yet been determined. It has also been suggested that crimp definition may be associated with fibre length and curvature variation (Lockhart 1958; Swan 1994). Crimp frequency and crimp definition are also associated with a number of other wool quality characteristics including fibre diameter (Lockhart 1958), SL and wool style. At present it is not possible to routinely measure fibre length or fibre length variation on large numbers of fleece samples. However, it may be possible to predict mean fibre length and fibre length variation using staple characteristics that are currently measured for staple strength and fibre diameter.

SL is the outcome of the average growth of the constituent fibres of the staple. These fibres are crimped and bound within the staple, which results in the true fibre length not being reflected in staple length alone. The average ratio of fibre length to staple length is reported to range from 1.18 to 1.43 in a review by Murray (1996). Fibre curvature is significantly related to crimp frequency with r ranging from 0.82 to 0.95 (Swan 1994; Smuts *et al.* 1995; Hansford and Humphries 1997; Nimbs *et al.* 1998). Mean fibre curvature and fibre curvature variation are now routinely measured using the OFDA and LASERSCAN systems as part of routine fibre diameter determinations.

This paper describes and evaluates a number of alternative methods of determining mean fibre length and fibre length variation in staples of wool. Throughout the paper the three techniques are compared with each other, as it is not assumed that the autoradiographic technique estimates true fibre length and diameter measurements. The measurement techniques utilise autoradiography, dyebands, image analysis and measurements of fleece characteristics in grazing sheep.

Materials and Methods

Sixteen 2-year-old fine wool Merino wethers were maintained as a single grazing mob for the duration of the experiment at the Kirby Rural Research Station, approximately 10 kilometers north west of Armidale, NSW (Latitude 30° 27’ South, Longitude 151° 38’ East). The pasture consisted of the improved grass species

Phalaris (*Phalaris aquatica*), Perenial and Annual Ryegrass (*Lolium sp.*), Tall Fescue (*Festuca arundinacea*), Silver grass or Rat Tail Fescue (*Vulpia sp.*), Paspalum (*Paspalum dilatatum*), Star or Windmill grass (*Chloris truncata*) and other species is less dominance.

Autoradiographic (^{35}S) technique

The autoradiographic technique is a modification of the techniques of Downes *et al.* (1967) and Hynd (1994) to determine fibre diameter and fibre length. In brief, the wethers were intra-dermally injected on days 0 and 28 with 0.3mls of a solution containing 5.1μCi/mL of ^{35}S-cysteine hydrochloride (Amersham Australia Pty Ltd, Baulkham Hills, Sydney) in normal saline. On day 49 the labelled staples were harvested, cleaned and stained with picric acid. Approximately 70 fibres were randomly selected from the sample and mounted on glass slides with polyvinylpyrrolidone (BDH Limited Poole England) and exposed to X-ray film (AGFA Structurix D7FW, AGFA-Gevaert Ltd, Nunawading, Victoria) for 7 days. The film was superimposed onto the slides with DPX (Ajax Chemicals Pty Ltd, Auburn, Sydney). Fibre diameter was measured at 10 sites approximately equidistant between the labeled sites on at least 50 fibres, using image analysis (Leica Quantimet 500MC Leica Cambridge Ltd.). Fibre length was measured on 50 fibres for each sheep by tracing the fibre between the labeled points using image analysis. The mean fibre diameter measured by ^{35}S, fibre diameter variation (CV of FD measured by ^{35}S), mean fibre length (^{35}S FL) and fibre length variation (CV of FL measured using ^{35}S) for the 28 days of wool growth were calculated for each sheep. The ratio of fibre length growth per day (μm/day) to MFD measured by ^{35}S was calculated (^{35}S L/D).

Dyeband based techniques

A dyeband was placed at the base of the staple, according to the method of Wheeler *et al*. (1977) (anterior to the left-hand mid-side patch) on the same day as each injection of the radioisotope. Dyebanded staples were harvested on the same day as for the ^{35}S labeled fibres. Five staples were used to measure mean staple length (SL) and crimp frequency (crimps/cm) between dyebands using a crimp gauge (CSIRO Wool Technology, Australia). Using this measure of SL the ratio between fibre length (^{35}S FL) and SL was calculated for the autoradiographic technique (^{35}S FL:SL). The staple snippet and the dyeband techniques were developed to estimate fibre length from dyebanded wool staples.

Staple snippet

Snippet fibre length measurement was determined using image analysis (Schlink *et al.* 1998). A dyebanded staple was randomly drawn from the sample, wrapped in fine wire mesh, washed in two changes of Shell X2, and dried at 20°C and 65% relative humidity. The staples were measured for staple (overall snippet) length between the dyebands (snippet SL), cut at the base of the dyebands and a bundle of at least 200 fibres was drawn from the staple snippet. All fibres from the snippet were placed between glass slides, conditioned at 20°C and 65% relative humidity and the edges sealed with silicone rubber. Fibre length was measured in dark field (Wild M3Z, Heerbrugg, Switzerland), the images were captured and length estimated using image analysis (VideoPro, South Australia). The mean fibre length (snippet FL), fibre length standard deviation and coefficient of variation (CV of FL measured using snippets) were measured. The remainder of the staple snippet not used to measure snippet fibre length was cut into 2mm sections to determine mean fibre diameter (MFD measured by snippet) and fibre diameter variation (CV of FD measured by snippet) using the OFDA. L/D ratio (snippet L/D) was calculated for each sheep in the same way as previously described. The ratio between fibre length (snippet FL) and staple length (snippet SL) was calculated (snippet FL:SL).

Dyeband

This technique is a modification of the techniques of McKinley *et al.* (1976) and Schlink *et al.* (1998). A dyebanded staple was randomly selected from the sample, fifty individual greasy fibres were removed from the staple, placed between glass slides to maintain orientation, and measured using the same image analysis system as used in the radioisotope technique. The base of the dyed sections of the fibres were used as reference points to measure fibre length growth. The mean fibre length (dyeband FL), fibre length variation (CV of FL measured using dyebands) and L/D ratio (dyeband L/D) were calculated for each sheep as in the autoradiographic technique. The remaining part of the staple was then used to measure mean fibre diameter and fibre curvature with OFDA using 2mm snippets at each dyeband. These two OFDA measurements were averaged to provide mean fibre diameter (MFD measured by dyeband), fibre diameter variation (CV of FD measured by dyeband), fibre curvature (degrees/mm) and fibre curvature variation (CV of fibre curvature). The ratio between fibre length (fibre length measured by dyeband) and staple length (SL) was calculated (dyeband FL:SL).

Fibre length prediction

Mean fibre length was estimated from combinations of SL, crimp frequency and fibre curvature using three different prediction techniques. Fibre length measured using the ^{35}S technique were used as the reference fibre length measurement for statistical comparisons of the prediction measurements of fibre length.

Prediction method 1

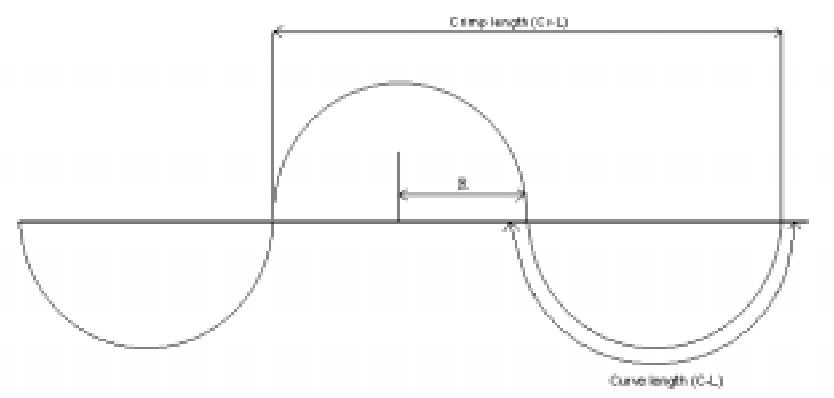
Fibre length was estimated using horizontal length of staple crimp and crimp frequency between the dye bands. The horizontal length of each crimp (crimp length), number of crimps over the length of staple between dyebands (crimps per SL), the radius of crimp arc (R) and the circumference distance of each side of a crimp (curve length) (Figure 1) were determined for each wool sample. The equations used were;

Crimp length (mm) =1 / (crimp frequency / 10)
Crimps per SL =SL / crimp length
Crimp radius (R, mm) =(SL / (crimps per SL)) / 4
Curve length (mm) = $\prod$ * R

Predicted fibre length using method 1 = curve length * crimps per SL * 2000 (1)

Using predicted FL from method 1 and MFD measured by dyeband the L/D ratio (predicted L/D using method 1) was estimated.

Figure 1. Parameters used by prediction method 1 to estimate fibre length



Prediction method 2

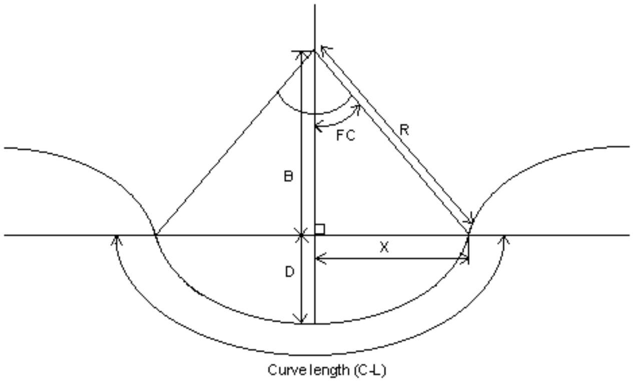
Fibre length was estimated using average fibre curvature from OFDA and assumes that the curvature of the fibre remains the same between the points of crimp inflection (Figure 2). The radius of the crimp arc, R, was estimated from fibre curvature and crimp length. The curve length between points of crimp inflection was then estimated from the circumference of a circle with a radius of R using the known components crimp length and fibre curvature. X (Figure 2) was calculated by dividing crimp length by 4. The parameters estimated were:

Crimp radius (R, mm) =X/(sin(fibre curvature/2))
Crimp height (B, mm) =$(R^2 – X^2)$^$^{0.5}$
Crimp diameter (D, mm) =R-B
Curve length (mm) =2∏R*(fibre curvature/365)

Fibre length predicted using method 2 = curve length*2*Cr/SL (2)

Using predicted FL from method 2 and MFD measured by dyeband the L/D ratio (predicted L/D ratio using method 2) was estimated.

Figure 2. Components used predict fibre length using method 2



Prediction method 3

The third predictor of fibre length (predicted FL using method 3) used average curve length from prediction methods one and two and crimps per SL in the following equation:

Predicted FL using method 3 = average curve length*2*crimps per SL (3)

Using predicted FL from method 3 and MFD measured by dyeband the L/D ratio (predicted L/D using method 3) was estimated.

Statistical analysis

Group means were compared using least squares analysis of variance conducted using the General Linear Model procedure of SAS (1990). The relationships between the variables were examined using correlation and multiple regression procedures of SAS (1990).

Results

Mean values (±s.e.m.) for fibre length and fibre diameter using the 3 techniques for estimation of fibre length are shown in Table 1. The ^{35}S and dyeband techniques differed significantly for MFD and CV of FD. The dyeband and snippet techniques were significantly different for CV of FL. Mean fibre diameter, CV of fibre diameter and CV of FL were significantly different for ^{35}S and snippet.

Table 1. Least squares means ($\pm$ s.e.m.) for measurement of fibre length and diameter from the ^{35}S, dyeband and snippet techniques

	^{35}S	Dyeband	Snippet	Probability
MFD (µm)	17.3 ± 0.15^a	16.8 ± 0.15^b	16.6 ± 0.15^b	0.006
CV of FD (%)	11.5 ± 0.30^a	16.2 ± 0.30^b	15.8 ± 0.30^b	<0.001
FL (µm)	8881 ± 145^a	8773 ± 152^a	8819 ± 145^a	0.877
CV of FL (%)	11.0 ± 0.71^a	11.6 ± 0.74^a	15.4 ± 0.71^b	<0.001
L/D ((µm/d)/µm)	18.4 ± 0.28^a	19.0 ± 0.30^a	19.1 ± 0.28^a	0.216
FL:SL (ratio)	1.4 ± 0.02^a	1.4 ± 0.02^a	1.4 ± 0.02^a	0.917

Means within each row with different superscripts are significantly different (P<0.05)

Table 2. Correlation coefficients (r) for the relationships between the fibre properties estimated using the radioisotope technique and those obtained using dyeband and snippet techniques

	FL	CV of FL	MFD	CV of MFD	L/D	FL:SL
Snippet	0.59**	0.40	0.84**	0.19	0.81**	0.26
Dyeband	0.84**	0.11	0.81**	0.16	0.91**	0.57**

** Correlation coefficients highly significant P<0.05

The correlation coefficients for the relationships between the ^{35}S technique and dyeband and snippet techniques are shown in Table 2. The MFD measured by snippet was highly correlated with both the MFD measured by ^{35}S (r=0.84, P<0.001) and MFD measured by dyeband (r=0.96, P<0.001). MFD measured by

^{35}S was significantly correlated to MFD measured by dyeband (r=0.81, P<0.0001). Fibre lengths measured using the dyeband technique were significantly correlated with ^{35}S measured fibre length (r=0.84, P=0.001) and snippet fibre length (r=0.67, P=0.006). The mean fibre length measured by the snippet technique was also significantly correlated to the ^{35}S fibre length measurement (r=0.59, P=0.016). CV of FD and CV of FL were not related between the dyeband and ^{35}S techniques (0.16 and 0.11 respectively). The CV of FD (r=0.47, P=0.049), L/D ratio (r=0.77, P=0.001) and FL:SL ratio (r=0.60, P=0.017) were all significantly correlated between the snippet and dyeband techniques. There was no significant relationship between CV of FL measured using dyebands and CV of FL measured using snippets (r=0.07, P=0.80). FL:SL was significantly correlated between the ^{35}S and dyeband techniques (r=0.57, P<0.05).

Dyeband FL and ^{35}S FL were both significantly correlated with SL (r=0.91 and 0.79, respectively; P<0.001). snippet FL was moderately correlated with SL (r=0.67, P=0.004). This resulted in the L/D ratio based on SL growth per day/MFD measured by dyeband and SL per day/MFD measured by snippet being highly correlated with the L/D ratio calculated using the radioisotope technique (r=0.88 and 0.85, respectively; P < 0.0001). ^{35}S L/D and SL/MFD (using SL and MFD measured by dyeband) were significantly correlated (r=0.88, P=0.0001). The average ratio between fibre length and SL was 1.41 (± 0.12) and ranged between 1.2 to 1.63.

Fibre length prediction

Mean fibre length measured by ^{35}S, dyeband, snippet and predicted FL using method 3 were not significantly different (P < 0.05) (Table 3). The mean fibre length values of predicted FL using method 1 and predicted FL using method 2 were significantly (P < 0.05) different from all the other fibre length measurement techniques. Predicted FL using method 1 explained a large proportion (62%, P=0.001) of the variation in ^{35}S FL. Predicted FL using method 2 and method 3 explained 48% (P=0.003) and 60% (P=0.004) of the variation in ^{35}S FL respectively. Together in a multiple regression equation, SL and predicted FL using method 1 explained 65% (P=0.001) of the variation in ^{35}S FL. The combination of staple characteristics that explained the most variation of ^{35}S FL (72%) was MFD measured by dyeband and predicted FL using method 1. Dyeband FL was best predicted by SL, which explained 82% of the variation. Predicted FL using method 3 explained 48% of the variation in snippet FL. The remaining characteristics did not significantly explain any more of the variation in these characteristics.

Table 3. Least squares means (±s.e.m.) for the fibre length measurements from the ^{35}S, dyeband, snippet and three prediction techniques

	^{35}S FL	Dyeband FL	Snippet FL	Predicted FL using method 1	Predicted FL using method 2	Predicted FL using method 3	Probability	Pooled s.e.
Fibre Length (µm)	8881a	8778a	8819a	9927b	7459c	8693a	0.0001	128
L/D Ratio	18.4a	19.1a	19.0a	21.6b	16.3c	18.9a	0.0001	0.28

Means with different superscripts are significantly different (P<0.05)

The multiple regression equations were;

^{35}S FL=5566.5 ($\pm$ 2199.7) – 210.53 * MFD measured by dyeband ($\pm$ 96.7) + 0.69 * predicted FL using method 1 ($\pm$ 0.13)
(r=0.849, n=16, $P < 0.001$)

Dyeband FL=2773.5 ($\pm$791.9) + 951.2 ($\pm$123.8) * SL
(r=0.906, n=15, $P < 0.001$)

Snippet FL=2986.4 ($\pm$1691.2) + 0.7 ($\pm$0.2) * predicted FL using method 3
(r=0.693, n=16, P=0.004)

Predicted L/D using methods 1 and 2 were significantly ($P<0.05$) different to ^{35}S L/D (Table 3). Predicted L/D using method 3 was not significantly ($P>0.05$) different to ^{35}S L/D. Predicted L/D using methods 1, 2 and 3 were highly and significantly correlated with ^{35}S L/D (r=0.85, 0.87 and 0.87, P=0.001, respectively).

CV of FL measured using ^{35}S was not significantly related to CV of fibre curvature (r=0.27, P=0.305) and accounted for only 7.3% of the variation in CV of FL measured using ^{35}S. There were significant relationships between SL, crimp frequency and fibre curvature, where SL with crimp frequency and SL with fibre curvature were both negatively correlated (r=–0.61 and –0.64, P=0.011 respectively), while crimp frequency and fibre curvature were positively correlated (r=0.86, P=0.001). Fibre curvature and CV of fibre curvature were negatively correlated (r=-0.83, P=0.001). Fibre diameter variation was positively correlated with fibre length variation for the ^{35}S and snippet techniques while negatively correlated for the dyeband technique (r=0.33, 0.26 and r=-0.12 respectively ($P>0.05$ for all three correlations)).

Discussion

Fibre length measurements were closely related between the three techniques. Mean fibre length measurements for each of the three techniques were not significantly different and were highly correlated. The highest correlation (r=0.84) was observed between the ^{35}S and the dyeband techniques. This result may be influenced by the similarity in methods of fibre sampling techniques used for these two methods of fibre length determination. The results also indicated that the three techniques produce very different estimates of fibre diameter and fibre length variation.

An important consideration of the dyeband techniques is quality of dyeband after application. In some animals the fibre quickly absorbs the dyeband fluid, which migrates up the fibre (Wheeler *et al.* 1977) resulting in the final dyebands being very large. With short intervals between dyebands the second dyeband can obscure the base of the first dyeband on many fibres and during measurement it is difficult to identify the base of the first dyeband. This suggests that, while the results have indicated that fibre length may be able to be accurately estimated on most animals, some types of wool may make the technique inaccurate. In most cases these animals would be able to be identified during measurement. A major advantage of the snippet technique is that it is not sensitive to dyeband migration, as the overall base of the dyeband only needs to be identified to make the cuts across the dyebanded staples.

One of the advantages of any dyeband-based techniques is that they can be easily applied at regular intervals throughout the year (Wheeler *at al.* 1977). The mean fibre diameter at the dyebands and SL growth between the dyebands can then measured at regular intervals. In this experiment the L/D ratio measured by the snippet and dyeband techniques were highly correlated (r=0.81 and 0.91 respectively) with L/D ratio measure by autoradiography. Furthermore L/D ratio based on SL and MFD measured by dyeband and SL and MFD measured by snippet were highly correlated (r=0.88 and 0.85) with the ^{35}S L/D. These results suggest that fibre L/D ratio may be accurately estimated using dyebanded staples, whereas in the past the use of dyebands to calculate L/D ratio has not been considered accurate due to variations in the fibre length to SL ratio.

The dyeband technique provides the most accurate estimation of these fibre parameters (mean fibre length, mean fibre diameter and L/D ratio). The dyeband technique explained 66% of the variation between animals in fibre diameter, 71% of the variation between animals in fibre length and 83% of the variation between animals in L/D ratio measured using the ^{35}S technique. This technique has the added benefits of being low cost and less time consuming. It must be remembered that both the ^{35}S and dyeband techniques rely on individual fibre selection and as a result may not be an accurate representation of the staple (Schlink *et al.* 1998; Schlink *et al*. 1999). It is anticipated that the broader fibres are easier to see and are therefore sampled more readily, which has implications on the accuracy of the estimates of both mean fibre diameter and fibre diameter variation.

The fibre diameters obtained from the snippet and dyeband sampling techniques were not different but were both significantly lower than the ^{35}S technique. All three estimates of fibre diameter were significantly correlated to each other. A previously published report supports these observations indicating that single fibre selection techniques may result in samples with higher average fibre diameter than those of the fleece sample (Schlink *et al.* 1998). The snippet technique selected a bundle of fibres from the staple and measured all fibres in the bundle regardless of length and diameter and is assumed to produce an unbiased sampling of wool fibres. The time consuming nature of the ^{35}S technique restricted the number of fibre measured from between 50 and 100 fibres per fleece sample. Conversely fibre diameter measurement made using the OFDA or Laserscan measures 2000 fibres per sample or a larger number according to the manufacturers instructions. Methods that increase the number of fibres measured and use a random sample of fibres from the fleece, will significantly improve the accuracy of the measurements of the fleece samples.

Mean fibre length is usually longer than mean SL due to fibre crimp and entanglement. However, fibre length is generally highly correlated with SL (r > 0.90, Gee 1975; Murray 1996). Murray (1996) summarized 10 published papers, which gave a significant linear relationship between mean fibre length and SL (r=0.94). The average relationship between SL and fibre length observed in this experiment of r=0.79 is lower than that previously reported. In this experiment fibre length to SL ratio fell within the range previously reported for Merino sheep (Murray 1996; Schlink *et al.* 1998) with our results averaging at a ratio of 1.4.

Multiple regression indicated that fibre length (^{35}S estimated) could be accurately modeled using MFD measured by dyeband and predicted FL using method 1. Using these two variables 72% of the variation in fibre length could be explained. The usefulness of the three prediction equations will depend on the desired use of the predicted fibre length measurements. If actual measurements of fibre length are required, predicted FL using method 3 may be more useful as the means of the predicted measurements were not significantly different from those of the ^{35}S technique. If a ranking of animals on fibre length is desired then it may be more beneficial to use predicted FL using method 1, as while the mean of these predicted measurements was significantly different, the measurements were highly correlated with those of the ^{35}S technique. It was anticipated that if fibre crimp and curvature were uniform throughout the growth period of concern, the true length of the fibre would be a function of these fibre properties. Therefore it may be possible to use SL, mean fibre curvature and curvature variation to predict average fibre length and fibre length variation. However, the remaining variation in fibre length may be attributed to variation along fibres in crimp (Wheeler *et al.* 1977) and curvature. Wool fibres also grow in a three dimensional space and the prediction equations used in this study only considered a wool fibre in two dimensions. Differences in the characteristics of this third dimension may help explain additional variation in mean fibre length.

Previous research has demonstrated that fibre crimp, fibre curvature and SL are significantly related. Nimbs *et al.* (1998) and Swan (1994) observed correlation coefficients between crimp frequency and fibre curvature (measured by the OFDA) of 0.85 and 0.95, respectively. The correlation of 0.86 between crimp frequency and fibre curvature in this experiment is similar to this earlier research. Nimbs *et al.* (1998) also reported correlation's of 0.95 between standard deviation of curvature and average curvature, –0.86 between coefficient of variation of curvature and average curvature, –0.44 between SL and average curvature and –0.64 between SL and crimp frequency. The correlation coefficients of 0.94, -0.84, -0.64 and –0.62 observed in this experiment are also similar to this previous research.

Schlink *et al.* (1998) observed no significant relationship between fibre length variation and fibre diameter variation. A non-significant but small positive relationship between these variables (r=0.33 and 0.26) was observed for the ^{35}S and snippet techniques in this experiment. Conversely fibre diameter and fibre length variation were negatively correlated for the dyeband technique (r=-0.12). This study also demonstrated that fibre curvature variation and fibre length variation were not significantly correlated.

Conclusion

Estimating fibre growth properties is time consuming and expensive using currently available techniques. The dyeband and snippet techniques allow mean fibre length, fibre diameter and L/D ratio to be estimated within a reduced time frame. The dyeband and snippet techniques accurately duplicated mean length growth data produced by the ^{35}S technique. The fibre diameter estimated from these techniques was significantly different to that of the ^{35}S technique. The snippet and dyeband technique resulted in similar fibre diameter and fibre length measurements. All three techniques produced different estimations of fibre length variation and fibre diameter variation. The dyeband technique requires care to be taken during dyeband application and measurement to ensure accurate measures of fibre growth. As the snippet technique involves no single fibre selection there is evidence to suggest that it may provide less biased samples for fibre diameter and length estimations. L/D ratio based on SL and mean fibre diameter at dyebands can also give an accurate estimate of the mean fibre L/D ratio that is currently measured using the ^{35}S technique. Mean fibre length (^{35}S technique) can also be predicted with moderate accuracy using staple characteristics however fibre length variation could not be accurately predicted. The relationship between segment based fibre diameter and length measurement with full staple based measurements of fibre diameter and length is yet to be determined.

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