CHAPTER 6

Determinants of environmental responsiveness of fibre diameter in grazing fine wool Merino sheep

6.1 Introduction

The preceding chapters have demonstrated that FDP characteristics vary between environments, bloodlines, sire groups and individual sheep. The results also show that the FDP characteristics are associated with and explain additional variation in staple strength. From this it can be concluded that differences in environmental responsiveness of fibre diameter results in differences in staple strength. However while these trends are apparent within bloodlines these same trends are not seen when bloodlines are compared. At present the major physiological or biological mechanisms determining the variation between sheep in environmental responsiveness of fibre diameter, and therefore FDP variation, are not fully known.

The contribution of fibre diameter and length to wool growth varies between fibres, over time and between sheep. The ratio of fibre length growth to fibre diameter (L/D ratio) is an important consideration for changing wool growth and the characteristics of the fibre grown. Individual sheep have a characteristic and relatively constant L/D ratio. There are also significant differences between fibres and sheep in L/D ratio (Woods and Orwin 1988) ranging approximately from 10:1 to 30:1.

Research has demonstrated that the L/D ratio of a sheep may determine the way in which they respond, in terms of fibre diameter, to changes in nutrition (Hynd 1992; Woods and Orwin 1988). Sheep with higher L/D ratios have lower increases in fibre diameter and greater changes in fibre length relative to diameter change (Hynd 1992). Associated with this, sheep with higher initial fibre diameter had greater increases in fibre diameter and lower changes in fibre length relative to changes in fibre diameter. A comparison of sheep with similar fibre diameter also indicated that those with a high fibre length had lower diameter increases. Therefore direct or indirect selection of sheep with high L/D ratio should have 2 desirable outcomes: greater fibre lengths and reduced fibre diameter variability along fibres (Hynd 1992). Actual changes in fibre length and fibre diameter are also highly variable between sheep (Hynd 1992). The ratio of the change in fibre length to the change in fibre diameter for individual sheep ranged from 13:1 to 80:1 (Hynd 1992). Differences in these characteristics may explain some of the large differences between sheep in staple strength.

L/D ratio has been thought to be relatively independent of nutrition (Cottle 1991; Cottle 1987; Downes 1971; Reis 1992a; Williams 1976) and therefore remained nearly constant with changes in the rate of wool growth (Reis 1991). However, L/D ratio has been found to change under some specific situations. Studies conducted throughout a year of wool growth have demonstrated that L/D ratio exhibits a seasonal trend (Woods and Orwin 1988; Schlink *et al.* 1996a). These trends are generally inverse to that of fibre diameter, fibre length, feed supply and photoperiod cycle. At this point in time there is no explanation for these trends that are observed, however it has been suggested that the mechanisms determining these growth parameters in the follicle are complex (Woods and Orwin 1988). The evidence indicates that not only does the L/D ratio vary between sheep but that the level of seasonal variation of these characteristics also varies between sheep. Woods and Orwin (1988) reported that there was large variation between sheep in the amplitude and timing of this seasonal variation in fibre growth characteristics. Variation between sheep in the levels of seasonal variation in fibre length and fibre diameter may influence staple strength.

Associated with these relationships, Kopke and Hocking Edwards (1998) illustrated that a group of sheep with lower initial fibre diameter and higher L/D ratio were less sensitive to changes in nutrition than the group that had higher initial fibre diameter and lower L/D ratio.

Based on the relationships discussed above, it appears that L/D ratio may influence the degree to which individual sheep respond to their environment. Therefore differences in L/D ratio may be associated with differences in FDP characteristics and staple strength, however these relationships have not yet been investigated.

Sheep with a lower initial fibre diameter can show a smaller proportional changes in fibre diameter with improved nutrition compared to those sheep with a higher initial fibre diameter

(Jackson and Downes 1979; Quinilivan 1990; Thompson 1993; Bow and Hansford 1994; Earl *et al.* 1994). These results were also observed in Chapter 5. Therefore differences between sheep in FDP characteristics may be influenced by differences in mean fibre diameter. At present these relationships have not been investigated in combination with L/D ratio, staple strength and body traits. .

Wool growth will be influenced by many physiological and nutritional factors throughout the year. The major factor controlling wool growth is the availability of nutrients to the wool follicle (Allden 1979; Reis 1979; Reis 1991). The supply of these nutrients is influenced by changes in nutrient partitioning and body composition. Nutrient availability to the animal varies substantially throughout the year (Adams *et al.* 1994). It is the skin that supports and nourishes the massive population of wool follicles. There are suggestions that skin thickness is related to wool growth (Gregory 1982b; Williams and Thornberry 1992)(section 2.5.4.3) and an indication of the body condition of sheep (section 2.5.1.2.2.1). The weight per unit area of skin shows similar trends to that of body weight (Hutchinson 1957; Lyne 1964; Williams and Morley 1994; Murray 1996; Schlink *et al.* 1996c). As a result it is expected that skin thickness will vary throughout the year in association with changes in body composition. It may be possible that differences in skin thickness and seasonal variation in skin thickness between animals may be associated with differences in FDPs. Sheep that have less variation in skin thickness throughout the year may be able to better maintain skin condition and therefore follicle nutrition. This would then result in reduced fibre diameter variation along the FDP.

Ultrasound scanning is an objective method for estimating subcutaneous fat thickness and is frequently used in both sheep and cattle (Dicker *et al.* 1988). Ultrasound scanning provides an objective, non-invasive and simple way to estimate skin (cross-section) and fat and muscle depths (Alexander and Miller 1979).

Adams and Briegel (1998) suggested that large body size might provide a buffer of body reserves for wool growth. Furthermore empty body weight, carcass fat, carcass muscle and visceral lean can show significant oscillation throughout the year when fed a constant intake (Ball *et al.* 1996). This may be due to seasonal shifts in metabolism and seasonal effects on the priorities for tissue deposition and retrieval that are independent of variation in feed intake and seasonal variation in the utilisation of feed. Differences between sheep in body weight and composition and seasonal variation in these traits may be associated with seasonal variation in fibre diameter and staple strength.

This study will examine the relationships between initial fibre diameter, average L/D ratio and seasonal variation in L/D ratio with FDP variation and staple strength. The influence of changes in body weight, body condition and skin thickness on these relationships will also be examined. The hypotheses for this study are;

1. Initial fibre diameter influences the level of variation in fibre diameter along the FDP in grazing sheep.
2. Differences between grazing sheep in L/D ratio are associated with differences in their responsiveness of fibre diameter throughout the year and therefore FDP characteristics.
3. Seasonal variation in fibre length growth, fibre diameter and the ratio of length to diameter throughout the year is associated with increased variation in fibre diameter along the profile and reduced staple strength in grazing sheep.
4. Seasonal variation in body weight, fat depth and skin thickness is related to variation in fibre diameter along the FDP in grazing sheep.

6.2 Materials and Methods

6.2.1 Animals

A mob of 48, 2-year-old fine wool Merino wethers, was obtained from the Kirby Rural Research Station. All animals originated from the same mob and therefore had similar management histories. These sheep were approximately 1 month off shears. The mean fibre diameter of the 48 sheep was measured using a small wool sample from the left-hand mid-side patch. This sample was scoured (three hexane washes followed by one hot water wash), dried and the fibre diameter measured using the Sirolan Laserscan (Sirolan Laserscan^{TM} Technology) (Charlton 1995). The 48 animals were ranked on mean fibre diameter and divided into 16 consecutive groups of 3 animals each. Sixteen experimental animals were then selected using a stratified selection technique. One sheep was randomly selected from each group to give a relatively even distribution of initial fibre diameters (IMFD).

A four-week pre-experimental period in which all the sheep were maintained as a single grazing mob was used after the animals were selected and placed into experimental paddocks to reduce the environmental differences between sheep in fibre diameter. As the sheep were running together for an extended period prior to the experiment and had similar management histories the pre experimental period was effectively longer.

6.2.2 Environment

The sheep were maintained for the duration of the experiment at the Kirby Rural Research Station, approximate 10 kilometres north west of Armidale, NSW (Latitude 30°31'00 S and Longitude 151°39'50 E). The paddocks used were approximately 0.8 ha in size and were all located within a 5ha area.

6.2.2.1 Temperature and Rainfall

Figure 6.1 illustrates that the rainfall received in each month throughout the experiment was different to the long-term average rainfall in Armidale. Figure 6.2 depicts the average maximum and minimum temperatures for Armidale in each month throughout the experiment. The temperature at the experimental site was not recorded during the experiment.

Figure 6.1 The rainfall received during the experimental period (■) and the long-term average for Armidale (-■-) (Australian Bureau of Meteorology)

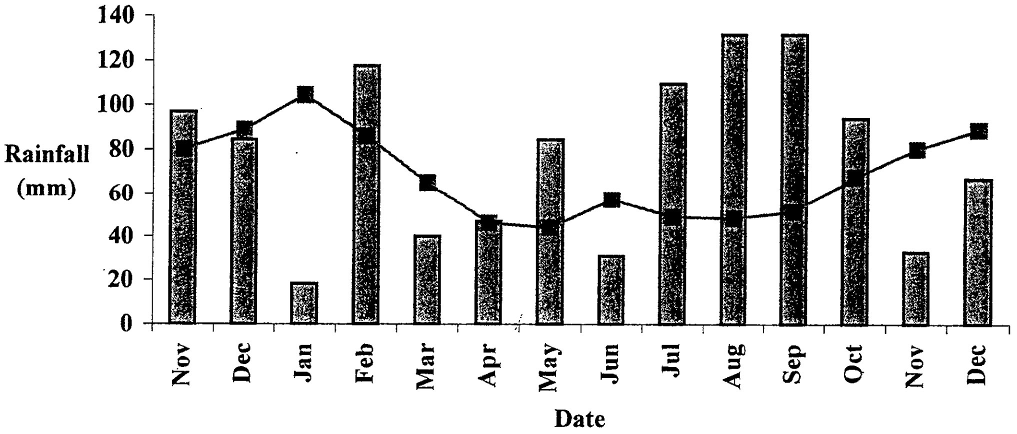
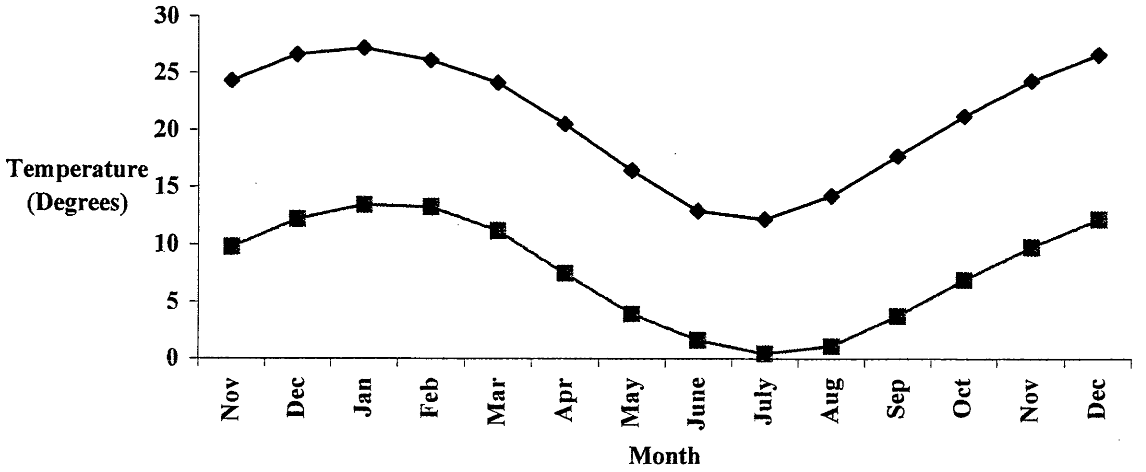


Figure 6.2 The mean maximum (—◆—) and mean minimum temperature (—■—) for Armidale (90 year average) for the months of the experiment (Australian Bureau of Meteorology)



6.2.2.2 Pasture

The experimental paddocks consisted of native and improved grass pasture species. The species included 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 in less dominance.

Pasture yield and quality was estimated using the Prograze technique (Allan 1994) when sheep were moved between plots. Briefly each plot was divided into 6 equally sized subdivisions and two randomly located median samples were cut from each. The median quadrat was used as it has been shown to give an unbiased estimate of the mean herbage yield (Hamilton 1976). The quadrat used in this technique was a 1.5 x 0.5m quadrat sub-divided into 5, 0.3 x 0.5m sections. At each randomly selected location the 2 highest and 2 lowest yielding sections were eliminated with the remaining section harvested (cut down to ground level). Therefore only one section of the quadrat was sampled at each point.

Plant material cut from the quadrats at each sampling site were pooled and dried at 60°C overnight. The sample was then mixed thoroughly and a sub sample (approximately 100g) was randomly taken. This sub sample was then hand separated into three fractions, green, dead and legume. As no legume was present at any sampling only the green and dead fractions were used and the results are expressed on a percentage basis. The sub sample was recombined with the main sample and ground using a mill (Christy Hunt Hammer Mill, Christy Hunt Industrial Ltd.) and 1mm sieve and then weighed. The nitrogen content was estimated from these ground samples using a LECO FP – 2000 combustion based nitrogen / protein determinator (Leco Corporation). Crude protein (CP) (g/kg) was estimated by multiplying the nitrogen content (g/kg) by 6.25 (McDonald *et al.* 1991). CP was expressed on a dry matter basis, with dry matter content of the sample being estimated by oven drying of a sub-sample for 24 hours at 105°C. The amount of dry matter of feed on offer (FOO) was calculated using the amount of pasture harvested from the quadrats expressed on a dry matter basis, corrected for area of sample.

6.2.3 Sheep Management

The sheep were subjected to the standard "Wormkill" program (Davidson 1985; Holdsworth 1993) used on the research station. Two faecal samples were collected throughout the experiment, one on 25th February and the other on 3rd August 1998. Faecal egg counts were measured using a McMaster egg counting technique (Dunn 1978). The results are tabulated in Appendix 6.1 and illustrate that on average the 16 sheep were not significantly burdened by internal parasites.

The sheep were rotated between 3 paddocks (0.8ha) to avoid severe feed shortages. The sheep were crutched on 25th May 1999 and received no supplementary feed during the experiment. After August the sheep remained in the same paddock as with the onset of spring and increasing temperature (Figure 6.1) and rainfall (Figure 6.2) pasture growth was sufficient to feed the sheep.

6.2.4 Sampling regime

The animals were sampled at 12 times throughout the experiment, approximately 4 weeks apart. The number of days between periods varied slightly as a result of unfavourable weather conditions on the scheduled day of sampling. The actual sampling regime is described in table 6.1. At each of these samplings the un-fasted body weight (Bwt) of the sheep was measured using Ruddweigh electronic sheep scales. The skin thickness and fat depth were measured (using callipers and ultrasound) and a dyeband inserted at each of these samplings as described below.

Table 6.1 The sampling regime and ^{35}S-cysteine Injections for the duration of the experiment

Sampling Number	Date	Day	^{35}S-cysteine Injections
1	15-Dec-97	1	
2	13-Jan-98	30	
3	16-Feb-98	64	1st Injection
4	16-Mar-98	92	2nd Injection
5	28-Apr-98	135	
6	25-May-98	162	
7	6-Jul-98	204	1st Injection
8	3-Aug-98	232	2nd Injection
9	31-Aug-98	260	
10	28-Sep-98	288	
11	28-Oct-98	318	1st Injection
12	23-Nov-98	344	2nd Injection

6.2.5 Wool Measurements

6.2.5.1 Dyebands

At each sampling time a dyeband was inserted at the base of a line of staples (approximately 10cm long running in a dorsal-ventral direction) using a blunt 21 gauge needle and 1ml syringe. The dyeband fluid was mixed at 0.8% (w/v) Durafur Black flakes and 0.8% (w/v) concentrated hydrogen peroxide dissolved in cold water. These staples were located approximately 10cm anterior of the right mid-side patch.

At the end of the experiment a mid-side sample was collected. This sample was not from the true mid-side region as this site was used for skin measurements. The sample used to represent the mid-side sample was collected adjacent to the mid-side area. This sample consisted of all wool staples between the clipped patch used for the skin thickness measurements and the staples that were dyebanded.

Three wool staples were randomly selected from the dyebanded staples and used to measure fibre diameter at, and staple length between, each dyeband. Staple length growth throughout the experiment was measured between dyebands on three staples from the sample. These measurements were averaged to give staple length growth between each dyeband. From these measurements average ($AvSL^{Bands}$) and variation ($SDSL^{Bands}$ and $CVSL^{Bands}$) in staple length growth between the dyebands were calculated. A 2mm snippet was guillotined at each dyeband, washed (3 x 5-minute hexane washes and one 5-minute hot water wash), dried overnight and the fibre diameter measured using 500 counts by the Sirolan Laserscan.

6.2.5.2 L/D ratios

The autoradiographic technique used is a modification of the technique described by Hynd (1994a) using image analysis to determine fibre diameter and fibre length. Three measurements of fibre length and fibre diameter were made as described in Table 6.1. The measurements were made on a small bundle of staples located approximately 120mm dorsally of the right mid-side patch. Each measurement period consisted of two intra-dermal injections approximately 28 days apart with 0.3ml of normal saline solution containing 5.1 µCi/ml of ^{35}S-cysteine hydrochloride (based on activity at harvest). Twenty-one days after the second injection the labelled staples were harvested, cleaned, stained with picric acid, washed in hot water and dried overnight. 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) for 7 days. The film was superimposed onto the slides with DPX (Ajax Chemicals). The fibre diameter was measured at 10 sites approximately equidistant between the labelled sites on at least 50 fibres using an image analysis system (Leica Quantimet 500MC Leica Cambridge Ltd.). The image analysis program was calibrated using a standard haemocytometer. Fibre length was measured on 50 fibres for each sheep by tracing the fibre between the labelled points using the same image analysis system. The mean fibre diameter, fibre diameter variation, mean fibre length and fibre length variation for the period of wool growth were calculated for each sheep. The ratio of fibre length growth per day (µm/day) to mean fibre diameter was calculated (L/D ratio). The average fibre length (AvFL), fibre length variation (AvFLCV), L/D ratio (AvL/D), variation in

L/D ratio (L/DCV), variation in average fibre diameter (FDCV) and the variation in fibre growth rate (FGCV) between the three L/D ratio measurement periods were also calculated for each animal. The average absolute change in fibre length growth rate (△FL), fibre diameter (△FD) and the ratio of change in fibre length growth to change in fibre diameter (△FL/△FD) between the three measurement periods were also calculated.

6.2.5.3 FDPs and FDP characteristics

A wool staple was randomly selected from the mid-side sample collected at the end of the experiment. A FDP was generated using the FDP prediction technique (1 in 4 level of inclusion) described in section 4.4. The FDP characteristics of Max, Mindiam, AstCV, Roc1, Roc2 and AvSnipCV were calculated as described in section 4.2.1. While only the results for Max, Mindiam, AstCV, Roc1, Roc2 and AvSnipCV are discussed the results for the full range of FDP characteristics as described in section 4.2.1 are presented in Appendix 6.2 to 6.5.

6.2.5.4 Staple strength and staple length

Ten staples were randomly selected from the mid-side sample using a sampling board. The board was 24cm wide and 30cm long with 5 randomly placed holes (32mm in diameter). This board was randomly placed on the mid-side sample, which was spread out on a bench. A staple was randomly selected from each hole and the board was rotated 90 degrees and another staple selected from each hole. These staples were left to condition overnight (20±2 °C and 63±2% humidity). Staple length (SL) and staple strength (SS) were measured for each staple using the Agritest StapleBreaker Model 2 (Vizard *et al.* 1994; Baxter 1996).

6.2.5.5 Fibre diameter and Yield

The remaining mid-side sample was used to measure mean fibre diameter. The entire sample of approximate 20 grams was scoured using two hot water and Lissapol detergent (manufactured by ICI Chemical and distributed by Spectrum Distributors as Hydropol TN450) washes and a final plain hot water wash. The samples were then spun for approximately 2 minutes and dried at 70°C for 30 minutes. Yield (Yld) was then calculated using conditioned clean wool weight over conditioned greasy wool weight expressed as a percentage. The sample was then mini-cored and the fibre diameter (mid-side MFD) and fibre diameter variation (mid-side MFDCV) measured using 2000 counts by the Sirolan Laserscan.

6.2.6 Fat depth

The depth of subcutaneous fat (Fat) at the C site (over the eye muscle of the 12th rib) was measured within three days either side of each of the 12 sampling times. These measurements were made using an Aloka 500V real time ultrasound scanner at a frequency of 3.5 Mega Hertz. The probe was 17.5cm long and designed for use in cattle. Although it would have been more appropriate to use a smaller, higher frequency probe financial constraints made this unfeasible.

6.2.7 Skin thickness

6.2.7.1 Calliper method

The average skin thickness of the sheep was measured at each sampling time using a technique described by Williams and Thornberry (1992). Skin thickness was measured at two points randomly selected on the right mid-side after close clipping (Oster small animal clippers size 30 blade). These two points were marked with a permanent marking pen and used for the skin measurements at each sampling. A double fold of skin was measured using dial gauge callipers that exerted a constant pressure of 1250g/cm^2 (Lyne 1964). A measurement was made at each spot with the callipers facing in anterior / posterior direction and a second measurement was made in a dorsal / ventral direction. Average skin thickness was calculated by dividing the sum of these measurements by 8. For each animal average skin thickness (Skin) and variation in skin thickness (SkinCV) over the experimental period were calculated.

6.2.7.2 Ultrasound method

Skin thickness was measured with the real time ultrasound scanner at the same time as the subcutaneous fat measurements described in section 6.2.5. For each animal average skin thickness (Skin$^{\text{Ultra}}$) and variation in skin thickness (SkinCV$^{\text{Ultra}}$) over the experimental period were calculated.

6.2.8 Statistical Analysis

The strength and direction of the relationships between the various fibre, staple and body characteristics were examined using simple correlation and stepwise multiple regression analysis performed using the CORR and REG procedures of SAS (1990). The stepwise multiple regression fitted the most highly correlated variable first and then individual variables were added one at a time to see which had the greatest effect on the proportion of variation explained. Only variables which added significantly ($P<0.15$) to the explained variance were retained in the model. Least squares analysis of variance was also used to compare L/D ratio between measurements, skin thickness between measurement techniques and initial and mid-side mean fibre diameter measurements. The model for each analysis of variance included the random effects of animal and measurement within animal.

Canonical correlation analysis was conduced using the CANCORR procedure of SAS (1990) to further examine the relationship between the initial fibre diameter and L/D ratio measurements and body traits with the FDP characteristics. Due to the small sample size of this experiment the number of variables included in the canonical correlation analysis was reduced. The characteristics included were selected based on their relationships from the simple linear correlation analysis. The L/D ratio measurements included the variables IMFD, AvL/D, L/DCV, $\text{CVSL}^{\text{Bands}}$ and $\triangle$FL/$\triangle$FD. Body traits included Bwt, BwtCV, Skin, SkinCV, Fat, FatCV. The FDP characteristics included in the analysis were Max, Mindiam, AstCV, Roc1, Roc2 and AvSnipCV.

6.3 Results

6.3.1 Pasture Analysis

Figure 6.3 demonstrates that the quantity of food on offer (FOO) declined from greater than 3000 kg/ha down to approximately 1200 kg/ha towards the end of the experiment. The crude protein (CP) content of the food on offer increased throughout the experiment. The percentage of dead and green components of the food on offer also varied slightly throughout the experiment (Figure 6.4).

Figure 6.3 The changes in food on offer (FOO ■) and crude protein g/kg (CP-◆-) of the feed on offer throughout the duration of the experiment

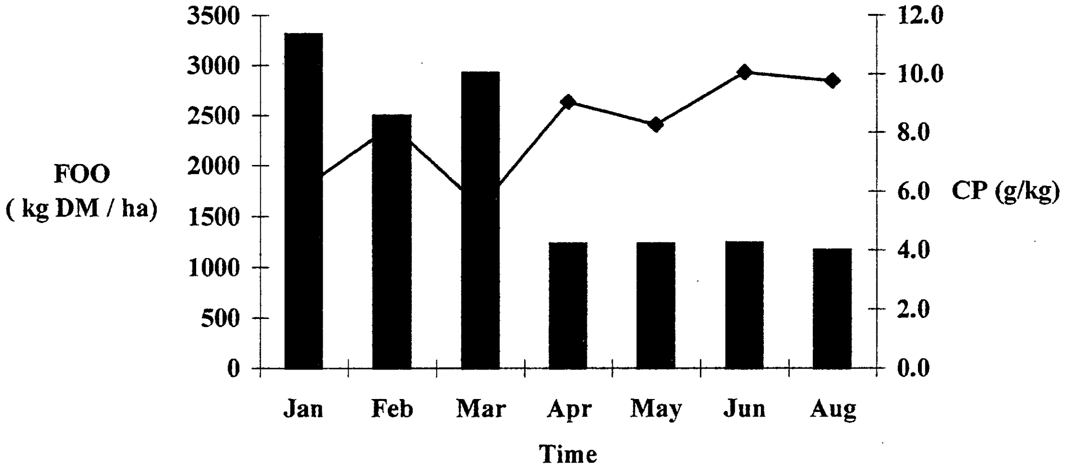
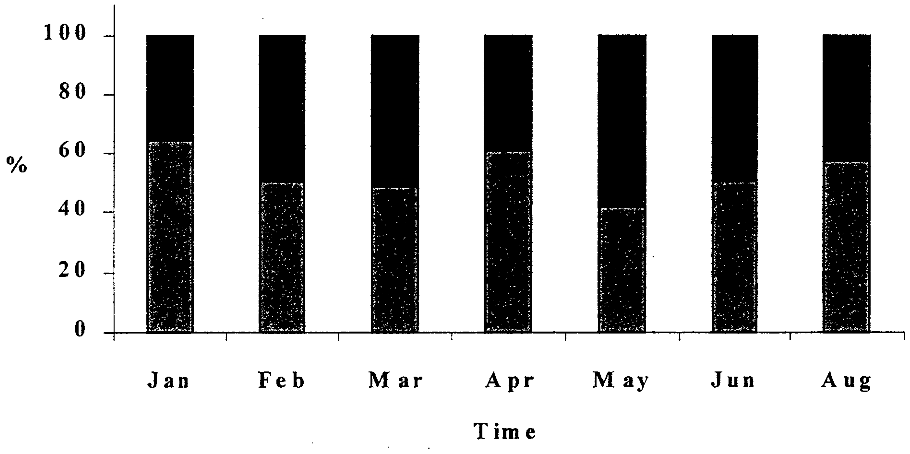


Figure 6.4 The percentage of dead (■) and green (▨) feed on offer throughout the duration of the experiment



6.3.2 Summary of traits measured throughout the experiment

Table 6.2 illustrates the mean levels of each trait measured during the experiment and the variation between the 16 experimental animals. There was large variation (>20% CV) between animals for SS, AstCV, Roc1, Roc2, 1stL/D, L/DCV, FGCV, ΔFL, ΔFD, ΔFL/ΔFD, $\text{CVSL}^{\text{Bands}}$, SkinCV, Fat and $\text{Skin}^{\text{Ultra}}$.

Table 6.2 Summary of the mean values and variation between animals for each of the wool and body characteristics measured during the experiment

	Mean	CV		Mean	CV
Mid-side wool quality characteristics			***L/D ratio measurements***		
IMFD (µm)	17.51	7.66	**1stL/D ((µm/day)/µm)**	17.01	21.27
IMFDCV (%)	16.50	8.42	**2ndL/D ((µm/day)/µm)**	18.43	14.91
Mid-side MFD (µm)	18.20	7.86	**3rdL/D ((µm/day)/µm)**	18.93	15.43
Mid-side MFDCV (%)	17.30	10.90	**AvL/D ((µm/day)/µm)**	18.16	15.71
SL (mm)	88.13	15.28	**L/DCV (%)**	7.49	53.11
Yld (%)	76.80	4.36	**FGCV (%)**	7.26	62.77
SS (N/Ktex)	40.47	24.99	**FDCV (µm)**	11.35	16.44
POB (%)	65.32	8.00	**AvFL (µm)**	9455.51	15.08
			AvFLCV (%)	10.55	18.49
FDP characteristics			**ΔFL (µm)**	47.48	61.08
Max (µm)	20.03	9.06	**ΔFD (µm)**	3.07	28.72
Mindiam (µm)	16.32	7.61	**ΔFL / ΔFD**	15.45	55.50
AstCV (%)	5.82	21.65	**AvSL$^{\text{Bands}}$ (mm)**	6.74	10.99
Roc1 (µm/mm)	0.07	36.83	**CVSL$^{\text{Bands}}$ (%)**	24.57	35.30
Roc2 (µm/mm)	0.16	38.59			
AvSnipCV (%)	15.88	14.39			
Body weight and composition					
Bwt (kg)	45.54	9.55	**Fat (mm)**	2.07	27.15
BwtCV (%)	6.80	19.18	**FatCV (%)**	37.36	18.69
Skin (mm)	1.77	10.10	**Skin$^{\text{Ultra}}$**	1.93	10.69
SkinCV (%)	6.15	25.26	**SkinCV$^{\text{Ultra}}$**	24.22	22.61

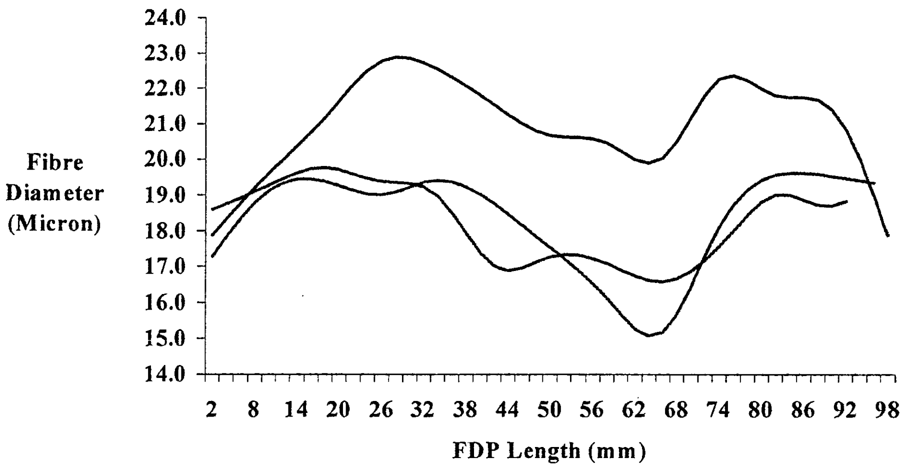
Table 6.3 illustrates the variation in fibre diameter and staple length growth at each sampling time throughout the experiment. The mean fibre diameter and length growth per day showed a trend throughout the experiment similar to that observed in the FDP (Figure 6.5). There was large variation between sheep in their FDP. This variation can be seen in the coefficient of variation values for the FDP characteristics in Table 6.2, with along-staple variation in fibre diameter and the rates of fibre diameter change having a coefficient of variation greater than

20%. The large variation between sheep in FDP shape can also be observed in Figure 6.5, which illustrates three FDPs from sheep with similar IMFD and FDP length.

Table 6.3 The mean fibre diameter at dyeband and staple length growth in-between dyebands throughout the experiment

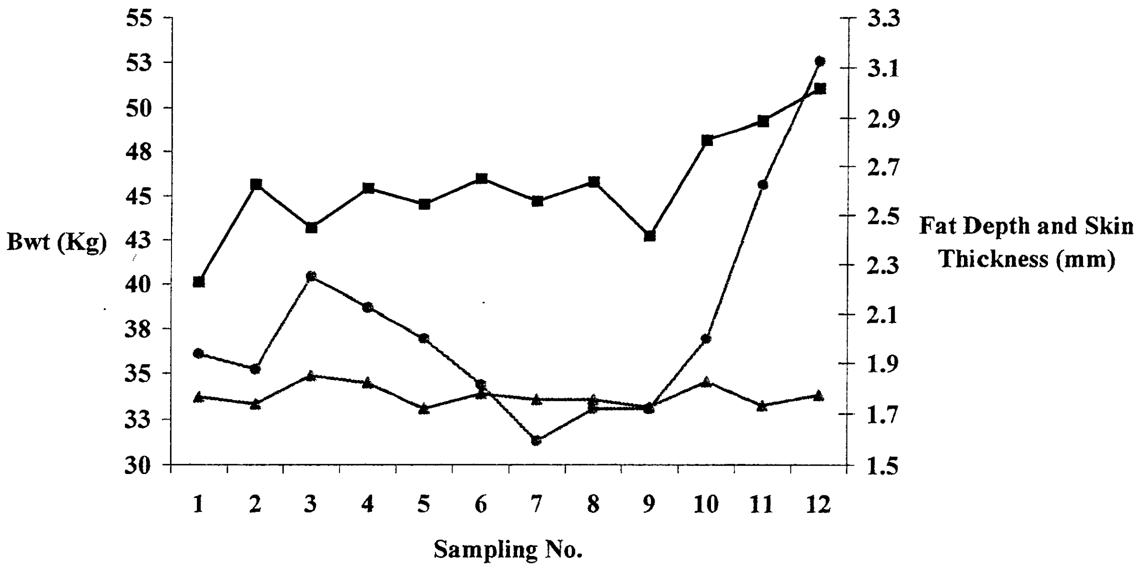
	Fibre diameter at dyeband		**Staple length between dyebands**			
Sampling number	**Mean**	**CV**	**Period of growth**	**Mean**	**CV**	**L / Day**
1	19.23	8.53	**0-1**	.	.	.
2	19.44	9.19	**1-2**	6.05	17.12	0.22
3	19.33	8.57	**2-3**	6.12	14.97	0.17
4	19.40	8.62	**3-4**	5.92	17.40	0.21
5	17.77	8.28	**4-5**	7.99	14.53	0.19
6	17.68	8.82	**5-6**	5.45	9.31	0.20
7	17.26	9.37	**6-7**	8.20	12.89	0.20
8	16.78	8.42	**7-8**	5.66	10.44	0.20
9	16.66	10.74	**8-9**	5.41	9.84	0.17
10	18.50	11.87	**9-10**	6.53	13.32	0.27
11	19.12	11.48	**10-11**	7.32	15.85	0.24
12	18.91	10.85	**11-12**	6.13	14.75	0.24

Figure 6.5 Example of the FDPs from three of the experimental animals of similar FDP length and IMFD



Body weight (Bwt) showed a steady increasing trend throughout the experiment rising from 40.1kg at the start of the experiment to 51.1 kg at the end of the experiment (Figure 6.6). Fat depth showed a seasonal trend that was similar to that of the FDPs, temperature and feed on offer. The variation in skin thickness throughout the experiment was smaller relatively to that of Fat and the FDPs.

Figure 6.6 The changes in body weight (Bwt ■), fat depth (Fat ●) and skin thickness (Skin ▲) throughout the experimental period



There were significant ($P<0.05$) differences in L/D ratio between animals and between L/D ratio measurements (Table 6.4). The first L/D ratio measurement was significantly lower ($P<0.05$) than the 2nd and 3rd measurements but highly correlated with each ($r= 0.87$, $P<0.05$ and 0.93, $P<0.05$ respectively). The second and third L/D ratio measurements were also highly correlated ($r= 0.90$, $P<0.05$) and not significantly different ($P>0.05$).

Table 6.4 The least squares means for each L/D ratio measurements throughout the experiment

1st L/D ((μm/day)/μm)	2nd L/D ((μm/day)/μm)	3rd L/D ((μm/day)/μm)	Probability
16.78 ± 0.31^a	18.43 ± 0.27^b	18.93 ± 0.27^b	0.0001

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

The least squares means for the mean fibre diameter and variation of fibre diameter made at the start (initial) and the end (mid-side) of the experiment are illustrated in Table 6.5. Initial mean fibre diameter was highly correlated with ($r= 0.83$, $P<0.01$) but significantly lower than ($P<0.05$) mid-side mean fibre diameter. . Initial fibre diameter variation did not differ significantly ($P>0.05$) from mid-side Mid-side fibre diameter variation but was not highly correlated with it ($r= 0.21$, $P>0.05$).

Table 6.5 The least squares means for the mean fibre diameter and fibre diameter measurement made at the beginning (initial) and at the end of the experiment (mid-side)

	Initial	Mid-side	s.e.	Probability
Mid-side MFD (μm)	17.51^a	18.20^b	0.14	0.0041
Mid-side MFDCV (%)	16.50^a	17.30^a	0.37	0.1490

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

6.3.3 Relationship between the FDP characteristics and the fibre based measurements

Table 6.6 illustrates the relationship between L/D ratio and associated fibre measurements with the FDP characteristics. AvL/D was negatively correlated with Max, Mindiam, Roc1 and Roc2.

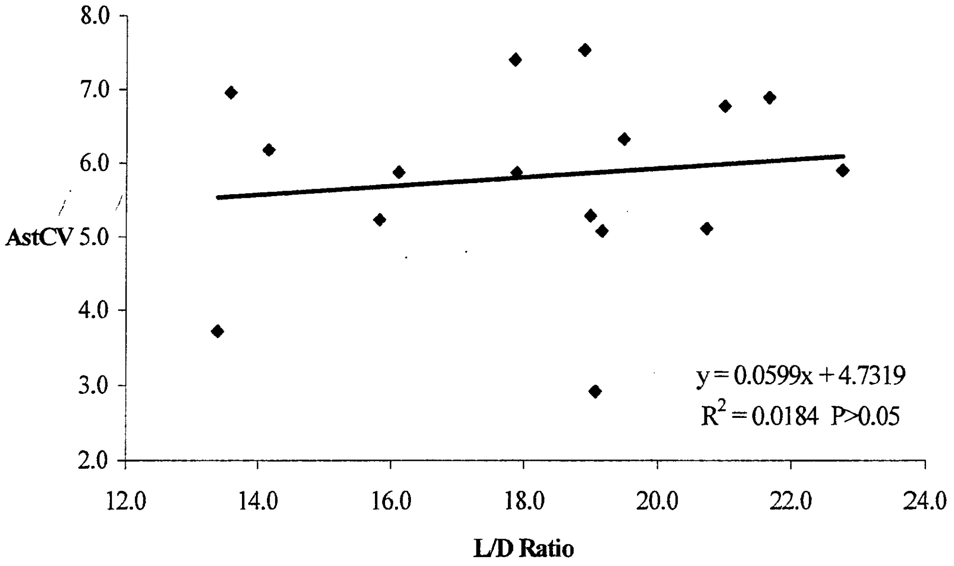
Table 6.6 Correlation coefficients for the relationships between the wool fibre characteristics and the FDP characteristics (n=16)

Characteristics	Max	Mindiam	AstCV	Roc1	Roc2	AvSnipCV
AvL/D	-0.61*	-0.70*	0.14	-0.42*	-0.08	-0.44
L/DCV	0.16	0.28	-0.36	-0.17	-0.19	0.45*
FGCV	-0.08	-0.20	0.32	0.09	0.04	-0.21
FDCV	-0.11	-0.09	0.11	0.42*	-0.16	-0.30
AvFL	-0.08	-0.25	0.52*	-0.11	0.31	-0.29
AvFLCV	0.35	0.48*	-0.27	-0.10	-0.37	0.65*
ΔFL	0.05	0.10	0.46*	0.15	0.12	-0.20
ΔFD	0.43*	0.32	0.65*	0.74*	0.44*	-0.23
ΔFL / ΔFD	0.00	-0.14	0.29	-0.04	-0.02	0.02
AvSL(bands)	0.28	0.06	0.63*	0.09	0.50*	-0.16
CVSL(bands)	0.18	0.03	0.18	-0.01	-0.13	0.46*

* Correlation highly significant ($P<0.05$)

Over all animals in the study average L/D ratio was not highly correlated with along-staple variation in fibre diameter (Figure 6.7) however there were strong relationships observed within micron groups. The relationship between average L/D ratio and along-staple variation in fibre diameter increased to r= 0.70 when only the eight animals with mid-side mean fibre diameter values between 17.5 and 18.8 microns were examined. This relationship further strengthened (r= 0.98) when the five animals between 18.2 and 18.8 microns were compared.

Figure 6.7 The relationship between L/D ratio and AstCV (n=16)



Average L/D ratio was also significantly negatively correlated with variation in fibre diameter between fibres (r=- 0.44). L/DCV was negatively correlated with along-staple variation in fibre diameter and the rates of fibre diameter change but positively correlated with variation between-fibres. Average fibre length was positively correlated with along-staple variation in fibre diameter and the rates of fibre diameter change. Fibre length variation was also highly significantly positively correlated with variation in fibre diameter between fibres (r= 0.65). △FL and △FD were positively correlated with all FDP characteristics. In a multiple regression equation the characteristics of CVSL (bands) (13.6%), △FD (42.3%), △FL (2.5%) and FDCV (18.6%) explained in total 77% (P<0.05) of the variation of AstCV. The remaining characteristics did not significantly explain any additional variation in AstCV.

6.3.4 Relationship between FDP characteristics and mid-side wool quality characteristics

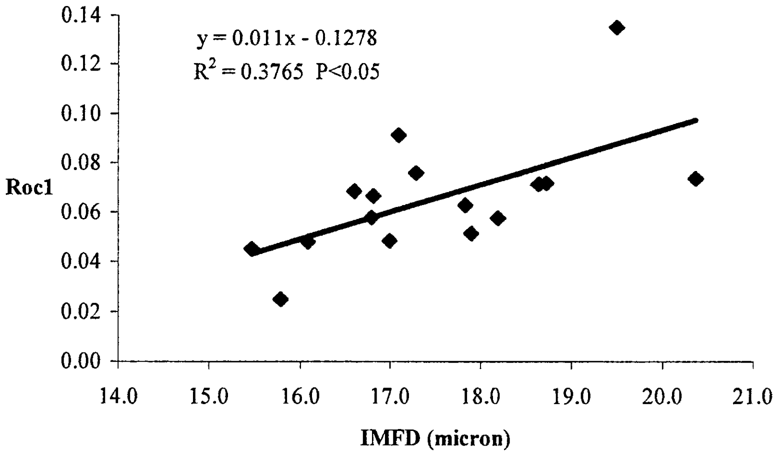
The relationships between initial mean fibre diameter (IMFD) and the mid-side wool quality characteristics with the FDP characteristics are shown in Table 6.7. Initial mean fibre diameter and mid-side mean fibre diameter were significantly and positively correlated with all FDP characteristics except variation between-fibre in fibre diameter.

Table 6.7 Correlation coefficients for the relationships between the wool quality characteristics and the FDP characteristics (n=16)

Characteristics	Max	Mindiam	AstCV	Roc1	Roc2	AvSnipCV
IMFD	0.86*	0.79*	0.61*	0.61*	0.59*	0.22
IMFDCV	0.20	-0.06	0.30	0.01	0.21	0.53*
Mid-side MFD	0.92*	0.88*	0.45*	0.51*	0.44*	0.42
Mid-side MFDCV	0.54*	0.63*	-0.09	0.03	-0.09	0.79*
SL	-0.05	-0.19	0.51*	0.01	0.50*	-0.54*

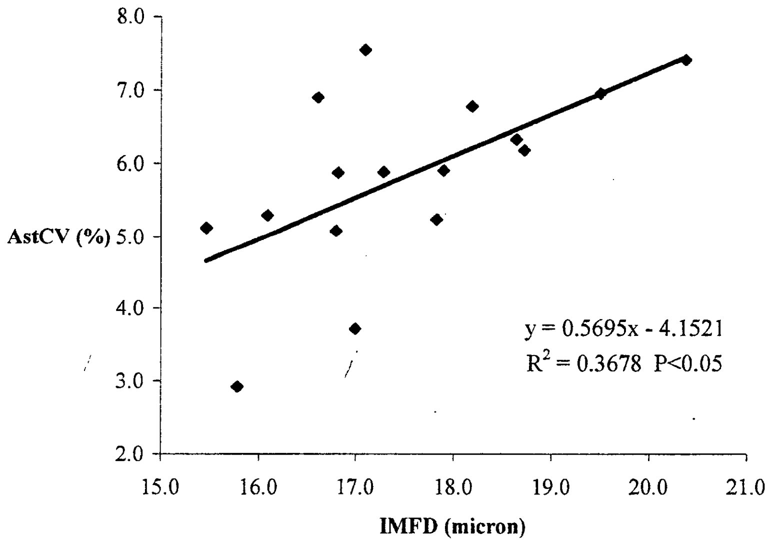
* Correlation significant (P<0.05)

Figure 6.8 The relationship between IMFD and Rocl (n=16)



The positive association (r= 0.61) between initial mean fibre diameter and the first rate of fibre diameter change is illustrated in Figure 6.8 while Figure 6.9 depicts that positive relationship (r= 0.61) between initial mean fibre diameter and along-staple variation in fibre diameter. Initial fibre diameter variation was only significantly correlated with between-fibre variation in fibre dimeter (r= 0.53) while mid-side fibre diameter variation was significantly and positively correlated with absolute fibre diameter values in the FDP.

Figure 6.9 The relationship between IMFD and AstCV (n=16)



Staple length was significantly positively correlated with along-staple variation in fibre diameter and the second rate of fibre diameter change while negatively correlated with variation in fibre diameter between-fibres. Mid-side variation in fibre diameter was not significantly correlated with along-staple variation in fibre diameter (r= -0.09 P>0.05) but significantly positively correlated with between-fibre variation in fibre diameter (r= 0.79 P<0.001 respectively). Between fibre variation in fibre diameter was also not significantly correlated with along-staple variation in fibre diameter (r= -0.10 P>0.05).

6.3.5 Relationship between FDP characteristics and body traits

The relationship between the body traits and FDP characteristics are shown in Table 6.8. Bwt was lowly negatively correlated (P>0.05) with all FDP characteristics except variation in fibre diameter between fibres while variation in body weight (BwtCV) was positively correlated with all FDP characteristics except variation in fibre diameter between-fibres. The relationship between variation in body weight and along-staple variation in fibre diameter is illustrated in Figure 6.10.

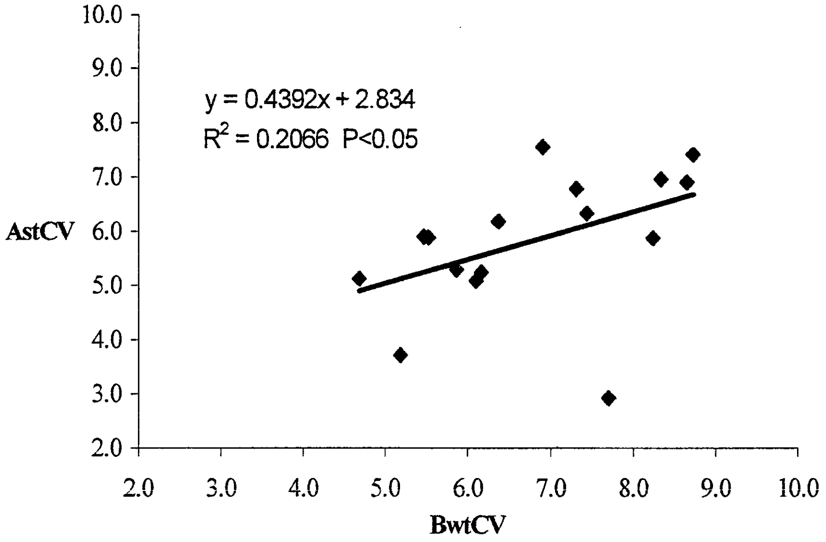
Table 6.8 Correlation coefficients for the relationships between the body characteristics and the FDP characteristics (n=16)

Characteristics	Max	Mindiam	AstCV	Roc1	Roc2	AvSnipCV
Bwt	-0.11	-0.02	-0.02	-0.40	-0.24	0.11
BwtCV	0.30	0.24	0.46*	0.36	0.37	-0.10
Skin	0.35	0.48*	-0.46*	-0.10	-0.27	0.61*
SkinCV	0.20	0.03	0.47*	0.56*	0.43*	0.31
Fat	-0.30	-0.14	-0.11	-0.45*	-0.26	0.14
FatCV	0.01	0.04	0.09	0.35	0.57*	-0.46

* Correlation significant (P<0.05)

Skin thickness was positively correlated with absolute fibre diameter within the FDP and variation between-fibres while negatively correlated with variation in fibre diameter along-fibres and the rates of fibre diameter change. Seasonal variation in skin thickness (SkinCV) was positively correlated with all FDP characteristics. Figure 6.11 illustrates the positive relationship between seasonal variation in skin thickness and seasonal variation in fibre diameter.

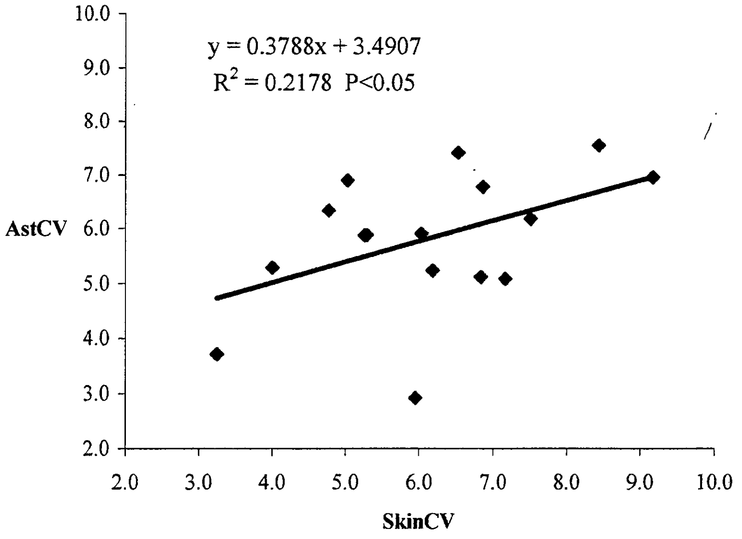
Figure 6.10 The relationship between BwtCV and AstCV (n=16)



Average fat depth was negatively correlated with all FDP characteristics except AvSnipCV. Seasonal variation in fat depth (FatCV) was positively correlated with the rates of fibre diameter change and negatively correlated with variation in fibre diameter between-fibres.

The full table of correlations observed within the body traits are shown in Appendix 6.6. Briefly, body weight was negatively correlated with skin thickness (r= -0.23) and positively correlated with fat depth (r= 0.62). Seasonal variation in body weight was not significantly (P>0.05) but positively correlated with both seasonal variation in skin thickness and fat depth (r= 0.22 and 0.14) while BwtCV and FatCV were not correlated (r= 0.07).

Figure 6.11 The relationship between SkinCV and AstCV (n=16)



Multiple regression analysis indicated that seasonal variation in skin thickness (21.9%) and average skin thickness (14.2%) were the only body traits that significantly explained the variation in along-staple variation in fibre diameter (r^2= 0.36 $P<0.05$).

6.3.6 Relationships between the fibre based and mid-side measurements

A full table of correlations between the fibre based and mid-side measurements is shown in Appendix 6.7. Initial mean fibre diameter was positively correlated with △FL, △FD and △FL/△FD (r= 0.31, 0.63 and 0.17 respectively). A full table of correlations within the fibre based measurements is shown in Appendix 6.8. AvL/D ratio was positively correlated with △FL and the ratio of △FL/△FD (r= 0.67 and 0.41 respectively) while negatively correlated with △FD (r= -0.12). △FL was positively correlated with △FD (r= 0.35). Sheep that had higher average L/D ratio also had greater seasonal variation in L/D ratio (r= -0.47), mid-side mean fibre diameter (r= -0.65) and mid-side fibre diameter variation (r= -0.61). Mid-side fibre diameter variation was also was significantly positively correlated (r= 0.62) with variation in fibre length.

6.3.7 Relationships between the fibre based measurements and body traits

Body weight and fat depth were both positively correlated with L/D ratio and fibre length growth (r= 0.30 and 0.33 for Bwt and r= 0.50 and 0.53) while average skin thickness was negatively correlated with L/D ratio and fibre length growth (r= -0.75 and -0.71). Seasonal variation in body weight, fat depth and skin thickness were positively correlated with the absolute changes in fibre length and diameter between the measurements of L/D ratio. Seasonal variations in the body traits were not significantly related to the remaining fibre based measurements.

6.3.8 Canonical correlation analysis

The canonical correlation analysis indicated that there was one significant canonical correlation (r_c= 0.99, $P<0.05$) between a canonical variate formed from IMFD and the L/D ratio measurements and a canonical variate formed from the FDP characteristics.

Table 6.9 Correlations and standardised canonical coefficients for the canonical variables for IMFD and the L/D ratio measurement and FDP characteristics (n=16)

	Canonical Variate	
	Correlation	**Coefficient**
IMFD and L/D ratio measurements		
IMFD	0.88	0.78
AvL/D	-0.73	-0.40
L/DCV	0.20	-0.02
CVSL(bands)	0.06	0.15
ΔFL / ΔFD	-0.12	-0.16
FDP characteristics		
Max	0.95	0.15
Mindiam	0.93	0.61
AstCV	0.41	-0.08
Roc1	0.61	0.25
Roc2	0.49	0.21
AvSnipCV	0.41	0.13

Table 6.9 illustrates the relationships between the estimated canonical variables and the original variables for initial mean fibre diameter and the L/D ratio measurements and the FDP characteristics. The canonical variable formed from initial mean fibre diameter and the L/D ratio measurements was most positively related to initial mean fibre diameter and negatively related to AvL/D ratio. The canonical variable formed from the FDP characteristics was moderately related to all FDP characters. The canonical variable formed from initial mean fibre diameter and the L/D ratio measurements explained 44.4% of the standardised variance of the FDP characteristics.

Table 6.10 Correlations and standardised canonical coefficients for the canonical variables for the body traits and FDP characteristics (n=16)

	Canonical Variate	
	Correlation	**Coefficient**
Body traits		
Bwt	0.78	0.36
BwtCV	0.03	0.22
Skin	-0.13	0.06
SkinCV	-0.14	-0.16
Fat	0.83	0.49
FatCV	-0.72	-0.40
FDP characteristics		
Max	-0.14	-2.32
Mindiam	0.02	2.01
AstCV	-0.08	1.64
Roc1	-0.53	-0.88
Roc2	-0.46	-0.37
AvSnipCV	0.27	0.47

The canonical correlation analysis that include the body traits indicated that there was one significant canonical correlation (r_c= 0.97, $P<0.05$) between a canonical variate formed from the body traits and a canonical variate formed from the FDP characteristics. The canonical variable formed from the body traits was positively related to Bwt and Fat while negatively related to seasonal variation in fat depth (Table 6.10). The canonical variable from the FDP characteristics was positively related to variation in fibre diameter between fibres and negatively related to the rates of fibre diameter change. The canonical variable formed from the body traits explained 9.0% of the standardised variance of the FDP characteristics

6.3.9 Relationship between FDP and mid-side measurements with staple strength

Table 6.11 illustrates the relationships between the FDP and wool quality characteristics with SS. Max, Mindiam, AstCV, AvSnipCV, IMFDCV, mid-side MFD and mid-side MFDCV were all negatively correlated with SS. Figure 6.12 depicts the strong negative relationship between variation in fibre diameter between-fibres and staple strength.

Table 6.11 Correlation coefficients for the relationships between the FDP and wool quality characteristics and staple strength (n=16)

Characteristics	SS	Characteristics	SS
Max	-0.22	**SL**	0.14
Mindiam	-0.06	**IMFD**	-0.16
AstCV	-0.17	**IMFDCV**	-0.66*
Roc1	0.13	**Mid-side MFD**	-0.24
Roc2	0.08	**Mid-side MFDCV**	-0.60*
AvSnipCV	-0.71*		

* Correlation significant ($P<0.05$)

In a multiple regression of FDP characteristics with staple strength, between-fibre variation in fibre diameter significantly explained 50.6% (Table 6.12) of the variation in staple strength ($P<0.05$) while the remaining FDP characteristics did not significantly explain any additional variation in staple strength. Mid-side fibre diameter variation (MFDCV) was the only mid-side wool quality characteristic which significantly explained any proportion (36%) of the variation of staple strength ($P<0.05$). In the stepwise multiple regression with all FDP and mid-side wool quality characteristics, between-fibre variation in fibre diameter (50.6%) and staple length (8.4%) significantly explained 59% ($P<0.05$) of the variation in staple strength.

Figure 6.12 The relationship between staple strength (SS) and AvSnipCV (n=16)

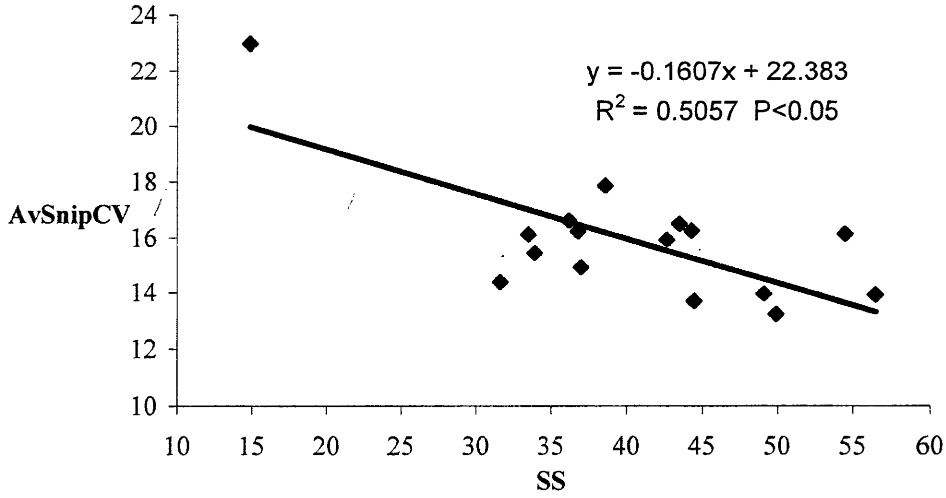


Table 6.12 The proportion of variation of staple strength (SS) explained by wool quality, FDP and both wool quality and FDP characteristics in stepwise multiple regression analysis

Wool Quality Characteristics		**FDP characteristics**		**FDP and Wool quality characteristics**	
Characteristics	**% of variation in SS explained**	**Characteristics**	**% of variation in SS explained**	**Characteristics**	**% of variation in SS explained**
Mid-side MFDCV	36.0	AvSnipCV	50.6	AvSnipCV	50.6
				SL	8.4
Total	**36.0**	**Total**	**50.6**	**Total**	**59.0**

6.3.10 Relationship between the fibre based measurements with staple strength

Table 6.13 illustrates how the fibre length and diameter measurements were related to SS. All the characteristics except △FD and FDCV were negatively correlated with staple strength. Average L/D ratio was not significantly correlated with staple strength. Seasonal variation in fibre length growth was negatively correlated with staple strength, r= -0.23, -0.31 and –0.63 for FGCV, △FL and $CVSL^{Bands}$ respectively. In contrast seasonal changes in fibre diameter between measurement of L/D ratio was positively correlated with staple strength, r= 0.31 and 0.18 for FDCV and △FD respectively. The ratio of △FL to △FD and FLCV were also negatively correlated with staple strength (r= -0.51 and –0.47).

Table 6.13 Correlation coefficients for the relationships between the wool fibre characteristics and staple strength (n=16)

Characteristics	**SS**	**Characteristics**	**SS**
AvL/D	-0.02	**△FL**	-0.31
L/DCV	-0.20	**△FD**	0.18
FGCV	-0.23	**△FL / △FD**	-0.47*
FDCV	0.31	**AvSL(bands)**	-0.10
AvFL	-0.17	**CVSL(bands)**	-0.63*
AvFLCV	-0.51*		

* Correlation significant (P<0.05)

When combined in a stepwise multiple regression the only characteristics from Table 6.13 that significantly explained some of the variation in SS were $CVSL^{Bands}$ (39.9%), L/DCV (10.9%)

and $\triangle$FL/$\triangle$FD which explained 67.7% ($r^2 = 0.68$, $P < 0.05$) of the variation in staple strength. The remaining characteristics did not significantly explain any more of the variation in staple strength.

6.3.11 Relationship between the body traits with staple strength

The relationships between the measured body traits and SS are illustrated in Table 6.14. Bwt ($r = -0.40$), Skin ($r = -0.29$), SkinCV ($r = -0.23$) and Fat ($r = -0.24$) were all negatively but not significantly correlated with SS. BwtCV ($r = 0.15$) and FatCV ($r = 0.45$) were positively correlated with SS. Seasonal variation in fat depth (FatCV) was the only body trait in the multiple regression analysis which significantly explained a proportion (29%) of the variation in SS ($r^2 = 0.29$, $P < 0.05$).

Table 6.14 Correlation coefficients for the relationships between the body traits and staple strength (n=16)

Characteristics	SS	Characteristics	SS
Bwt	-0.40	**SkinCV**	-0.23
BwtCV	0.15	**Fat**	-0.24
Skin	-0.29	**FatCV**	0.45

* Correlation significant ($P < 0.05$)

6.3.12 Comparison between skin thickness measurements

The means, standard errors and correlation coefficients for both the techniques used for skin thickness measurement at each sampling time are illustrated in Table 6.15. The measurements made using the ultrasound technique at the 3, 4, 8, 9, 10, 11, 12 sampling times were not significantly ($P > 0.05$) different from the measurements made using the calliper technique. The measurements from the two techniques were highly correlated at sampling number 8 ($r = 0.84$) and moderately correlated at sampling 3, 7, 11 and 12 ($r = 0.46$ to 0.66). The mean, standard deviation and coefficient of variation of the measurements throughout the experiment were significantly different ($P < 0.05$) and moderately correlated ($r = 0.51$ to 0.66) between techniques. The relationship between the mean measurements form the ultrasound with the calliper technique is also illustrated in Figure 6.12.

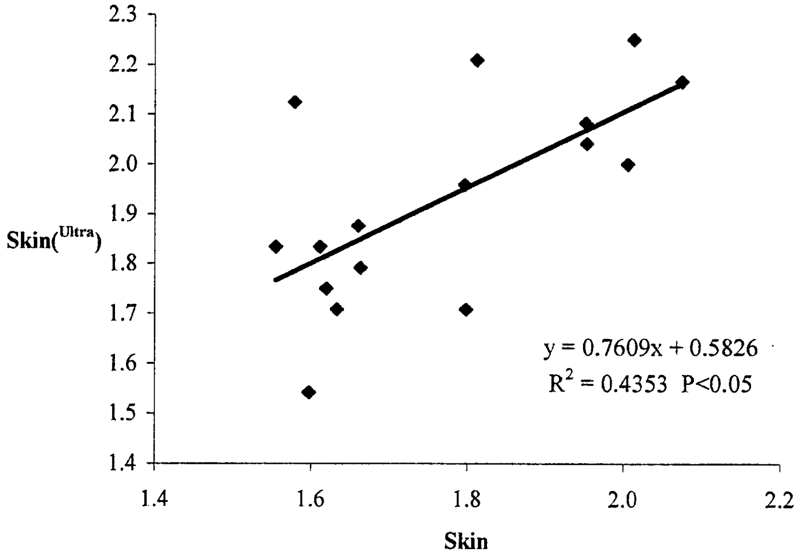
Table 6.15 The mean values, standard errors (s.e.) and correlation coefficients for the relationship between the skin thickness measurement made using skin calliper and those made using real time ultrasound equipment throughout the experiment

Sampling Time	Callipers	Ultrasound	s.e.	Correlation coefficient
1	1.77^a	2.25^b	0.11	0.05
2	1.74^a	2.56^b	0.13	0.09
3	1.85^a	1.91^a	0.06	0.46*
4	1.82^a	2.00^a	0.10	0.07
5	1.72^a	2.16^b	0.06	0.18
6	1.78^a	2.06^b	0.06	0.24
7	1.76^a	1.50^b	0.04	0.66*
8	1.76^a	1.75^a	0.03	0.84*
9	1.73^a	1.56^a	0.08	0.19
10	1.83^a	1.75^a	0.07	0.41
11	1.73^a	1.81^a	0.06	0.55*
12	1.77^a	1.84^a	0.07	0.50*
Mean	1.77^a	1.93^b	0.03	0.66*
SD	0.11^a	0.47^b	0.03	0.51*
CV	6.15^a	24.22^b	1.14	0.56*

* Correlation significant ($P<0.05$)

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

Figure 6.13 The relationship between mean skin thickness measured using callipers (Skin) and mean skin thickness measured using real time ultrasound ($\text{Skin}^{\text{Ultra}}$)



6.4 Discussion

The first hypothesis for this study was that initial mean fibre diameter influences the level of variation in fibre diameter along the FDP in grazing sheep. This hypothesis was accepted. As initial mean fibre diameter and mid-side mean fibre diameter were highly correlated it is assumed that both initial mean fibre diameter and mid-side mean fibre diameter provide a similar estimate of the absolute mean fibre diameter of the sheep. The mean values of the initial and mid-side mean fibre diameter measurements were significantly different due to the fact that the measurements were taken at different times of the year. Initial fibre diameter variation, while not significantly different from the final mid-side fibre diameter variation measurement, they were not highly correlated. This correlation suggests that the rankings of animals on overall mid-side fibre diameter variation cannot be predicted from measurements of fibre diameter variation from short periods of wool growth.

Sheep with higher mean fibre diameter have greater absolute changes in fibre diameter throughout the year. Associated with this, sheep with higher mean fibre diameter also had greater variation in fibre diameter along the staple, changes in fibre diameter that occur over a shorter length of the staple and greater variation of fibre diameter and fibre length between fibres.

A number of other authors have observed that sheep with greater mean fibre diameter have greater variation in fibre diameter throughout the wool growth period (Jackson and Downes 1979; Quinilivan 1990; Thompson 1993; Bow and Hansford 1994; Earl *et al.* 1994). Furthermore, Hynd (1992) also observed that initial fibre diameter was positively correlated with absolute change in fibre diameter. In contrast, Adams and Briegel (1998) did not find any evidence to suggest that variation in diameter, measured by variance along-fibres, might be correlated with mid-side mean fibre diameter.

The biological causes for these relationships have not been established. As sheep with higher mean fibre diameter have larger follicles and bulbs (Schinckel 1961; Hynd 1995; Hill *et al.* 1997b) hence have a greater capacity to produce a fibre with diameter. Alternatively, sheep with follicles that produce finer fibres do not have the physical ability to produce large fibres and as a result do not change fibre diameters as much relative to the broader fibres. Furthermore mean fibre diameter is negatively correlated with the ratio of secondary to primary follicles (Skerritt *et al.* 1997). Therefore sheep with higher mean fibre diameter should have a greater proportion of fibres from primary follicles which have been suggested to be more sensitive in terms of fibre diameter responses to changes in wool growth (Lockart 1956; Onions 1962; Quinnell *et al.* 1973).

Associated with these results, neither average fibre length nor changes in fibre length growth throughout the experiment were significantly correlated with mean fibre diameter measurements. Hynd (1992) also found that initial fibre diameter was not significantly correlated with change in fibre length (-0.16).

The overall effect of increasing initial and mid-side mean fibre diameter on staple strength was not large with initial mean fibre diameter and mid-side mean fibre diameter being negatively, but not significantly, correlated with staple strength. These results are in contrast the majority of correlations reported in Table 2.1, which are generally positive. This relationship was have been reduced as a result of the strong relationship between mean fibre diameter and variation in fibre diameter between and along fibres which in turn was negatively correlated with staple strength.

The second hypothesis for this experiment was that differences between grazing sheep in L/D ratio are associated with differences in their responsiveness of fibre diameter throughout the year and therefore FDP characteristics. After examining the results this hypothesis was also accepted.

The influence of L/D ratio on the FDP characteristics is a combination of the influence of fibre length growth and mean fibre diameter. Examining individually first, sheep with higher average fibre length growth had greater variation in fibre diameter along and between-fibres. As detailed above average fibre diameter was positively associated with variation in fibre diameter along the staple. There was no significant relationship between average fibre length growth and average fibre diameter.

L/D ratio itself was significantly and negatively correlated with the first rate of fibre diameter change with in the FDP. The sheep with higher L/D ratio may alter fibre length preferentially to diameter resulting in changes in fibre diameter throughout the year being over longer length of fibre growth and hence lower rates of fibre diameter change. However, while L/D ratio was not significantly associated with the overall level of along staple it was negatively correlated with between-fibre variation in fibre diameter.

The lack of relationship between L/D ratio and along staple variation in fibre diameter can be explained by examining how L/D ratio is related to fibre length growth and average fibre diameter. Sheep with higher L/D ratios, while having significantly greater fibre length growth rates also had significantly lower average fibre diameters. As fibre length growth and average fibre diameter were both positively associated with along-staple variation in fibre diameter, the increase fibre length growth rate and reduced mean fibre diameter resulting from higher L/D ratios appear to counteract each other and result in no significant relationship between L/D ratio and along-staple variation in fibre diameter. This suggests that the relationship between L/D ratio and FDP characteristics is due to both length and fibre diameter, rather than fibre diameter or fibre length alone. When animals were examined within micron group, which removed the influence of mean fibre diameter, L/D ratio was strong positively correlated with along-staple variation in fibre diameter.

The canonical correlation analysis indicated that average L/D in combination with initial mean fibre diameter were the main determinants of the overall variation in the FDP characteristics. This analysis has the important benefit that it not only accounted for the relationships between the explanatory variables and all the FDP characteristics but also the relationship within the fibre based measurements and the FDP characteristics.

The negative relationships between L/D ratio and mean fibre diameter are consistent with the negative correlation (r= -0.54) observed by Hynd (1992) between initial fibre diameter and L/D ratio. These results confirm that sheep with higher average fibre diameter have lower fibre length growth relative to average fibre diameter.

The results observed also demonstrated that sheep with greater L/D ratios had slightly smaller changes in fibre diameter between measurements of L/D ratio (r= -0.12), greater changes in fibre length between L/D ratio measurements (r= 0.67) and a greater ratio of change in fibre length to that of change in fibre diameter ($\triangle L/\triangle D$, r= 0.41). These relationships observed in grazing fine wool Merino wethers strongly agree with those of Hynd (1992) using housed and pen fed South Australian strong wool Merino sheep. Hynd (1992) also observed that sheep with higher L/D ratios had lower increases in fibre diameter (r= -0.66), slightly smaller changes in fibre length (r= -0.08) and greater $\triangle L/\triangle D$ (r= 0.51). Hynd (1992) concluded that direct or indirect selection for sheep with high L/D ratio would have the 2 desirable outcomes of greater fibre length and reduced fibre diameter variability. In this experiment L/D ratio was positively correlated with average fibre length growth and staple length while negatively correlated with most characteristics that describe fibre diameter variation along the staple and between fibres. These results support these previous conclusions, though at a phenotypic level only.

The third hypothesis for this study was that seasonal variation in fibre length growth, fibre diameter and the ratio of length to diameter throughout the year is associated with increased variation in fibre diameter along the FDP and reduced staple strength in grazing sheep. This hypothesis was accepted. Variation in L/D ratio throughout the year was, although not significantly, negatively correlated with along-staple variation in fibre diameter and the rates of fibre diameter change. It may be that these sheep alter fibre length growth rate preferentially to fibre diameter throughout the year. However, it was observed that sheep with greater variation in L/D ratio throughout the year had less changes in fibre growth rates throughout the year.

All the measures of changes in fibre length growth and fibre diameter throughout the experiment measured at the individual fibre, FDP and mid-side levels were negatively correlated with staple strength to varying degrees. All these results have illustrated that increasing variation in fibre length growth and diameter throughout the year increases the variation of fibre diameter along the FDP and reduces staple strength.

In the wool examined in this study variation in fibre diameter and fibre length between fibres were of approximately equal importance in explaining variation in staple strength. Fibre diameter and length tend to change together in response to changes in nutritional conditions (Hynd 1994a). Therefore it is anticipated that sheep with lower variation in fibre diameter between fibres would have lower variation in fibre length. The significant positive correlations observed in this study between mid-side fibre diameter variation (mid-side MFDCV) and between fibres within snippets (AvSnipCV) with fibre length variation support these theories. However mid-side mean fibre diameter was not correlated with average fibre length growth. A weak positive relationship between fibre diameter variation between fibres and variation in fibre length was also found by Peterson *et al.* (1998). Contrary to these results, Schlink *et al.* (1998b) found no significant relationship between variation in fibre diameter (CV between fibres) and variation in fibre length (CV between fibres) within a staple. As described in section 2.4.4, lower variation in fibre length can result in greater staple strength. This again was supported in this study with a significant negative correlation between fibre length variation and staple strength (r= -0.51). Negative associations between fibre length variation and staple strength have also been observed by de Jong *et al.* (1985) and Peterson (1997a). Selection for staple strength has been shown to influence fibre length variation (Bray *et al.* 1995a; Peterson *et al.* 1998).

Absolute change in fibre diameter between L/D ratio measurements was positively correlated with staple strength. It has generally been observed that greater variation in fibre diameter throughout the year reduced staple strength. Another trend observed in this experiment was that sheep with higher mean fibre diameter had lower staple strength. The results that were observed in the previous chapter and most other published research (Table 2.1) indicated that sheep with greater fibre diameter have greater staple strength. This negative association with staple strength may be due to the significant positive relationships between average fibre diameter and variation in diameter along and between fibres.

The fourth hypothesis for this study was that seasonal variation in body weight, fat depth and skin thickness is related to variation in fibre diameter along the FDP in grazing sheep. This hypothesis was accepted. Seasonal variation in body weight, fat depth and skin thickness were positively correlated with the level of overall fibre diameter of the FDP, variation in fibre diameter along the FDP and rates of fibre diameter change throughout the FDP. Variation in skin thickness was the body characteristic that was most related to variation in fibre diameter along the FDP. Sheep that had greater seasonal variation in body weight and condition may alter feed intake and/or metabolism throughout the year, which results in increased variation in the availability of nutrients to the wool follicle. As fibre diameter and length growth rates depend heavily on the quantity and quality of nutrients available to the follicle, the increased variation in skin thickness throughout the year may have resulted in greater variations in follicle nutrition and therefore wool growth throughout the experiment. This supports the theories that skin thickness is related to the level of overall sheep nutrition and follicle nutrition (Hutchinson 1957; Lyne 1964; Williams and Thornberry 1992; Williams and Morley 1994; Schlink et al. 1996c). While these characteristics were correlated with variation in fibre diameter along the staple, they explained less overall variation in the FDP characteristics than the fibre-based measurements.

Despite the positive association between seasonal variation in body weight and condition with fibre diameter variation along the staple, sheep that showed greater variation in body weight and fat depth throughout the experiment also tended to have stronger wool (r= 0.15 and 0.45 respectively). In contrast sheep that showed greater variation in skin thickness tended to have reduced staple strength. The positive association between seasonal variation of body weight and fat depth with staple strength may indicate that some animals partition more nutrients towards the skin and therefore wool growth when nutrients become limiting rather than maintaining body weight and fat depth. However these relationships were not a result of reductions in variation in fibre diameter along the staple rather reductions in the variation in fibre diameter and length between-fibres. Seasonal variation in body weight and fat depth were negatively associated with variation in fibre diameter and length between fibres while seasonal variation in skin thickness was positively associated with variation in fibre diameter and length between fibres. These results indicate that the reduced variation in skin thickness throughout the year may have resulted in less variation in nutrient supply to the follicle and therefore reduced variation in fibre diameter and length between-fibres which were both significantly and negatively correlated with staple strength.

Hill *et al.* (1997a) found that skin weight of a biopsy, which it would be assumed that skin weight is related to skin thickness, was positively genetically correlated with mean fibre diameter. This agrees with the phenotypic relationship observed in this study. These authors also found a positive genetic association between skin weight and staple strength. This observation is in contrast with the non-significant negative phenotypic correlation observed between skin thickness and staple strength in this study. The significant positive associations between average skin thickness and both fibre length and diameter variation between-fibres would have influenced this relationship.

Seasonal variation in body weight was not significantly correlated with either variation in fat depth nor variation in skin thickness. Williams and Thornberry (1992) also found that skin thickness was not significantly related to either live weight or body condition score. Seasonal variation in fat depth and skin thickness were also not related. These relationships further indicate that body weight, fat depth and skin thickness follow different seasonal patterns throughout the year.

Furthermore sheep with thicker skins have less variation in fibre diameter along the FDP but more fibre length growth and variation in fibre diameter and fibre length between fibres. The greater skin thickness may indicate that the follicles of the sheep with greater skin thickness have improved nutrition to express a higher wool growth and therefore fibre diameter and length variation between fibres. The thicker skins may also provide a buffer of nutrient reserves for when nutrients become limiting and hence less variation in fibre diameter along fibres.

The positive association between seasonal variation in body weight and the FDP characteristics observed in this study is in contrast to the previously reported studies of Adams and Briegel (1998). Despite finding significant differences in the level of variation in wool growth and fibre diameter patterns throughout year, Adams and Briegel (1998) found no significant differences between three strain of grazing Merino wethers in the pattern of liveweight change throughout the year. Furthermore there were no significant relationships between wool growth rate and either loss of lean or loss of fat. There have been no other studies of the relationship between seasonal variation in body weight and condition with FDP characteristics. Adams and Briegel (1998) also rejected the hypothesis that the large sheep could buffer wool growth throughout the year by mobilising body reserves. The fact that in the present study average body weight and fat depth were non-significantly correlated with the level of fibre diameter variation along the FDP support these previous findings. However results also suggest that mean skin thickness and seasonal patters of body weight, fat depth and skin thickness influence both variation in fibre diameter and length growth between fibres.

The three L/D ratio measurements during this experiment were all highly correlated (r= 0.87 to 0.93). The second L/D ratio measurement was also significantly higher than the first L/D ratio measurement. These results indicate that while there is seasonal variation in L/D ratio measurements they remain highly correlated thereby indicating that the animals maintain their rankings on L/D ratio. These result agree with those of Hynd (1992) who found that L/D ratio was highly repeatable with nutritional change (r= 0.95). Schlink *et al.* (1996a) and Woods and Orwin (1988) observed significant seasonal variation in L/D ratio in grazing sheep throughout the year, and also noted that despite the seasonal variations in L, D and L/D ratio the ranking of the animals for these characteristics remained similar throughout the experiment.

Seasonal changes in fibre diameter, length and L/D ratios have been shown to be highly variable between sheep (Woods and Orwin 1988; Hynd 1992; Hynd and Schlink 1992). The results from the present study support these previous findings. There was substantial variation between animals for the characteristics of the FDP and the L/D ratio measurements. All these characteristics relate to variation in fibre diameter and length along fibres, between fibres or throughout the year. The cause of this variation may be due to difference in genotype, nutrient partitioning, metabolism, the level and composition of the nutrient supply to the follicle or differences in the responses of the follicle to the nutrients that it receives. Hynd (1992) found that the actual increases in fibre length and fibre diameter (△L, △D) ranged between 34 - 123µm/day and 0.9 - 6.4µm respectively. The ratio of change in fibre length to change in fibre diameter was also variable between sheep ranging from 13:1 to 80:1. In this current experiment the change in fibre length (△L), fibre diameter (△D) and △L/△D ranged between 3.85 to 129.31µm/day, 1.93 to 5.12µm and 1.99 to 33.62 respectively. Despite the fact that the results of Hynd (1992) were based on housed and pen fed South Australian strong wool sheep the results strongly agree with these results from grazing fine wool Merino wethers. The large differences between sheep in these characteristics may be able to be utilised to select sheep with less variation in fibre diameter and length growth throughout the year. Based on the phenotypic results observed in this study it would result in improved staple strength.

As was observed in the previous chapter, this experiment again demonstrated that the FDP characteristics are correlated with staple strength and explain additional variation in staple strength above that which could be explained by the measurements of mid-side mean fibre diameter, mid-side fibre diameter variation and staple length. Also in agreeance of the results from Chapter 5 there was no benefit, in terms of explaining staple strength, by measuring both mid-side and FDP measurements. The FDP characteristics used alone explained a greater proportion of the variation between animals in staple strength compared to the mid-side measurements used alone. This confirms the benefits that can be gained by measuring FDPs.

In the wool samples generated in this experiment the rates of fibre diameter change were not significantly correlated with staple strength. In Chapter 5 and a number of previous published studies (Table 2.1) the rates of fibre diameter change were negatively correlated with and helped to explain additional variation in staple strength. The lack of relationship in this experiment may be due to the unusual rainfall and pasture growth during the experiment. There was above average rainfall (Figure 6.1) in the late winter period which resulted in greater amounts of green feed on offer and crude protein. This may have resulted in increased wool growth at the period in the year that is most likely to influence staple strength. The level of along staple variation in fibre diameter and rates of fibre diameter change were similar but slightly lower to those observed in the FDPs from the Tablelands environment used in experiment 1 in Chapter 5. In these FDPs there was a significant negative relationship between the rates of fibre diameter change and staple strength. The shape of the FDP may have also influenced the relationship between the rates of fibre diameter change and staple strength.

Thompson and Hynd (1998), Adams and Briegel (1998) and the results from Chapter 5 demonstrated that large variation in fibre diameter along fibres is not reflected in the total variation of fibre diameter in the fleece sub-samples (mid-side samples). The results from this experiment also agree with these previous findings. Mid-side fibre diameter variation was not significantly correlated with along-staple variation in fibre diameter but was significantly positively correlated with average variation between fibres within snippets.

Skin thickness measurements made using the skin fold callipers could be estimated using an ultrasound technique however the accuracy achieved varied throughout the experiment. More accurate measurements may be able to be made with equipment operating at higher frequency and resolution. Inaccuracy also occurred due to the fact that the image was small and measurements could only be made to the nearest 0.5mm.

6.5 Conclusions

Results demonstrate that differences between sheep in fibre length, diameter and L/D ratio are associated with differences in FDP characteristics. Fibre length growth rate and mean fibre diameter appear to be more useful in explaining variation in fibre diameter and staple strength than L/D ratio. Mean fibre diameter of the sheep has a strong influence on the levels of variation along and between fibres, however sheep can be identified which have similar levels of mean fibre diameter but markedly different levels of variation of fibre diameter along the staple. For sheep of similar fibre diameter there was a strong positive relationship between fibre length growth rate and L/D ratio with along staple variation in fibre diameter. Seasonal variation in fibre length and diameter growth were positively correlated with each other, increased the variation in fibre diameter along the FDP and reduced staple strength. Both mean and seasonal variation in staple length growth were also significantly related to variation in fibre diameter along and between-fibres. However the FDP characteristics were related to staple strength in ways that could not be explained at the biological level.

The study clearly illustrates that both variation in fibre diameter and fibre length growth, which are positively related to each other, are strongly associated with staple strength. While these two properties most likely influence staple strength through the number of fibres strained at peak force, the influence on processing performance is yet to be determined. Unlike the relationships illustrated in Chapter 5, minimum fibre diameter was not significantly related to staple strength again illustrating the variability of these relationships at the phenotypic level.

Seasonal changes in body weight, body condition and skin thickness can be related to changes in fibre diameter and length between-fibres, fibre diameter along the FDP and staple strength. The influence of body weight and fat depth on wool growth was different to that of skin thickness.

This study was unable to fully define why sheep grazing in the same mob produce wool with FDPs of different shape and staples of different strength. It is clear that mean and seasonal variation in body weight, fat depth, skin thickness, mean fibre diameter, mean fibre length growth are all associated with variation in both fibre diameter and length growth rate throughout the year which in turn are associated with staple strength. As this study only involved 16 sheep a larger study is required using more sheep of different genotypes over a number of environments to confirm these relationships. This must be a definitive study that examines cause and effect relationships so that the actual determinants of seasonal variation in fibre growth rate and staple strength can be investigated.

However the technique required to measure mean fibre length and fibre length variation is very time consuming and expensive. Therefore it would be beneficial if the technique could be modified to make estimation of fibre length and fibre length variation more practical.

CHAPTER 7

Methods for estimating fibre length and diameter in wool staples

7.1 Introduction

Fibre length growth rate, diameter and the ratio of length to diameter has been shown to be associated with wool production and quality (Chapter 6). Staple length 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 (Murray 1996). Fibre length variation is negatively associated with staple strength (Chapter 6) through its influence on peak force but not work to break (de Jong *et al.* 1985; Peterson 1997a). Selection for increased staple strength has been shown to reduce fibre length variation (Bray *et al.* 1995a; Peterson *et al.* 1997). The influence of staple fibre length variation on processing performance is as yet to be determined.

The current method of measuring short-term changes in fibre diameter, rate of fibre elongation and L/D ratio relies mainly on the use of intra-dermal injections of radioactive isotopes (Downes *et al.* 1967). 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.* 1996b; Peterson and Gherardi 1996a), between which there is significant variation in fibre diameter (Quinnell *et al.* 1973; McKinley *et al.* 1976), and hand sampling a small numbers 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.* 1998a; Schlink *et al.* 1999).

An alternative technique to the use of radioisotopes was proposed by Schlink *et al.* (1998a) to estimate fibre length and fibre diameter parameters in dyebanded wool samples using image analysis and measurements obtained from the OFDA. 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) previously investigated the use of dyebands to measure the components of fibre variation. Their technique utilised the base of dyebands as the time point reference on individual wool fibres.

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. The predicted fibre length measurements in combination with the fibre diameter measurements at the dyebands may also be used to estimate L/D ratios. Crimp definition and frequency may be associated with fibre length and curvature variation (Swan 1994). Fibre curvature is significantly related to crimp frequency with R^2 ranging from 0.67 to 0.91 (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 Optical Fibre Diameter Analyser (OFDA) and LASERSCAN systems as part of routine fibre diameter determinations. Crimp frequency and crimp definition are also associated with a number of other wool quality characteristics including fibre diameter (Lockhart 1958; Purvis 1997b), staple length (Purvis 1997b) and wool style (Lockhart 1958; Purvis and Swan 1997a). Crimp frequency, fibre curvature and fibre curvature variation may also be able to be used to predict fibre length and fibre length variation.

This study aims to describe and evaluate a number of alternative methods of determining mean fibre length and fibre length variation in staples. The measurement techniques utilize dyebands, image analysis and measurements of fleece characteristics in grazing sheep. This research was published in a journal paper that is presented in Appendix 9.2.

The hypotheses for this study were;

1) The dyeband based techniques can be used to measure fibre length, fibre length variation, fibre diameter and L/D ratio.
2) Fibre length, fibre length variation and L/D ratio can be predicted using staple length, fibre curvature and crimp frequency measurements.
3) L/D ratio can be estimated using staple length growth and mean fibre diameter measurements between dyebands on wool staples.

7.2 Materials and Methods

The data utilised in this study originates from the second measurement of L/D ratio during the experiment described in Chapter 6. Briefly, sixteen fine wool Merino wethers were maintained as a single grazing mob for the duration of the experiment.

7.2.1 Fibre length measurement techniques

7.2.1.1 Autoradiographic (^{35}S) technique

The autoradiographic technique is a modification of the technique reported by Hynd (1994a) to determine fibre diameter and fibre length. In brief, the wethers were intra-dermally injected twice at a 28 day interval with 0.3mls of normal saline solution containing 5.1μCi/mL of ^{35}S-cysteine hydrochloride. On day 49 labeled 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) for 7 days. The film was superimposed onto the slides with DPX (Ajax Chemicals). 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 (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 by ^{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 mean fibre diameter measured by ^{35}S was calculated (^{35}S L/D). The ratio between fibre length and staple length between dyebands (SL) (as described in section 7.2.2) was also calculated (^{35}S FL:SL).

7.2.1.2 Dyeband based techniques

A dyeband was placed at the base of the staple according to the method of Wheeler *et al.* (1977) (anterior of the left-hand mid-side patch) on the same days as the injection of the radioisotope. Dyebanded staples were harvested on the same day as for the ^{35}S labeled fibres. Five staples were manually measured for mean staple length (SL) using a ruler as well as being measured for crimp frequency (crimp frequency) (crimps/cm) between dyebands using a crimp gauge (CSIRO Division of Wool Technology).

7.2.1.2.1 Snippet technique

Snippet fibre length measurement was determined using image analysis by Dr. Tony Schlink and A.M. Murray at the CSIRO Animal Production and CRC for Premium Quality Wool, WA, using the method described by Schlink *et al.* (1998a). 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 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) by capturing the images and measuring length with image analysis (VideoPro, South Australia). The mean fibre length (snippet FL), fibre length standard deviation and coefficient of variation (CV of FL measured by snippet) were measured. The remainder of the staple snippet that was 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 ratio) 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).

7.2.1.2.2 Dyeband technique

This technique is a modification of the techniques of McKinley *et al.* (1976) and Schlink *et al.* (1998a). 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 section of the fibre was used as a reference point to measure fibre length growth. The mean fibre length (dyeband FL), fibre length variation (CV of FL measured by dyeband) and L/D ratio (dyeband L/D ratio) were calculated for each sheep as in the autoradiographic technique. The remaining part of the staple was then used to measure mean fibre diameter, fibre diameter variation, mean fibre curvature and fibre curvature variation with OFDA using 2 mm 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 (FL measured by dyeband) and staple length (SL) was calculated (dyeband FL:SL).

7.2.2 Fibre length prediction

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

7.2.2.1 Prediction method 1

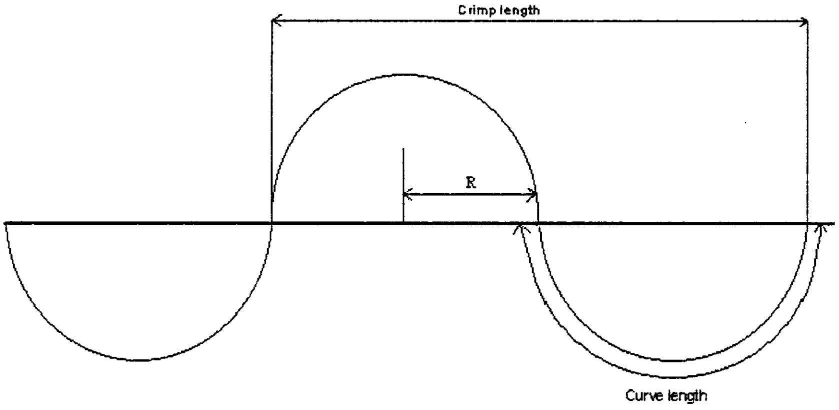
Fibre length was estimated using SL (horizontal length of staple) and crimp frequency between the dye bands. The horizontal length of each crimp (crimp length), the radius of the crimp arc (R) and the circumference distance of each side of a crimp (curve length) (Figure 7.1) were determined for each wool sample. The equations used were;

Crimp length (mm) = 1 / (crimp frequency / 10)
Crimps per SL = SL / Crimp Length
Crimp radius (R, mm) = crimp length / 4
Curve length (mm) = ∏ * 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 ratio using method 1) was estimated.

Figure 7.1. Parameters used in prediction method 1 to estimate fibre length



7.2.2.2 Prediction method 2

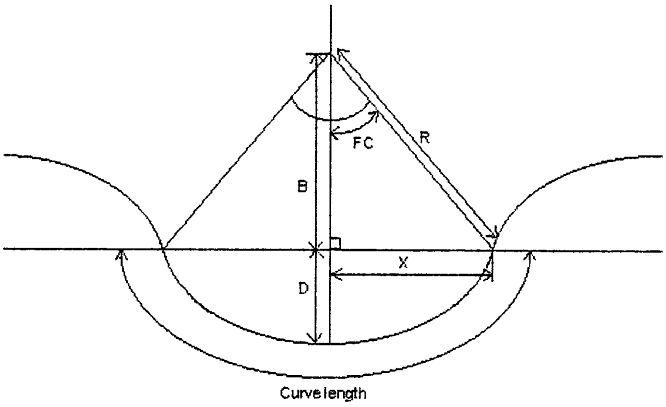
Fibre length was estimated using average fibre curvature from OFDA and assumes that the curvature of the fibre remains the same between the points of crimp inflection (Figure 7.2). The radius of the crimp arc, R, was estimated from fibre curvature and crimp length. The curve length between points of crimp inflection was then estimated from the circumference of a circle with a radius of R using the known components of crimp length and fibre curvature. The parameters estimated were:

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

Fibre length predicted using method 2 = curve length * 2000 * crimps per 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 7.2. **Components used by prediction method 2 to estimate curve length**



7.2.2.3 Prediction method 3

The third predictor of fibre length (predicted FL using method 3) used average curve length from methods 1 and 2 and crimps per SL in the following equation:

Predicted FL using method 3 = mean curve length * 2000 * crimps per SL (3)

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

7.2.3 Statistical analysis

Group means for the fibre length and diameter measurements from each measurement and prediction techniques were compared using least squares analysis of variance conducted using the General Linear Model procedure of SAS (1990). The relationships between the fibre length and fibre length measurements were also examined between each of the techniques using correlation analysis. Stepwise multiple regression procedures of SAS (1990) were utilised in an attempt to model ^{35}S using all the fibre diameter and fibre length measurements, calculated and predicted, as described above.

7.3 Results

Mean values (±s.e.m.) for fibre length and fibre diameter using the 3 fibre measurement techniques are presented in Table 7.1. The ^{35}S and dyeband techniques differ 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 between the ^{35}S and snippet techniques.

Table 7.1. Least squares means (±s.e.) for measurement of fibre length and diameter from the 3 techniques evaluated (n=16)

	^{35}S	Snippet	Dyeband	Probability
FL (μm)	8881 ± 145^a	8819 ± 145^a	8773 ± 152^a	0.877
CV of FL (%)	11.0 ± 0.71^a	15.4 ± 0.71^b	11.6 ± 0.74^a	0.001
MFD (μm)	17.3 ± 0.15^a	16.6 ± 0.15^b	16.8 ± 0.15^b	0.006
CV of FD (%)	11.5 ± 0.30^a	15.8 ± 0.30^b	16.2 ± 0.30^b	0.001
L/D (μm/mm)	18.4 ± 0.28^a	19.1 ± 0.28^a	19.0 ± 0.30^a	0.216
FL:SL	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 ($P<0.05$)

The correlation coefficients for the relationships between the ^{35}S technique, snippet and dyeband techniques are shown in Table 7.2. Mean fibre length measured by the snippet technique was significantly correlated to the ^{35}S fibre length measurement ($r=0.59$, $P<0.01$). Fibre lengths measured using the dyeband technique were also significantly correlated with ^{35}S measured fibre length ($r=0.84$, $P<0.01$) and snippet fibre length ($r=0.67$, $P<0.01$). MFD measured by snippet was highly correlated with both mean fibre diameter measured by ^{35}S ($r=0.84$, $P<0.01$) and MFD measured by dyeband ($r=0.96$, $P<0.01$). MFD measured by ^{35}S was significantly correlated to MFD measured by dyeband ($r=0.81$, $P<0.01$). CV of MFD and CV of FL were not related between the dyeband and ^{35}S techniques (0.16 and 0.01-0.11 respectively). The CV of MFD ($r=0.47$, $P<0.05$), L/D ratio ($r=0.77$, $P<0.05$) and FL:SL ratio ($r=0.60$, $P<0.05$) were all significantly correlated between the snippet and dyeband techniques. There was no significant relationship between CV of FL measured by dyeband and CV of FL measured by snippet ($r=0.07$, $P>0.05$). FL:SL was significantly correlated between the dyeband and ^{35}S techniques ($r=0.57$, $P<0.05$) but not significantly correlated between the snippet and ^{35}S techniques ($r=0.26$, $P>0.05$).

Table 7.2. Correlation coefficients (r) for the relationships between the fibre properties estimated using the radioisotope technique and those obtained using dyeband and snippet techniques (n=16)

	FL	CVFL	MFD	CVMFD	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 significant $P<0.05$

Dyeband FL and ^{35}S FL were both significantly correlated with SL (r=0.91 and 0.79, respectively; $P<0.01$). Snippet FL was moderately correlated with SL (r=0.67, $P<0.05$). This resulted in the L/D ratio based on SL growth per day between the dyebands and mean fibre diameter measured by the dyeband technique being highly correlated with the L/D ratio calculated using the radioisotope technique (r=0.88, $P<0.05$). L/D ratio using SL growth per day between the dyebands and mean fibre diameter measured by the snippet technique was also highly correlated with the ^{35}S L/D (r=0.85, $P<0.05$). The average ratio between fibre length (^{35}S) and staple length was 1.41 (±0.12) and ranged between 1.2 to 1.63.

7.3.1 *Fibre length prediction*

Mean fibre length from the ^{35}S and predicted FL using method 3 were not significantly different ($P<0.05$) (Table 7.3). The mean fibre length values of predicted FL using method 1 and method 2 were both significantly different ($P < 0.05$) from the ^{35}S fibre length measurements. Predicted FL using method 1 explained a large proportion ($P<0.05$) of the variation in ^{35}S FL. Predicted FL using method 2 and method 3 explained 48% ($P<0.05$) and 60% ($P<0.05$) of the variation in ^{35}S FL respectively.

Table 7.3. Least squares means (±s.e.) for the fibre length and L/D ratio measurements from the ^{35}S and three prediction techniques

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

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

Together in a multiple regression equation SL and predicted FL using method 1 explained 65% ($P<0.05$) of the variation in ^{35}S FL. The combination of characteristics that explained the most variation of ^{35}S FL was MFD measured by dyeband and predicted FL using method 1. The multiple regression equation was;

^{35}S FL = 5566.5 (±2199.7) – 210.53 * MFD measured by dyeband (±96.7) + 0.69 * predicted FL using method 1(±0.13)
($r^2=0.720$, $n=16$, $P<0.01$)

While predicted L/D ratio using method 3 was not significantly ($P>0.05$) different to ^{35}S L/D, predicted L/D ratio using methods 1 and 2 were significantly ($P<0.05$) different to ^{35}S L/D (Table 7.3). Predicted L/D ratio using method 1, 2 and 3 were highly and significantly correlated with ^{35}S L/D ($r=0.85$, 0.87 and 0.87, $P<0.01$, respectively).

CV of FL measured by ^{35}S was not significantly related to CV of fibre curvature ($r=0.27$, $P>0.05$). 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, $P<0.01$ respectively), while crimp frequency and fibre curvature were positively correlated ($r=0.86$, $P<0.01$). Average fibre curvature and variation in fibre curvature were negatively correlated, $r=-0.94$ for standard deviation of fibre curvature and $r=-0.84$ for coefficient of variation of fibre curvature. 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 $r=-0.12$ ($P>0.05$ for all three correlations)).

7.4 Discussion

The first hypothesis for this study was that the dyeband based techniques can be used to measure fibre length, fibre length variation, fibre diameter and L/D ratio. This hypothesis was partially accepted. Fibre length measurements were closely related between the three techniques. All three techniques produced mean group values for fibre length that were not significantly different from each other. The highest correlation ($r=0.84$) was observed between the ^{35}S and the dyeband techniques. As a result the ranking of animals using the dyeband technique are very similar to that of the ^{35}S. This result may be influenced by the similarity in methods of fibre sampling techniques used for these two techniques for fibre length determination. The results also demonstrated that the three techniques produced very different estimates of fibre diameter variation and fibre length variation.

An important consideration of the dyeband techniques is the quality of the 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 fibre length may accurately estimated on most animals, some types of wool may make the technique inaccurate. In most cases these animals would 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. A disadvantage of the dyeband techniques is that it cannot be used to measure short periods of wool growth.

Variations between the dyeband and the ^{35}S techniques are likely to also occur as a result of inaccurate dyeband application. If dyebands are not applied carefully it is possible that the finished dyeband in not perpendicular and not exactly at the skin level. It is also possible, and likely, that the base of the dyeband is not on the same position on every fibre. The ^{35}S technique is also likely to result in inaccuracy as a result of fibre sampling as was discussed earlier.

Of the techniques, the dyeband technique provides the most accurate estimation of the 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 in comparison to the snippet technique (Schlink *et al.* 1998a; 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. It is also probable given the relationships observed in Chapter 6 between fibre diameter and length that this sampling bias may also have influenced the measurements of fibre length and fibre length variation.

The fibre diameters obtained from the snippet and dyeband sampling techniques were not different from each other but were both significantly lower than the ^{35}S technique. All three estimates of fibre diameter were significantly correlated to each other (r>0.81). Previous research 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.* 1998a). 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 restricts the number of fibres 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 (IWTO 1993). Methods that increase the number of fibres measured and that uses a random sample of fibres from the fleece, will significantly improve the accuracy of the measurements of the fleece samples.

The second hypothesis was that fibre length, fibre length variation and L/D ratio can be predicted using staple length, fibre curvature and crimp frequency measurements. This hypothesis was partially accepted. 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 fibre length 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 fibre length prediction 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. Fibre length variation was not able to be predicted using staple characteritsics.

The final hypothesis for this study was that L/D ratio can be estimated using staple length growth and mean fibre diameter measurements between dyebands on wool staples, was also accepted. 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 staple length growth between the dyebands can then be easily measured at regular intervals. In this experiment L/D ratio based on staple length and mean fibre diameter measured by dyeband and 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 previously the use of dyebands to calculate L/D ratio has not been considered accurate due to variations in the fibre length to SL ratio.

Mean fibre length is usually longer than mean staple length due to fibre crimp and entanglement. However, fibre length is generally highly correlated with staple length (r > 0.90, Gee 1975; Murray 1996). A review of 10 studies (Murray 1996) concluded that a significant linear relationship existed between mean fibre length and staple length (r=0.94). While the average relationship between staple length and fibre length observed in this experiment (r=0.79) is lower than that previously reported, the average fibre length to staple length ratio (1.4) did fall within the range previously reported for Merino sheep (Murray 1996; Schlink *et al.* 1998a).

Previous research has demonstrated that fibre crimp, fibre curvature and staple length 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 correlations 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 staple length and average curvature and –0.64 between staple length and crimp frequency. The correlation coefficients of 0.94, -0.84, -0.64 and –0.61 observed in this experiment are also very similar to this previous research.

Multiple regression indicated that ^{35}S estimated fibre length could be accurately modeled using mean fibre diameter measured by dyeband and fibre length predicted from staple length and crimp frequency. These two variables were capable of explaining 72% of the variation in fibre length between animals, which was approximate 10% more of the variation in fibre length between animals than could be explained by the fibre length prediction methods alone.

Schlink *et al.* (1998a) 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. These results support the significant correlation (r= 0.65) observed in Chapter 6 between fibre length variation and between-fibre diameter variation. Conversely fibre diameter and fibre length variation were negatively correlated for the dyeband technique, though not appreciably (r=-0.12). This study also demonstrated that fibre curvature variation and fibre length variation were not significantly correlated.

7.5 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 staple length growth and mean fibre diameter at dyebands without actual measurement of individual fibre length can also give an accurate estimate of the mean fibre L/D ratio that is currently measured using the ^{35}S technique. Mean ^{35}S estimated fibre length 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.

CHAPTER 8

General Discussion

The unifying hypothesis of this thesis was that differences between sheep in responsiveness of fibre diameter throughout the year might be able to be exploited to improve staple strength. The results from the experiments illustrated in this thesis indicated that this hypothesis could be accepted.

The first experimental chapter of this thesis demonstrated that the characteristics of the FDP could be estimated without using all the original snippets. A profile prediction technique that utilised cubic spline functions based on a subset of snippets from the full profile was found to be the most beneficial. The results indicate that only 10% of the original segmented staple needed to be measured to give an accurate estimation of absolute fibre diameter and overall variation in fibre diameter along the FDP. However the relationships between the full FDP and the predicted FDPs for the positions of maximum and minimum fibre diameter points and the rates of fibre diameter change were less reliable. Measuring one snippet in every four of the original snippets (approximately 27%) using the profile prediction technique generated FDP characteristics that were not significantly different from ($P>0.05$) and highly correlated with ($r>0.80$) those of the original profile. The intended use of the data will dictate the level of inclusion used. The number of snippets used for the profile prediction technique influenced both the similarity of rankings of the animals and the differences between means for some of the FDP characteristics. These results therefore indicate that the profile prediction technique can be used to measure FDPs with reduced time and therefore cost whilst still obtaining accurate estimates of the full original FDP. This would enable FDPs to be measured on more sheep (staples) for a given total budget, however further refinement or automation is warranted if a commercial test was required.

The second study in this thesis examined the differences in the FDP and wool quality characteristics between environments, bloodlines and sire groups. The results from these experiments indicated that there were significant differences between bloodlines and sire groups for many FDP and mid-side wool quality characteristics, as well as evidence of genotype by environment interaction. These results indicate that within a particular environment different bloodlines and sires within bloodlines could be identified to potentially produce more desirable FDP characteristics. However the results from Chapter 4 also demonstrated that these differences in FDP characteristics between bloodlines did not result in differences in staple strength between the bloodlines. The large differences in staple strength between animals within each bloodline may have masked any differences between bloodlines as a whole. The differences between individual sheep and sire groups in the FDP characteristics may still be able to be utilised to improve staple strength within individual bloodlines.

Following on from this, Chapter 5 examined the relationship between the FDP and wool quality characteristics with staple strength over several environments and bloodlines. These experiments demonstrated that the FDP and wool quality characteristics were associated with staple strength. The FDP characteristics also explained additional variation in staple strength above that which could be explained using the standard mid-side wool quality characteristics of mean fibre diameter, fibre diameter variation and staple length alone. However, the most appropriate combination of explanatory characteristics and the magnitude of their effects varied between environments and bloodlines. The results demonstrated that the best model to predict variation between animals in staple strength, will differ between environments and in some cases between genotypes of sheep. Despite this variation, the four traits of minimum fibre diameter, along-staple variation in fibre diameter, between-fibre diameter variation and mean fibre diameter, stood out as the most consistent predictors of staple strength. It is anticipated that these differences would also exist for the prediction of hauteur. These are important considerations for any commercial use of FDP characteristics.

The inclusion of the FDP characteristics as explanatory variables provides for an alternative interpretation of how absolute fibre diameter and variation in fibre diameter combine to explain variation in staple strength. This trend was observed in several of the multiple regression analyses. For example, the overall analysis in experiment 1 of the wool quality characteristics indicated that fibre diameter variation explained approximately 10% more variation in staple strength than fibre diameter. However analysis of the FDP characteristics alone indicated that minimum fibre diameter was twice as important in explaining staple strength as fibre diameter variation (42 compared to 21%). The Armidale analysis in experiment 1 also demonstrated that the priority of the measures of absolute fibre diameter relative to that of fibre diameter variation in explaining staple strength altered between the analysis of the mid-side and the FDP characteristics. The mid-side measurements suggested that absolute fibre diameter and fibre diameter variation explained approximately equal proportions of the variation in staple strength (approximately 36 and 37% respectively). However the FDP characteristics demonstrated that minimum fibre diameter was approximately three times more important than that of fibre diameter variation (59 and 20% respectively). Similar trends were observed in experiment 2. In both environments the interpretation as to the importance of the measurements of absolute fibre diameter values relative to measures of fibre diameter variation in predicting staple strength varied between the models. Utilising the mid-side measurements only, suggested that mean fibre diameter was most important in explaining staple strength in the Armidale environment however fibre diameter variation was of greatest importance in the Condobolin environment. The reverse was observed when the FDP characteristics only were analysed.

All of these results have illustrated that the mid-side measurements alone do not provide a consistent explanation of how absolute fibre diameter and variation in fibre diameter along and between-fibres is related to staple strength. This again illustrates the benefits that are gained with the measurement of fibre diameter profiles.

Considering the phenotypic relationships that are observed between the FDP characteristics and staple strength and the differences observed between bloodlines and sire groups in these characteristics, it is possible that these FDP traits are genetically controlled. Detailed genetic studies are required to examine the level of genetic variation in FDP characteristics and their genetic relationship with other important wool quality characteristics. The results have clearly illustrated that the phenotypic relationships between the FDP characteristics and staple strength are variable across environments and genotypes. Similar variations have been observed for the relationship between mid-side variation in fibre diameter and staple strength at the phenotypic level. However this relationship is consistently higher at the genetic level, across environments and genotypes. Given the large environmental influences on FDPs a similar trend may appear in the relationship between the FDP characteristics and staple strength, with the correlations being more consistent at the genetic level. Therefore it would be worthwhile to conduct a larger study examining the genetic aspects of FDP characteristics. The profile prediction technique developed and evaluated in Chapter 4 may now make these studies more practical.

The physiological or biological causes of the differences between bloodlines, sire groups and individual sheep in FDP characteristics and staple strength remain unknown. This was the focus of Chapter 6, the fourth research chapter in this thesis. This chapter examined the relationships between L/D ratio and associated measurements, standard mid-side measurements and body traits with differences between sheep in FDP characteristics and staple strength. Mean fibre diameter, L/D ratio and seasonal variation in fibre growth rate appear to be the important determinants of the shape of the fibre diameter profile. These determinants and therefore the FDP characteristics are further influenced by mean, and seasonal variation of, body weight, fat depth and skin thickness. The relationships between the FDP characteristics and staple strength were not as strong as in the previous experiments also undertaken in the Armidale environment. This may be due to differences between the studies in the shape of the FDPs and level of fibre diameter variation along staples. Staple strength was most influenced by variation between fibres in fibre diameter and length. Seasonal variation in fibre length growth was also significantly related to staple strength. These characteristics were also significantly influenced by seasonal variation in body weight, fat depth and skin thickness. The effects of seasonal variation in body weight and fat depth on wool growth were different to the effects of seasonal variation in skin thickness. These relationships are complex and much research is required to fully examine how these characteristics combine to influence variation in fibre diameter throughout the year and staple strength.

Results from Chapters 5 suggested that the FDP characteristics may provide more benefit in terms of explaining variation in staple strength where variation in fibre diameter along the FDP is lower. An experiment to test the hypothesis that the level of seasonal variation in fibre diameter influences the way in which the FDP characteristics are related to staple strength would be beneficial. This research could be combined in an experiment to further investigate the results observed in Chapter 6. This experiment would be most beneficial by creating a factorial design with high and low fibre diameter groups each nutritionally managed to produce high or low seasonal variation in fibre diameter along the FDP. Sheep should be selected from the same genotype and maintained in the same environmental conditions for the duration of the experiment. Fibre length growth, fibre length variation and seasonal variation in body weight, condition and skin thickness should all be measured throughout the experiment.

With further research, variation in fibre diameter, length and L/D ratio might be able to be used in combination with FDPs, wool quality characteristics and body traits to reduce seasonal environmental responsiveness of fibre diameter. The results from Chapters 4, 5 and 6 have demonstrated that this should result in improved staple strength and wool quality. As this study only involved 16 sheep a larger study is required using more grazing sheep of different genotypes over a number of environments to confirm these relationships. The present method required to measure fibre length and fibre length variation is time consuming and expensive and would benefit from a modified technique to make estimation of fibre length and fibre length variation more practical.

The final research chapter investigated a number of techniques that could be used to estimate these fibre growth characteristics from larger numbers of sheep. The results demonstrated several methods that accurately estimated average fibre length, fibre diameter and L/D ratio. These techniques may be used to examine the relationship between these fibre and FDP characteristics in a large number of sheep. This would lead to a better understanding of how these characteristics are related to environmental responsiveness of fibre diameter and length and wool quality.

The results illustrated in this thesis have important implications for both previously published research and future studies. Jackson and Downes (1979), Denny (1990), Hansford (1997) and Yamin *et al.* (1999) have all reported on studies conducted using a fibre diameter profiling technique utilising only 10 segments or snippets from the original profile. The results from Chapter 3 indicate that these estimates for the absolute fibre diameter values and the measures of along-staple variation in fibre diameter from the FDPs should be accurate. However it is likely that the reported rates of fibre diameter change are not accurate representations of the full original FDP.

At this point in time there are no published validation studies for the OFDA2000 (Brims *et al.* 1999) which has been developed to measure FDPs in greasy or clean staples. The results from the studies detailed in Chapters 3, 4 and 5 have implications for these future validation studies that are required for the OFDA2000. The profile prediction procedure could be utilised to generate full fibre diameter profiles to compare to the fibre diameter profiles measured using the OFDA2000. The level of inclusion used will depend on the characteristics measured and the intended use of the estimates. The differences between environments and genotypes in FDP characteristics and their relationship with staple strength will also need to be accounted for.

The findings presented in this thesis have significant implications for the management and prediction of staple strength. Staple strength is closely related to variations in fibre diameter and length between and along fibres. Variations in fibre length are also closely related to variation in fibre diameter. This finding supports the suggestions that the strong and consistent relationship between mid-side variation in fibre diameter and staple strength is a result of the relationship between fibre length variation and staple strength. The relationship between variation in fibre diameter along the staple and staple strength was more variable between environments and genotypes. The results tend to suggest that FDP characteristics provide more benefits for the prediction of staple strength in environments where along-staple variation in fibre diameter is lower. In these environments minimum fibre diameter appeared to increase in importance as a predictor of staple strength. The biological reasons for these trends are unclear and therefore warrant further investigation. The importance of absolute fibre diameter measurements in explaining staple strength were also variable depending on the characteristics included in the prediction equation. This is likely to be a direct result of the way in which the measurements were obtained. Mid-side measurements contain samples from the entire length of the staples whereas absolute fibre diameter measurements from the FDP are collected at specific points that can be related biologically to staple strength. While seasonal fibre diameter and length variation can be related to staple strength their exact influence on the processing performance to top is yet to be determined. As there is a need to target research more towards the end users of wool, this is an area that warrants significant research.

Fibre diameter profiles and staple strength are a result of a complex interaction between the sheep and its environment. Results illustrated in this thesis suggest that the FDP traits may be, at least partially, controlled by the genes of sheep and are related to staple strength. With more extensive research and a better understanding of these traits, they may provide an important additional tool for woolgrowers to manage flocks and select animals for breeding purposes. This thesis has clearly demonstrated that this additional research is warranted.