Measurement of Medullation in Wool and Mohair Using an Optical Fibre Diameter Analyser[1,2]

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ABSTRACT: We conducted three experiments to evaluate the Optical Fibre Diameter Analyser (OFDA) for estimating medullation (med [M], kemp [K], and total [T] medullated fiber content) in mohair and wool produced by Angora goats and sheep, respectively. Medullation can be a beneficial characteristic in certain types of wool, but it is highly undesirable in mohair and apparel wools. Current techniques for evaluating medullation in animal fibers are laborious, slow, and expensive. The OFDA had been modified by the manufacturer to measure fiber opacity distribution, a characteristic known to be indicative of medullation in white fibers, and was capable of providing such measurements in a very short time. Measurements made on magnified fiber images produced with a projection microscope (PM) were used as a reference for M, K, and T in fiber samples. An initial experiment with 124 mohair samples (T = .10 to 9.10%) seemed to indicate that OFDA estimates of M, K, and T were only poorly correlated with corresponding PM values (r^2 = .5409, .1401, and .5576, respectively). However, a second experiment using wool and mohair samples containing a wider range of medullation (T = .58 to 26.54%) revealed that OFDA estimates of M, K, and T for wool were highly correlated with PM measurements (r^2 = .9853, .9307, and .9728, respectively). Evidence was also obtained indicating that the low r^2 values associated with mohair relationships were likely due to a combination of factors: 1) high variation among the standard PM measurements and 2) the relatively low M, K, and T contents of the mohair samples compared with wool. In a third experiment, greater accuracy was obtained in the PM measurements by evaluating many more individual fibers per sample (10,000). In this case, OFDA estimates of M, K, and T for mohair were highly correlated with corresponding PM measurements (r^2 = .8601, .9939, and .9696, respectively). However, the two sets of linear regression equations obtained for wool and mohair were somewhat different, indicating that separate calculations should be used to estimate PM measurements from OFDA data. In conclusion, it was demonstrated that the OFDA instrument is capable of providing relatively fast, accurate, and potentially less expensive estimates of medullated fiber characteristics in mohair and wool.

Key Words: Medullation, Mohair, Wool

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Introduction

Medullated fiber measurements quantify characteristics affecting appearance and performance (e.g., apparent dyeability and resilience) of wool and mohair fabrics. Consequently, medullated fiber content is an important selection criterion for Angora goats and certain breeds of sheep. Typically, medullated fibers are determined manually using a projection microscope and a ruler (ASTM, 1996). This standard test method defines two types of medullated fiber: “med,” when the medulla width is less than 60% of fiber diameter, and “kemp,” when the medulla width is greater than 60% of fiber diameter. Although kemp fibers alone result in visible faults in dyed mohair fabrics, med and kemp contents are selected against by Angora goat breeders because both types of medullated fiber seem to be a single trait (Lupton et al., 1991). In contrast, some sheep breeds (e.g., the Drysdale) were specifically developed for high medullated fiber content. In other sheep breeds producing apparel wool (e.g., the Rambouillet), the presence of medullated fibers in the fleece represents a serious

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fault. Because the standard method of measuring medullation is slow, labor-intensive, and expensive, relatively few fiber images per sample (e.g., less than 1,000) are examined and measured in normal commercial practice. Consequently, the accuracy and precision of such measurements have been reported to be low (Lupton et al., 1994). Three experiments were conducted to evaluate the Optical Fibre Diameter Analyser (**OFDA**; Baxter et al., 1992) for accurate and rapid estimation of med, kemp, and total medullated fiber content in wool and mohair.

Materials and Methods

The OFDA instrument used in these experiments was modified by the manufacturer (BSC Electronics Pty. Ltd., Attadale, Western Australia) to permit measurement of fiber opacity distribution in addition to its primary function, measurement of fiber diameter distribution. Fiber opacity is the relative capacity of a fiber to obstruct transmission of light. It was hypothesized that for white fibers, opacity would be dependent on degree of fiber medullation. It has been shown previously that OFDA-measured opacity is independent of average fiber diameter of non-medullated (solid) fibers (Lee et al., 1996).

Experiment 1. Mohair samples (approximately 8 cm × 8 cm) were shorn from the mid-side of 124 male Angora goats participating in a central performance test (Waldron and Lupton, 1996). After cleaning, med (**M**), kemp (**K**), and total (**T** = M + K) medullated fiber contents were determined for each sample by assessing 1,000 fiber images per sample using the standard ASTM projection microscope (**PM**) procedure. Subsequently, one test specimen per sample was also measured to obtain opacity distributions using an OFDA instrument by the procedure outlined in the International Wool Textile Organisation (**IWTO**) draft test method (IWTO, 1996). Opacity measurements were made on more than 5,000 fiber snippets per test specimen. The OFDA was calibrated for opacity measurement using a single standard slide of known opacity provided by the instrument manufacturer. Opacity distributions were then used to estimate med (**OFDAM**), kemp (**OFDAK**), and total (**OFDAT**) medullated fiber content in the following manner. Fibers having opacity greater than 80% and widths greater than the sample mean were considered to be medullated. Kemp fibers were those having opacities greater than 94% and fiber diameters larger than 25 μm (Brims and Peterson, 1994; IWTO, 1996). Total medullated fiber content minus kemp content was designated as med fiber content. The estimates of medullation obtained from OFDA opacity measurements were compared with PM-determined med (**PMM**), kemp (**PMK**), and total medullated (**PMT**) fiber contents using the PROC MEANS (for paired *t*-tests) and PROC REG (for simple linear regression analyses) procedures of SAS (1988).

Experiment 2. Med, kemp, and total medullated fiber contents were determined for five samples each of wool and mohair using the same PM and OFDA methods described in Exp. 1. The samples were selected (Turpie, 1995) to represent a wider range of med and kemp contents than that in Exp. 1. The PM measurements were made on five test specimens (slides) per sample, and 1,000 fibers per slide were examined. The OFDA opacity measurements were made on two test specimens (slides) that were obtained from two mini-cored subsamples. Each slide was measured three times with approximately 10,000 fibers being examined each time. Again, PM and OFDA results were compared using the procedures described in Exp. 1.

Experiment 3. Medullation characteristics were determined for 40 wool and 40 mohair samples that were selected to represent an even wider range of med and kemp contents than those in Exp. 2 (Turpie, 1996). The samples consisted of wool and mohair in scoured and top (a continuous untwisted strand of combed wool or mohair in which the fibers lie parallel, with short fibers having been combed out) form. Three test specimens per sample (1,000 fibers per slide) were characterized using the ASTM PM method. Two test specimens were measured for each sample using the OFDA method. In this experiment, a new standard slide was used to calibrate the OFDA for opacity. This slide was again provided by the manufacturer. In this third experiment, a total of ~20,000 fibers per sample were measured using the OFDA. Subsequently, six of the original 40 mohair samples were selected for additional analyses. For these six (only), 10,000 fibers per sample (= 10 slides) were assessed using the PM. Together, these six samples represented the full range of M, K, and T measured for the 40 mohair samples.

Results and Discussion

The M, K, and T of the 124 mohair samples in Exp. 1 ranged from 0 to 8.80, 0 to 1.60, and .1 to 9.10%, respectively (PM measurements, Table 1). For U.S. mohair, these represent wide ranges of medullated fiber contents. Commercially, K of raw mohair rarely exceeds 1%. Overall, the M and T were not different ($P > .05$) between PM and OFDA instruments. However, OFDA underestimated K (.23 vs .33% for PM, $P < .05$). Linear relationships between PM and OFDA measurements of M, K, and T are shown in Table 2. All coefficients of determination (r^2) were significant ($P < .0001$) but quite low, particularly the K relationship. In fact, only 14% of variability in PMK can be accounted for by the variability in OFDAK. This is somewhat similar to results reported by Peterson and Gherardi (1995) in which the r^2 value

Table 1. Simple statistics for medullation measurements made in Experiments 1, 2, and 3[a]

Item	Med, %		Kemp, %		Total medullation, %	
	PM	OFDA	PM	OFDA	PM	OFDA
Exp. 1 (fiber = mohair, n = 124)						
Minimum	0	.47	0	.02	.10	.55
Maximum	8.80	5.02	1.60	1.01	9.10	5.67
Mean	1.29	1.39	.33[b]	.23[c]	1.62	1.62
SD	1.27	.64	.24	.19	1.37	.80
Exp. 2 (fibers = wool and mohair, n = 10)						
Minimum	.46	.26	.12	.04	.58	.30
Maximum	17.44	12.66	9.10	8.70	26.54	20.96
Mean	6.48[b]	4.10[c]	2.65	2.64	9.13[b]	6.74[c]
SD	7.29	5.16	3.52	3.73	10.75	8.88
Exp. 3 (fibers = wool and mohair, n = 80)						
Minimum	0	.12	0	0	0	.12
Maximum	29.30	12.33	11.40	5.99	37.00	18.05
Mean	4.02[b]	1.92[c]	1.16[b]	.76[c]	5.18[b]	2.68[c]
SD	5.22	2.64	2.01	1.28	6.75	3.88

[a]PM = projection microscope and OFDA = Optical Fibre Diameter Analyser.
[b,c]Mean pairs with different superscript differ ($P < .05$).

was .45 ($P < .05$) for total medullation, and the linear relationship between PMK and OFDAK was not significant ($P > .05$) even though the range in K of their 133 mohair samples was 0 to 8.25% (PM measurements). The most likely cause of the poor agreement between PM and OFDA measurements of K in mohair is the poor accuracy and precision of the PM measurement when relatively small numbers of fibers are examined. This number was 1,000 in Exp. 1 and either 400 or 800 fibers in Peterson's experiment (Peterson and Gherardi, 1995). It has been reported previously that counting 1,000 fibers per sample for kemp measurement in mohair results in low accuracy (Lupton et al., 1994).

This realization caused us to participate in a second experiment in which the number of PM observations per sample was increased and, concurrently, the number of samples was reduced. Because mohair samples containing K > 1.6% were not available, some highly medullated wool samples were included into the experiment. Thus, in Exp. 2, M, K, and T ranged from .46 to 17.44, .12 to 9.10, and .58 to 26.54%, respectively (Table 1). Contrary to Exp. 1, OFDA underestimated M and T in Exp. 2. This observation was similar to that of Lee et al. (1996), who reported that OFDA underestimated medullated fibers by a factor of 8.2%. However, PMK and OFDAK did not differ ($P > .05$) for this set of samples. Simple linear

Table 2. Linear relationships between projection microscope and Optical Fibre Diameter Analyser measurements of medullation in wool and mohair (data combined)[a]

Regression equation	r^2	$P <$	n
Exp. 1			
PMM = –.7247 + 1.4474 × OFDAM	.5409	.0001	124
PMK = .2169 + .4706 × OFDAK	.1401	.0001	124
PMT = –.4618 + 1.2789 × OFDAT	.5576	.0001	124
Exp. 2			
PMM = .7353 + 1.408 × OFDAM	.9806	.0001	10
PMK = .2090 + .9251 × OFDAK	.9636	.0001	10
PMT = 1.0479 + 1.1986 × OFDAT	.9812	.0001	10
Exp. 3			
PMM = .7105 + 1.7230 × OFDAM	.7571	.0001	80
PMK = .0885 + 1.4085 × OFDAK	.8105	.0001	80
PMT = .9045 + 1.5933 × OFDAT	.8369	.0001	80

[a]PMM = projection microscope med content, %; PMK = projection microscope kemp content, %; PMT = projection microscope total medullation, %; OFDAM = Optical Fibre Diameter Analyser med content, %; OFDAK = Optical Fibre Diameter Analyser kemp content, %; and OFDAT = Optical Fibre Diameter Analyser total medullation, %.

Table 3. Simple statistics for medullation measurements made on wool and mohair samples[a]

Item	Med, %		Kemp, %		Total medullation, %	
	PM	OFDA	PM	OFDA	PM	OFDA
Exp. 2 (fiber = wool; n = 5)						
Minimum	2.94	.77	.12	.05	3.06	.83
Maximum	17.44	12.26	9.10	8.70	26.54	20.96
Mean	12.09[b]	7.72[c]	4.96	5.13	17.06[b]	12.85[c]
SD	6.38	5.19	3.81	3.99	10.13	9.18
Exp. 2 (fibers = mohair; n = 5)						
Minimum	.46	.26	.12	.04	.58	.30
Maximum	1.46	.73	.54	.31	2.00	1.04
Mean	.86[b]	.48[c]	.34[b]	.16[c]	1.20[b]	.64[c]
SD	.42	.17	.16	.10	.58	.28
Exp. 3 (fiber = wool ; n = 40)						
Minimum	0	.12	0	0	0	.12
Maximum	29.30	12.33	11.40	5.99	37.00	18.05
Mean	6.66[b]	2.92[c]	1.52[b]	1.10[c]	8.18[b]	4.02[c]
SD	6.27	3.42	2.58	1.68	8.38	5.06
Exp. 3 (fiber = mohair; n = 40)						
Minimum	.10	.23	0	0	.10	.25
Maximum	6.70	2.00	5.10	2.01	7.60	4.24
Mean	1.37[b]	.91[c]	.80[b]	.42[c]	2.17[b]	1.34[c]
SD	1.16	.49	1.08	.51	1.75	.98

[a]PM = projection microscope and OFDA = Optical Fibre Diameter Analyser.
[b,c]Mean pairs with different superscript differ ($P < .05$).

regression analyses between PM measurements and OFDA estimates of medullation in wool and mohair samples produced r^2 values that were highly significant ($P < .0001$) and all were greater than .96 (Table 2). Table 3 shows that the ranges in M and K for wool vs mohair are different (M = 2.94 to 17.44% vs .46 to 1.46% and K = .12 to 9.10% vs .12 to .54%, respectively). With the relatively small ranges in mohair M and K, it was not surprising that the r^2 values for the linear relationships between PM vs

Table 4. Linear relationships between projection microscope and Optical Fibre Diameter Analyser measurements of medullation: wool and mohair data separated[a]

Regression equation	r^2	$P <$	n
Exp. 2, wool			
PMM = 2.6852 + 1.2185 × OFDAM	.9853	.0008	5
PMK = .2495 + .9197 × OFDAK	.9307	.0079	5
PMT = 3.0720 + 1.0882 × OFDAT	.9728	.0019	5
Exp. 2, mohair			
PMM = –.0078 + 1.8232 × OFDAM	.5431	.1554	5
PMK = .1143 + 1.4359 × OFDAK	.7592	.0543	5
PMT = .1026 + 1.7318 × OFDAT	.6412	.1035	5
Exp. 3, wool			
PMM = 2.0162 + 1.5885 × OFDAM	.8198	.0001	40
PMK = –.0344 + 1.4153 × OFDAK	.8928	.0001	40
PMT = 2.0878 + 1.5159 × OFDAT	.8865	.0001	40
Exp. 3, mohair			
PMM = .6498 + .7890 × OFDAM	.1114	.0002	40
PMK = .0883 + 1.6750 × OFDAK	.6192	.0001	40
PMT = .5030 + 1.2412 × OFDAT	.4883	.0001	40

[a]PMM = projection microscope med content, %; PMK = projection microscope kemp content, %; PMT = projection microscope total medullation, %; OFDAM = Optical Fibre Diameter Analyser med content, %; OFDAK = Optical Fibre Diameter Analyser kemp content, %; and OFDAT = Optical Fibre Diameter Analyser total medullation, %.

Table 5. Detailed linear regression output between projection microscope (y) and Optical Fibre Diameter Analyser (x) measurements of 40 wool samples (Exp. 3)

Item	Med	Kemp	Total
r^2	.8198	.8928	.8865
Standard error of y estimate (root mean square error)	2.6004	.8396	2.8021
P	.0001	.0001	.0001
x coefficient	1.5885	1.4153	1.5159
Standard error of x coefficient	.1208	.0796	.0880
Intercept	2.0162	−.0344	2.0878
Standard error of intercept	.5422	.1590	.5670

OFDA for mohair were much lower than corresponding values for wool (Table 4), even though 5,000 fibers per sample had been examined using PM. It now became apparent that a single set of regression equations could not adequately predict PM measures of M, K, and T of wool and mohair from a knowledge of the corresponding OFDA estimates of M, K, and T values. In view of past experience with the OFDA instrument, this should not have been surprising. When calibrating the OFDA for measurement of fiber diameter distribution, it is necessary to use separate calibrations for wool, mohair, and cashmere. The physical and chemical differences among these fiber types apparently make this necessary. The same seems to be true for estimating PMM, PMK, and PMT from OFDA data.

To further investigate this aspect, a third experiment was planned in which 40 wool and 40 mohair samples were selected to produce even wider ranges of M, K, and T (0 to 29.30, 0 to 11.40, and 0 to 37.00%, respectively, Table 1). The r^2 values for the linear relationships between PM measures and OFDA estimates of medullation were all high (> .81) but not as high as those obtained in Exp. 2, probably because fewer fibers per sample (3,000 vs 5,000) were examined with PM in Exp. 3 than in Exp. 2. The linear relationships of M, K, and T for PM and OFDA were all highly significant ($P < .0001$, Table 2). Numerical differences in the regression equations between Exp. 2 and 3 are attributed to the two calibrations used. Table 4 shows that r^2 values for mohair linear relationships are again less than corresponding values for wool (also detailed in Table 5). We hypothesized that this was due to examining too few mohair fibers using the PM. In fact, fitting the wool med and total medullation (but not kemp) data using polynomial expressions produced slightly higher r^2 values than for the linear equations ($r^2 = .8533$ and .9012 vs .8198 and .8865, respectively). Because the improvements in fit were only modest, this observation was not pursued further. Subsequently, 6 of the 40 mohair samples were selected for further measurement. In all, a total of 10,000 fibers per sample were examined using the PM. Table 6 shows the simple statistics, and Table 7 shows results of linear regression analyses on these six samples. Inspecting and measuring a large number of mohair fibers on the PM finally provided convincing evidence that the OFDA is indeed capable of providing accurate estimates of PMK ($r^2 = .9939$, $P < .0001$) and PMT ($r^2 = .9690$, $P = .0003$) even for mohair. Corresponding r^2 values for the same six mohair samples when only 3,000 fibers were measured with the PM were .7552 and .8871, respectively, for PMK and PMT. We also obtained further evidence that accurate estimates of PMM, PMK, and PMT of wool and mohair from OFDAM, OFDAK, and OFDAT will require separate sets of regression equations.

Precision and Bias. In Exp. 2, five test specimens per sample were measured with the PM and two test

Table 6. Simple statistics for medullation measurements made on six mohair samples[a]

	Med, %		Kemp, %		Total medullation, %	
Item	PM	OFDA	PM	OFDA	PM	OFDA
Minimum	.15	.28	.01	.02	.16	.30
Maximum	2.23	1.77	2.69	1.58	4.39	3.33
Mean	1.18	.93	1.03[b]	.56[c]	2.21[b]	1.50[c]
SD	.73	.66	1.09	.66	1.76	1.31

[a]PM = projection microscope and OFDA = Optical Fibre Diameter Analyser.
[b,c]Mean pairs having different superscript differ ($P < .05$).

Table 7. Detailed linear regression output between projection microscope (y) and Optical Fibre Diameter Analyser (x) measurements for six mohair samples (Exp. 3)

Item	Med	Kemp	Total
r^2	.8601	.9939	.9696
Standard error of y estimate (root mean square error)	.3044	.0956	.3428
P	.0077	.0001	.0003
x coefficient	1.0186	1.6523	1.3204
Standard error of x coefficient	.2054	.0649	.1169
Intercept	.2293	.1019	.2360
Standard error of intercept	.2285	.0534	.2239

specimens per sample were measured three times each using the OFDA. Thus, we were able to calculate between-specimen variability for each instrument and within-specimen (slide) variability for the OFDA. Between-specimen variability (SD) for PMM, PMK, and PMT was 1.5, .8, and 2.0%, on average, for mean values of 6.5, 2.6, and 9.1%, respectively. Corresponding SD values for the OFDA were .2, .3, and .4%, respectively. Within-specimen variability for the OFDA estimates was small (SD = .1%) for M, K, and T. In order to investigate the existence of bias in the OFDA measurement, differences between the PM measurements and OFDA estimates of M, K, and T were regressed against the PM measurements. The resulting r^2 values of the linear relationships were .9170, .0405, and .7196 for M, K, and T, respectively. Thus, the OFDA estimate of kemp was shown to be unbiased, and OFDA estimates of M and T were biased because the PM-OFDA differences for M and T increased linearly as PMM and PMT increased.

Time of Measurements. In Exp. 3, three test specimens per sample were measured with the PM and two specimens per sample with the OFDA. Times for determining medullation values ranged from 50 to 150 min per sample for the PM and averaged less than 8 min per sample for the OFDA.

In conclusion, the results obtained in these three experiments confirm that the OFDA is a promising system for accurate and relatively rapid estimation of medullation in wool and mohair.

Implications

The Optical Fibre Diameter Analyser (OFDA) is a new test method that is available to testing laboratories that is more precise, less time-consuming, and potentially less expensive than the existing projection microscope test method. Because the OFDA is now internationally accepted for determination of fiber diameter distribution as well as medullation, we anticipate a rapid decline in the use of antiquated projection microscope methods by testing laboratories and textile-mill quality control laboratories. The net result should be improved efficiencies and savings in the selection programs of sheep and Angora goat producers and in the quality assessment and control programs of buyers and processors of wool and mohair.

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