Automatic Image Analysis System for Objective Measurement of Animal Fibers[1,2]

K. Qi[3], C.J. Lupton[3,4], F.A. Pfeiffer[3], D.L. Minikhiem[3], N.S. Kumar[5] and A.D. Whittaker[5]

Summary

The imaging system at the Texas Agricultural Experiment Station (TAES), San Angelo, TX, originally developed for measuring fiber diameter distributions only, was upgraded to a general-purpose image analyzer for quantifying numerous characteristics of animal fibers. By providing measurements of multiple traits in a single instrument, it is anticipated that the cost of measuring fibers can be reduced. A series of algorithms was developed for fiber image enhancement, fiber recognition and subsequent measurement of: 1) average fiber diameter (AFD) and standard deviation (SD); 2) average staple length (ASL) and its SD; 3) mechanical yield of cashmere; 4) medullation in mohair; 5) color of scoured fibers; and 6) colored fiber content. Results produced by the new system were compared with those from standard methods for AFD ($r = 0.994$, $P < 0.0001$), ASL ($r = 0.998$, $P < 0.01$), mechanical yield of cashmere ($r = 0.912$, $P < 0.0001$) and medullation in mohair ($r = 0.414$, $P > 0.20$). For measuring color of scoured white animal fibers, the imaging system was programmed to be a colorimeter equivalent. As a result, in Commission Internationale de l'Eclairage's (CIE) XYZ Color Space, the r values between X, between Y and between Z of measurements made with our system versus a colorimeter for 33 scoured U.S. wools were 0.950 ($P < 0.0001$), 0.940 ($P < 0.0001$) and 0.926 ($P < 0.0001$), respectively. The program for analyzing black and colored fibers in predominantly white samples distinguishes dark pigmented fibers from lighter-stained, yellow fibers. Preliminary data show that the program has a high speed of measurement with reasonable accuracy. All the developed programs except the one for measuring medullation provide satisfactory results. Further refinement of the medullation program is required. Commercialization of this versatile imaging system is under investigation.

Key words: image analysis, automation, animal fiber characterization.

Introduction

Since 1988, researchers at the Wool and Mohair Research Laboratory of the Texas Agricultural Experiment Station (TAES) in San Angelo, TX, have used an Image Analyzing System (Analytical Imaging Concepts, Irvine, CA) for measuring fiber diameter distributions of animal fibers. In 1992, an Optical Fibre Diameter Analyser (OFDA) was obtained (BSC Electronics Pty. Ltd., Attadale, Australia) for evaluation (Qi et al., 1994a). The aforementioned two instruments are limited in that they are only programmed to analyze black and white images and output average fiber diameter (AFD) and variability of fiber diameter (SD, CV). Source codes for the programs for these two instruments were retained by the manufacturers for commercial reasons. Consequently, modification of the programs is not possible by anyone except the manufacturers. Recently, a new image-capture board and a charge-coupled device (CCD) color video camera were added to the system with several compatible programming tools. These components provided the capability of developing programs for measuring other fiber characteristics. The economical importance of these fiber

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[3] Texas Agricultural Experiment Station, 7887 North Highway 87, San Angelo, TX 76901.

[4] To whom correspondence should be addressed.

[5] Department of Agricultural Engineering, Texas A&M University, College Station, TX 77843.

characteristics was summarized previously (Lupton, 1992; Qi et al., 1994a,b,c,d). Thus, research objectives were to: 1) develop software and apparatus for using automatic image analysis technology for measuring AFD and its SD, ASL and its SD, mechanical yield of cashmere, medullation in mohair, color of scoured fleeces and colored fiber content; and 2) evaluate the developed fiber image analysis software for application in the sheep and goat industries and for further commercialization.

Materials and Methods

The TAES Image Analysis System

Hardware components. The TAES Automatic Image Analysis System consists of: an analytical microscope (Nikon SCU-1) with a video adapter and a programmable stage (Nikon Scanning Stage); a CCD black-and-white camera (Javelin JE2362) and a CCD color video camera (JVC TK-1070U) with a zoom lens (H6X12.5R, Fujinon-TV), both of which can be fitted to the microscope or to a camera-stand when macro rather than micro views are required; a Targa-compatible display monitor (Sony Trinitron PVM-1271Q); a Truevision Targa+ ISA (64) Graphics Engine (Targa Imaging Board; Truevision, Inc., Indianapolis, IN); an IBM-compatible computer (Comtrade, Inc., Industry City, CA); an HP LaserJet III laser printer; and sample preparation and mounting devices.

The CCD camera captures fiber images and converts them into electric signals. These electric signals are then fed out to the Targa Imaging Board for digitization. The processing system is a 486DX/33MHz microcomputer with 16 megabytes of RAM, 180 kilobytes of cache memory and a 250-megabyte hard disk.

Program tools. The program tools used in the TAES Image Analysis System include Microsoft Visual C++ (version 1.5), Microsoft Windows Software Development Kit (Windows SDK; version 3.1) and Truevision Targa Compatible Toolkit (release 1.0).

Algorithms for Quick Capture of Fiber Image, and Subsequent Segmentation, Recognition and Measurement

Automation for continuous, real-time image capture and processing. In programming the TAES Image Analysis System for measuring AFD and its SD, medullation in mohair and colored fiber content, it was essential that the system be automated in order to continuously capture and analyze fiber images. This was necessary to ensure that enough fibers be analyzed to achieve certain specified precision (American Society for Testing and Materials [ASTM], 1993a,b,c) in a relatively short time. Thus the analytical microscope was fitted with a programmable stage (Nikon Scanning Stage) which was linked to a serial port and controlled by custom-designed programs. The capability was developed to scan and analyze 10,000 fibers in five minutes and the system was therefore named "The TAES Automatic Image Analysis System."

Algorithm for measuring fiber diameter. Recognition and distinguishing individual fibers from fibers lying side-by-side and from contaminating debris and dust were accomplished through a series of fiber image tests and model matching (Figure 1). In summary, a program was developed to distinguish fibers using specially designed masks (Kumar, 1995). The fiber images are considered to have straight edges (linearity test). For a fiber image both edges should parallel each other (symmetric test). Upon finishing linearity and symmetric tests, a conclusion was made regarding the image under consideration being a fiber image versus a contaminant image. Then a series of 18 fiber image masks with different orientations (10 degrees apart on consecutive masks) was fitted to the recognized fiber image to identify the best match (angle test). Finally, the diameter for the fiber image was calculated. This procedure was repeated several thousands of times in order to get an accurate estimate of AFD and SD for a sample. The program-measured diameters (in pixels) for a set of standard Interwool-labs IH wool tops (Qi et al., 1994a) were compared with the results obtained using the standard method (ASTM, 1993a) to evaluate the accuracy and precision of this program.

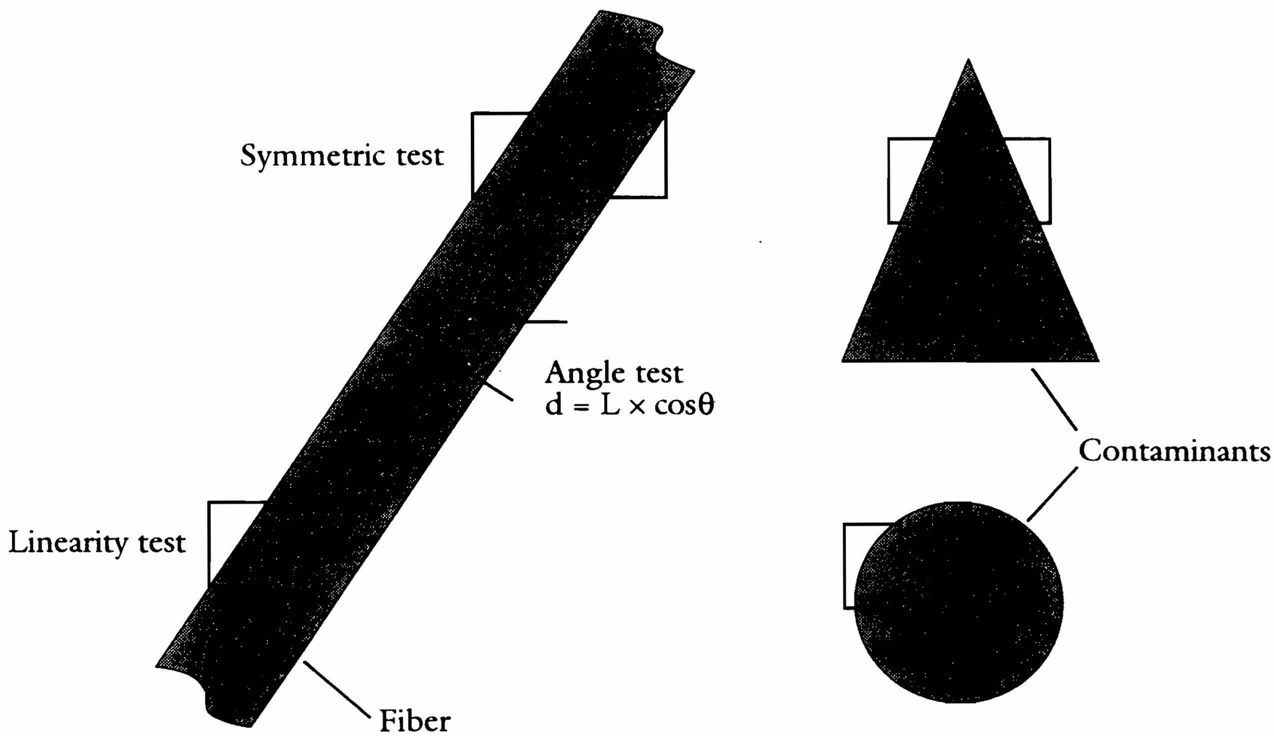
Algorithm for measuring wool staple length. Wool staples are relatively uniform in shape. Ideally, they may be considered as rectangles (Figure 2). If the staple has a trapezoid shape, one staple can be divided into two parts or two similar staples can be used, and by putting the end of one with the head of another longitudinally, the resulting staple shape becomes rectangular. Thus by measuring total area and perimeter of such a staple with the program, the ASL for each staple can be calculated (Qi et al., 1994d). The staples were placed on a background providing good contrast for easier object recognition (e.g., white staple on black paper). In order to increase the accuracy of measurements, multiple staples (three to six) from the same sample can be measured by the program at one time.

Algorithm for measuring mechanical yield of cashmere. Raw cashmere is a mixture of relatively fine fibers (cashmere down) and coarse guard hairs. Generally, the AFD of cashmere down is in the range of 13 to 19 µm (individual fiber diameters range from 6 to 30 µm), whereas the diameter range of guard hairs is from 31 to 250 µm. Mechanical yield of cashmere refers to the weight of cashmere fibers (less than or equal to 30 µm in fiber diameter) in the scoured, raw cashmere fleece expressed as a percentage (IWTO, 1992). Assuming that densities of cashmere fibers and guard hair fibers are the same, the mechanical yield of cashmere can be estimated using fiber diameter distribution obtained from the histogram of raw cashmere after analyzing for fiber diameter and its distribution in the range 6 to 250 µm (Marschall et al., 1994). These estimated results were compared with results obtained using the standard method (International Wool Textile Organization [IWTO], 1992) which utilizes a Shirley Analyser (Model SDL-102A) to achieve separation of down fibers from guard hairs.

Algorithm for measuring medullation in mohair. Using dark-field illuminating techniques, the opacity of medullated fibers was observed to be different from non-medullated fibers, and opacities of the two different types of medullated fibers (med and kemp) are quantitatively different. The opacities of different fibers were indicated by their pixel values. By selecting the correct threshold levels, a program was developed for distinguishing non-medullated from medullated fibers and also med from kemp fibers (Kumar, 1995). The program counted the numbers of med and kemp fibers and calculated their percentages in the population measured.

Algorithm for measuring color of scoured fibers. To develop a method for measuring color of scoured animal fibers using the TAES Automatic Image Analysis System, a CCD color video camera and a Targa Imaging Board were used to capture and digitize the fiber images in red-green-blue color space (Judd and Wyszecki, 1975). The red-green-blue color space was then converted to device-independent tristimulus values (X, Y, Z) using a cube-root color coordinate system (Glasser et al., 1958; Gentile et al., 1988) pertaining to CIE's illuminant C and 0° observer angle. Fiber samples in the custom-built camera stand were illuminated by four halogen light bulbs (32,000 °K; General Motors, Detroit, MI) to provide uniform illumination at the sample surface. A preliminary program was developed and a series of tests was conducted to: 1) identify the optimum light intensity for color measurement; 2) evaluate the linearity of image digitization of the Targa Imaging Board; 3) standardize the Targa Imaging Board with a proper reference; and 4) assess the glass effect for achieving a more uniform measuring surface with constant density in the wool sample (American Association of Textile Chemists and Colorists, 1990). Finally, the preliminary program was optimized based on the results of these tests (Qi et al., 1994c). The performance of this program for measuring color of scoured animal fibers was compared with a colorimeter (Macbeth 1500, Kollmorgen Instruments Co., New Windsor, NY) using a broad spectrum of wool types representing wools produced throughout the U.S.

Figure 1. The algorithm for fiber recognition and fiber diameter measurement.



To distinguish fibers from contaminating debris and dust, specially designed masks were laid upon the encountered images. Fiber images were considered to have straight edges (linearity test) and parallel edges (symmetric test). After conducting linearity and symmetric tests, a conclusion was drawn regarding the image being tested as to whether it was a fiber or a contaminant. Then a series of 18 fiber image masks with different orientations (10 degrees apart on consecutive masks) was laid upon the recognized fiber image to identify the best match between a fiber image and a specific mask (angle test). Finally, the diameter of the fiber image was calculated. This procedure was repeated thousands of times in order to get an accurate estimate of average fiber diameter for a sample with certain precision.

In the figure, two types of contaminant (circular and triangular) are shown to indicate the difference as tested by this algorithm. This algorithm is incapable of distinguishing real fibers from rectangular contaminants of similar dimensions.

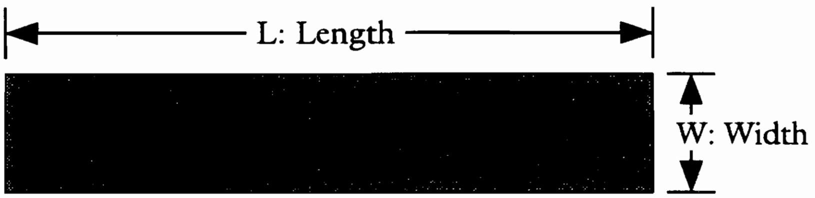
Algorithm for measuring colored fiber content. Recognition of fibers was achieved in a similar manner to that used in the fiber diameter algorithm (Figure 1). The CCD color video camera was used and the Targa Imaging Board was configured to capture and digitize the fiber image in red-green-blue color space (Judd and Wyszecki, 1975). Pigmented and stained fibers were distinguished from white fibers by measuring the color of light transmitted through the fibers. By experimentally establishing proper threshold levels, a program was written to distinguish among white, pigmented and stained/yellow fibers. The program was also capable of calculating percentages for each type of fibers in a particular sample.

This algorithm for measuring colored fiber content in white fleeces is similar to the algorithm for measuring medullation in mohair. Critical differences include: 1) the required illuminating light sources are different (a balanced illumination technique was used to facilitate distinguishing differences in the color of light transmitted through fibers, whereas opacity for medullation was measured using dark field illumination); and 2) measuring colored fiber content in white fleeces requires a color CCD camera and a color imaging board, whereas opacity can be captured and digitized by a black-and-white CCD camera and a black-and-white imaging board.

Results and Discussion

In developing the TAES Automatic Image Analysis System, efforts were focused on developing programs for original, novel applications which are suited for image analysis technology. Furthermore, the intention was to develop as many applications as possible using this single group of instruments. Although some fiber characteristics already have established instruments in the market for their measurement, we still plan to pursue image analysis programs for their measurement because the specialized instruments (usually built for a single application) are very expensive individually and collectively. The cost advantage of a versatile multiple-use system should help to assure

Figure 2. The algorithm for wool staple length measurement.



Algorithm:

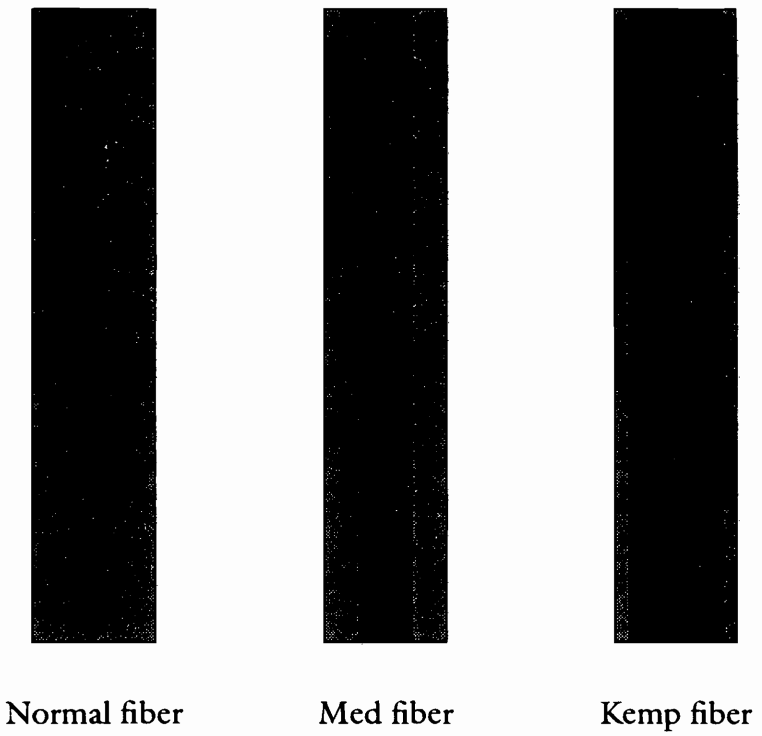
Perimeter: $P = 2 \times (L + W)$

Area: $A = L \times W$

Length: $L = [P + (P^2 - 16 \times A)^{1/2}]/4$

Wool staples are relatively uniform and rectangular in shape. A program was developed to measure area and perimeter of rectangular staples, from which staple length was calculated according to the formula.

Figure 3. The algorithm for medullation measurement.



Using dark field illuminating techniques, the opacity of medullated fibers can be made substantially different from non-medullated fibers, and opacity of med is quantitatively different from that of kemp fibers. The opacities of different fibers were indicated by their pixel values after being digitized by the Targa imaging board. By selecting critical threshold levels, a program was developed for distinguishing non-medullated from medullated fibers and also med from kemp fibers. The program counted all fibers and the numbers of med and kemp fibers and then calculated their percentages in the sample.

commercial success. Table 1 lists the proposed applications and progress to date for fiber characterization using this system.

The program for AFD analysis was shown to be highly accurate and precise (Kumar, 1995). A set of eight Interwoollabs IH tops with known AFD values (17.16 to 37.73 µm) was analyzed using this program (Table 2). The correlation coefficient between the micron values (µm) and the image analysis measurements (pixels) was $r = 0.994$ ($P < 0.0001$).

The program for measuring ASL was standardized using a set of five staples ranging from 5 to 15 cm in length. It was then evaluated by comparing results from the image analysis program versus four manual measurements (Table 3). The program-measured lengths and manually-measured lengths were highly correlated ($r = 0.998$, $P < 0.01$). This program has potential for eliminating operator errors and increasing speed of measurement.

The program for estimating mechanical yield of cashmere was evaluated by comparing its results with those obtained using the standard procedure. The results from the image analysis program and standard method for 75 raw cashmere fleeces were significantly correlated ($r = 0.912$, $P < 0.0001$; Marschall et al., 1994).

The program for analyzing med and kemp fiber contents requires further work. A set of 10 mohair samples was measured (10,000 fibers each) for med and kemp percentages using the standard procedure (ASTM, 1993b) and was then re-analyzed using the image analysis program (Table 4). The r values for med, kemp and total medullation between the results from our system and those obtained with the standard method (ASTM, 1993b) were 0.234 ($P > 0.20$), 0.325 ($P > 0.20$) and 0.414 ($P > 0.20$), respectively. These results are obviously not satisfactory.

The first program for measuring color of scoured fleeces was evaluated using a broad color range of 60 U.S. wools (McColl, 1993; personal communication). Preliminary results indicated that program measurements of color correlated moderately ($r = 0.73$, $P < 0.0001$) with results obtained using a colorimeter (Macbeth 1500, Kollmorgen, NY) at the International Textile Center (ITC), Texas Tech University, Lubbock, TX. This result was considered to be unsatisfactory. After optimizing the program according to indications from four tests (Qi et al., 1994c), 33 wool samples spanning the color range of the original 60 wools were re-measured. As a result, in CIE's XYZ Color Space, the r values between X, between Y and between Z of measurements made with the TAES System versus a colorimeter were 0.950 ($P < 0.0001$), 0.940 ($P < 0.0001$) and 0.926 ($P < 0.0001$), respectively.

Table 1. Proposed applications of the TAES Automatic Image Analysis System.

Proposed application	Progress to date
Average fiber diameter and its distribution	Finished
Wool staple length and its distribution	Finished
Mechanical yield of cashmere	Finished
Colored fiber content (pigmented and stained fibers)	Finished
Medullation in mohair (med and kemp percentages)	Continuing[a]
Color of scoured fibers	Finished
Luster in mohair, wool and cashmere	Started
Crimp in wool and cashmere	Pending
Style and character in mohair	Pending

[a] Further improvement of the program is needed to increase accuracy and precision.

Table 2. Evaluation of the average fiber diameter program using Interwoollabs IH tops.[a]

Top identity	Average fiber diameter	
	Stated values (Y, µm)	Measured values (X, pixel)
1	23.70	7.86
2	37.73	11.56
3	22.73	7.47
4	17.65	6.37
5	25.62	8.19
6	20.32	6.85
7	29.16	8.84
8	17.16	6.36

[a] Regression equation: $Y = -7.0043 + 3.9387 X$ ($r = 0.994$, $P < 0.0001$).

The program for quantifying colored fiber content in white fleeces distinguishes among white, pigmented fibers (dark brown and black) and stained/yellow fibers. The only existing U.S. method (ASTM, 1993c) requires manual counting of colored fibers in a specific weight of wool top. Results are reported as numbers of colored fibers per unit weight (15g) of wool top. The image analysis program is designed to count both pigmented and stained/yellow fibers, and report results as percentages of total fibers observed. Therefore, a direct comparison between image analysis results and results of ASTM standard method was not attempted.

Information concerning proportions of pigmented and stained/yellow fibers can be used in guiding animal breeding and management decisions as well as in quality control in the wool and mohair textile industries. Preliminary comparison of the results obtained using the image analysis program with manual measurements made on a projection microscope indicates the image analysis program has reasonable accuracy. Advantages of this automatic image analysis program include its high speed of measurement and the ability to distinguish between pigmented and stained/yellow fibers.

Beyond the described applications, this system has potential for measuring: 1) crimp in wool and cashmere; 2) style and character in mohair; and 3) luster in wool, mohair, cashmere and synthetic fibers. Programs for measuring crimp, style and character, and luster of animal fibers are in preparation.

Preliminary evaluation of the new programs for fiber characterization using the TAES Automatic Image Analysis System indicates that this system can be used for multiple types of measurement. The major advantage of the System is its versatility. Commercial users would need only to invest in one system which could perform multiple tasks. Availability of such measurements would have the potential of reducing costs of fiber testing and thus permit U.S. producers to better afford more fiber tests which in turn could result in enhanced selection for and marketing of wool, mohair and cashmere. Commercialization of this system is under investigation.

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Table 3. Standardization of staple length measurement and comparison of staple lengths by the image analysis program versus ruler measurement

Number	Staple length: Actual[a] (Y, cm)	Staple length: Program-measured (X, pixels)
1	5.00	122.48
2	8.00	162.82
3	10.00	184.26
4	12.00	220.32
5	15.00	258.65

Staple number	Program length, pixels	Predicted length, cm	Actual length, cm[a]	Residual error, cm[b]
1	241.47	13.76	14.00	0.24
2	135.71	6.08	6.00	-0.08
3	220.03	12.20	12.00	-0.20
4	175.41	8.96	9.00	0.04

[a] Staples were manually cut into these lengths and were then used as "absolute" standards. Standardization of the measurement by the image analysis program to actual length: $Y = -3.7724 + 0.0726\ X$ ($r = 0.998$, $P < 0.01$).
[b] Residual error calculated as actual length minus predicted length.

Table 4. Evaluation of the image analysis program for measuring medullation in mohair.

Sample identity	Standard method[a] Med, %	Standard method[a] Kemp, %	Standard method[a] Total, %	Image analysis program[b] Med, %	Image analysis program[b] Kemp, %	Image analysis program[b] Total, %
1	4.23	1.37	5.60	4.27	1.56	5.83
2	1.27	1.96	3.23	1.58	0.61	2.19
3	1.83	2.93	4.76	6.09	2.47	8.56
4	1.75	0.23	1.98	2.26	0.72	2.97
5	1.31	2.42	3.73	3.38	1.32	4.70
6	2.70	0.86	3.56	2.98	1.18	4.16
7	2.09	3.19	5.28	1.33	0.41	1.74
8	3.25	0.74	3.99	2.82	0.89	3.71
9	2.83	2.16	4.99	5.21	2.01	7.22
10	0.61	0.44	1.05	2.93	0.73	3.66

[a] Average of more than 10,000 fibers measured by five technicians.
[b] Average of 5,000 fibers measured.

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