Fiber production and properties in genetically furred and furless rabbits

A. D. Rogers,* C. J. Lupton,† and S. D. Lukefahr*[1]

*Department of Animal and Wildlife Sciences, Texas A&M University–Kingsville, Kingsville 78363-8202; and †Texas A&M University Agricultural Research and Extension Center, San Angelo 76901-9714

ABSTRACT: The objectives of this study were to describe and compare means and measures of variability of fiber characteristics and fiber production between genetically furred and furless rabbits and among classes of furless rabbits. An F_1 generation of rabbits was produced by mating New Zealand White does to a rare, furless Mini Lop buck. All F_1 offspring had normal coats of fur. Inter se random matings of the F_1 stock (barring full-sibling matings) were made to produce the F_2 generation that consisted of approximately 75% furred and 25% furless progeny. Furless animals were further subjectively classified into 3 distinct classes (1 to 3) having increasingly more fur. In yr 1, 17 furred and 20 furless rabbits (age 28 to 49 d) were randomly assigned to growing pens, and in yr 2, 17 additional furless and 9 additional furred rabbits were included to increase the size. After 6 wk, the rabbits were weighed, and a measured area of fur (~20 cm^2) was shorn from the left flank of each rabbit. This fiber was weighed and measured for staple length, fiber diameter, prickle factor (% of fibers >30 μm in diameter), and fiber curvature. Fiber production per unit area of skin was calculated and fiber production per animal was estimated. In yr 2, all of the furless and 2 of the furred rabbits were shorn over their entire bodies to obtain direct measurements of total fur weight. Furless rabbits were 9% heavier (1,941 vs. 1,783 g of BW, $P < 0.01$) and produced approximately 90% less fiber per unit area of skin than furred rabbits (1.74 vs. 15.83 mg/cm^2, $P < 0.01$). The fibers from furless rabbits were shorter (1.54 vs. 2.56 cm, $P < 0.01$) and coarser (15.8 vs. 14.5 μm diameter, $P < 0.01$) than those from furred rabbits and exhibited greater prickle factor (11.3 vs. 3.5%, $P < 0.01$) and curvature values (47.5 vs. 38.5 deg/mm, $P < 0.01$). Class 3 furless rabbits were heavier than rabbits of classes 1 and 2 (2,075 vs. 1,817 and 1,981 g of BW, respectively, $P < 0.05$). Means for actual total fiber production per animal for classes 1 to 3 were 0.64, 2.07, and 8.68 g, respectively, compared with 23.0 g for furred rabbits ($P < 0.01$). Although some similarities were present, several of the correlations involving fiber properties and BW were substantially different (e.g., BW vs. staple length and fiber diameter vs. weight of fiber per unit area) for furred and furless groups. These results, and those reported elsewhere from a series of experiments, support the potential for production of furless rabbits in arid and tropical environments.

Key words: fiber characterization, fur, genetics, production, rabbit

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INTRODUCTION

Rabbit production is particularly well suited for impoverished or subsistence farmers who live on small farms in arid and tropical regions of the developing world. However, furred rabbits reared in these areas are prone to heat stress, which can result in reduced rates of survival, reproduction, feed intake, and BW gains (McNitt et al., 2000). Heat-related deaths and low general performance of rabbits can prevent poor farmers from producing, selling, or consuming as much rabbit meat as is theoretically possible and have also resulted in failure of development projects to achieve target goals.

Housing of rabbits in air-conditioned facilities or use of electric fans is neither affordable nor practical in many situations. Clipping of fur from weanling rabbits has been shown to increase feed intake and BW gains (Lukefahr and Ruiz-Feria, 2003). An alternative approach to improving the rabbit's physical environment or morphology was to investigate the rare naked or furless gene, previously reported in Russia (Kislovsky, 1928), Great Britain (Castle, 1933), and France (Boucher et al., 1996). In the United States, a 3-yr investigation of the effects of the furless gene has, to date, demonstrated potential benefits on postweaning trait performance and physiological characteristics of rabbit fryers during the summer season (Jackson et al., 2006).

[1]Corresponding author: kfsdl00@tamuk.edu
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Figure 1. The rare, furless, Mini Lop buck, "Fuzz," grandsire to all of the rabbits in this study.

Our research objectives were to 1) quantify the statistical properties of fiber characteristics in classes of genetically furless and furred rabbits; 2) compare classes of furless and furred rabbits for estimated and actual total fur weight of the body coat; and 3) examine residual correlations among BW and fiber characteristics within furless and furred groups.

MATERIALS AND METHODS

Background and Management

All procedures were conducted under protocols approved by the Animal Care and Use Committee of Texas A&M University–Kingsville. The study was initiated with a rare, furless Mini Lop buck ("Fuzz," Figure 1) that was loaned to Texas A&M University–Kingsville (TAMUK) by the owner from El Campo, Texas. New Zealand White does from the TAMUK experimental population were mated to Fuzz to produce the F_1 generation, all of which had furred coats. Inter se random matings involving F_1 stock (barring matings between full siblings) were made to produce the F_2 generation, which yielded both furred and furless progeny (approximately 75 and 25%, respectively, due to a single recessive gene for furlessness; Jackson et al., 2006).

The population background, production, feeding and management, and experimental design were previously described in detail by Jackson et al. (2006). Briefly, a series of growth experiments involving 143 rabbit fryers were conducted in the summers of 2002, 2003, and 2004 (across years, mean ambient temperatures ranged from 30.2 to 35.1°C, and relative humidity ranged from 53.7 to 68.9%). For this study, the F_2 rabbits were scored at 28 d of age with respect to coat type: furred or furless. The furless animals were then further classified visually into 3 distinct classes: 1 = little to no fur on the body, head, neck, and feet; 2 = a light coat of fur all over the body, with little to no fur on the neck and head; or 3 = a light coat of fur over the entire body (but considerably less dense than the furred rabbits).

The rabbits were sampled from 6 age batches (each batch corresponding to litters weaned within 1 wk) over a 2-yr period. In yr 1, there were 4 age batches with 17, 7, 7, and 6 animals; in yr 2 there were 2 age batches with 6 and 20 animals each. Each batch included both furless and furred rabbits. The sampling strategy was to involve all furless rabbits from the larger experiment because, on average, only 25% of the fryers within litters were furless due to a recessive gene. Only 1 furred fryer was randomly sampled on a within-litter basis. A total of 37 furless and 26 furred fryers contributed fiber data to this experiment.

In the first year of the study, 17 furred and 20 furless fryers (age = 28 to 49 d) were randomly assigned to growing-rabbit pens containing either 2 or 3 nonlittermate furless or furred rabbits. In the second year of the study, 9 furred and 17 furless rabbits were used. All rabbits were fed for 42 d with an ad libitum supply of a commercial ration (CP content >16%, DM basis, Nutrena Medicated Rabbit Pellets, S-OXY 10-GD; Cargill-Nutrena Feeds Division, Minneapolis, MN). Management was the same in both years.

Fiber Analysis

At the end of the 6-wk postweaning period, BW was recorded and a sample of fiber was removed from a measured, small area (~20 cm^2) on the left flank of the rabbit using an Oster A-5 clipper fitted with a No. 40

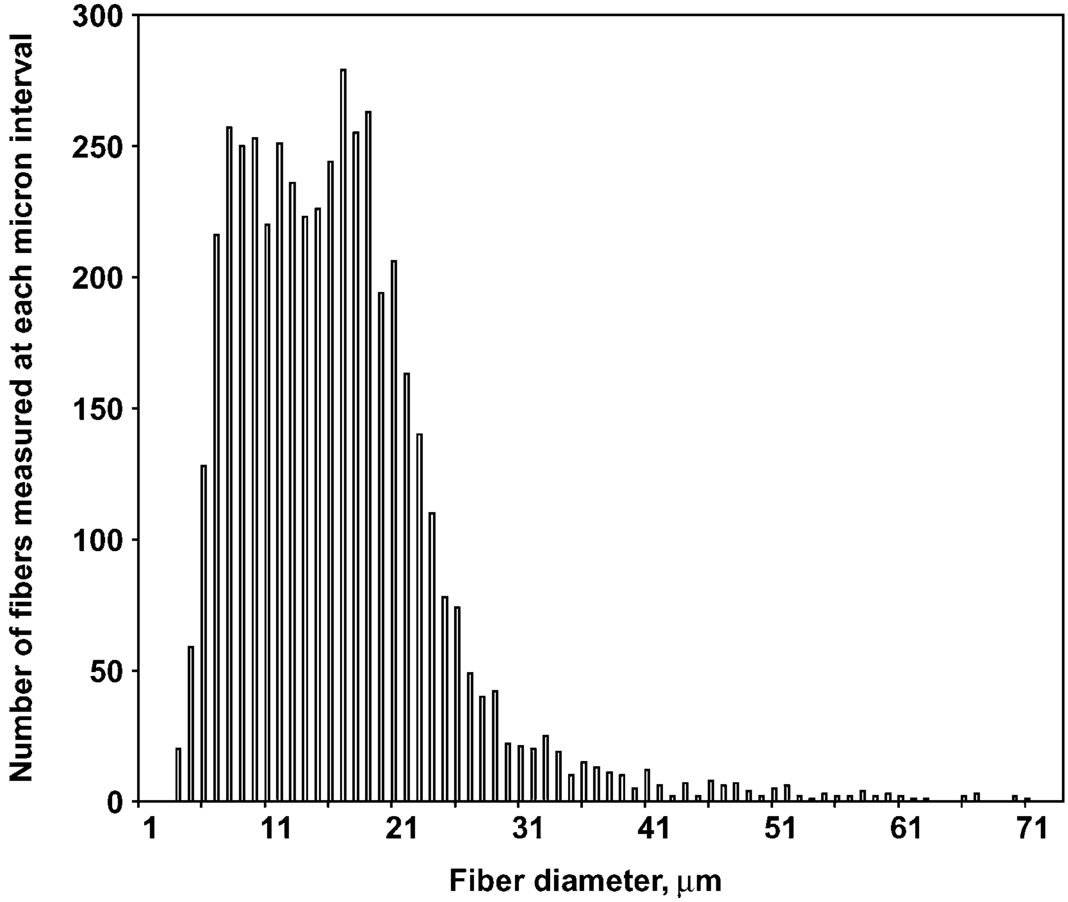

Figure 2. Frequency distribution of fiber diameter for "Fuzz," the furless grandsire of all of the rabbits in this study. The fiber sample was taken from the side of the rabbit at the cranial–caudal midpoint.

blade (leaving ~0.1 mm of fur on the skin). Each fiber sample was weighed (±0.0005 g) using an analytical balance. This permitted calculation of fiber production per unit area of skin (mg/cm^2) and an estimate of total fiber production (using rabbit BW in the calculation to estimate total body surface area; Jelenko et al., 1971). In yr 2, fiber samples from 7 furred rabbits were shorn from a small area on the left flank of the rabbit, and all 17 furless rabbits had their entire coats clipped to determine actual total fur weight. In addition, 2 furred rabbits were also sheared over their entire bodies so that total fur weight was also directly measured for this group. Based on values for estimated and actual fur weight, furless rabbits were then more objectively reclassified into classes 1, 2, or 3 that corresponded to values that were <1, 1 to 5, and 6 to 10 g of fur, respectively.

The average staple length of shorn rabbit fibers was determined using the methodology described in ASTM Test Method D1234 (ASTM, 2002a). This involved positioning the staples in a straightened but relaxed configuration on a flat board covered with black felt and measuring the length to the nearest 1 mm from tip to base using a ruler. Subsequently, the fibers were cut at random positions along the length of the staple with a guillotine designed to produce 2-mm snippets. The snippets were cleansed with solvents (1,1,1-trichloroethane, followed by boiling ethanol), dried in an oven for 1 h at 105°C, and conditioned for 12 h or more at 65% relative humidity and 21°C. Snippets were then distributed uniformly on a microscope slide and measured using an Optical Fiber Diameter Analyser 100 (BSC Electronics Pty., Ltd., Ardross, Australia; Baxter et al., 1992) using the technique described in ASTM Test Method D6500 (ASTM, 2001). Fiber characteristics measured by the optical fiber diameter analyzer included average fiber diameter, standard deviation (SD), and coefficient of variation (CV) of fiber diameter, prickle factor (% of fibers thicker than 30 μm), average fiber curvature, and SD and CV of fiber curvature.

The prickle factor measurement was originally devised to quantify the number of fibers >30 μm in width (i.e., those fibers capable of causing irritation to humans when worn next to the skin; Naylor et al., 1992). Also, 30 μm is used in cashmere metrology to distinguish between down (4 to 30 μm) and hair (>30 μm) fibers (ASTM, 2002b). Thus, in the present context, it may assist to distinguish between fine fur fibers produced in secondary follicles and relatively coarse guard hair produced in primary follicles. The average fiber curvature is a measure of the curvature in the 2-mm snippets and is related to fiber crimp or waviness. Typically,

Table 1. Least squares means (± SE) for BW and fiber characteristics of furred and genetically furless rabbits, including values from the original furless grandsire (Fuzz)[1]

Trait	Furred n = 26	Furless n = 37	Fuzz
BW, g	$1{,}783^b \pm 54$	$1{,}941^a \pm 50$	2.99
Weight of fiber per unit area,[2] mg/cm^2	$15.83^a \pm 0.9$	$1.74^b \pm 0.9$	<0.5
Staple length, cm	$2.56^a \pm 0.13$	$1.54^b \pm 0.12$	2.3
Average fiber diameter, μm	$14.5^b \pm 0.9$	$15.8^a \pm 0.8$	16.6
SD of fiber diameter, μm	$9.8^b \pm 0.9$	$13.3^a \pm 0.8$	8.4
CV of fiber diameter, %	$66.8^b \pm 3.0$	$84.8^a \pm 2.7$	50.6
Prickle factor, %	$3.5^b \pm 1.5$	$11.3^a \pm 1.4$	5.7
Average fiber curvature, deg/mm	$38.5^b \pm 2.0$	$47.5^a \pm 1.8$	38.7
SD of fiber curvature, deg/mm	$35.4^b \pm 1.7$	$45.0^a \pm 1.5$	43.0
CV of fiber curvature, %	92.2 ± 2.6	95.9 ± 2.5	111.1

[a,b]Means in the same row for furred and furless columns (excluding the Fuzz data) not sharing a common superscript letter differ, $P < 0.01$.
[1]Measurements taken at maturity.
[2]Results from yr 1 data only, involving 17 and 20 furred and furless rabbits, respectively.

guard hairs have little or no crimp (therefore, low curvature values), whereas down fibers have greater but variable amounts of crimp.

Statistical Procedures

For the fiber experiment, the data were taken as a subset of data from a larger fryer growth experiment (Jackson et al., 2006). A mixed model consisted of a fixed treatment source of furless and furred genetic classes. Data were blocked for the fixed, combined environmental effect of year-batch and the random litter source (nested within age-batch). Residual error was based on the pooled, within-litter variation. In preliminary analyses of fur traits, additional fixed effects of sex and all first- and second-order interactions, the random pen-within-treatment effect, and the linear covariate of initial age, were never important ($P > 0.05$), and therefore were eliminated from the final model. Data were subjected to ANOVA procedures employing a mixed-model program (Harvey, 1990). A second analysis was performed using the same mixed model but with the furless class subdivided into the 3 aforementioned subclasses. Lastly, linear contrast comparisons, adjusted for model effects, were made to test ($P < 0.05$) possible differences among means for BW and all fiber characteristics studied between furless and furred groups. From the same analyses, residual correlations among BW and fur characteristics were obtained, but were computed separately from data on furless and furred rabbits.

RESULTS AND DISCUSSION

Background

In general, the rabbit's coat consists of 2 main types of fiber, relatively coarse guard hairs and fine fur (undercoat) fibers (Von Bergen, 1963). The guard hairs are composed of 3 regions: the relatively fine shaft or proximal portion closest to the skin; the distal portion that is much wider, flatter and shield-like in appearance; which then tapers down to a very fine point. The guard hairs vary considerably in thickness and length but are generally longer than the fur fibers and thus project above the undercoat. Medullation in fur and guard hair appears ladderlike in projection microscope images (500×). The lower portion of guard hairs, fur fibers, and part of the guard hair tip contain a single medulla composed of a longitudinal series of cavities. Where the guard hairs coarsen and become shield-like, multiple series of cavities (2 to 6) make up the medulla. Only some of the very fine fur fibers (<8 μm) and the tips of the guard hair are solid protein. This medulla arrangement is very characteristic of rabbit fibers. In this study, samples of fibers shorn from the animal were subsampled at numerous random points along the staple length. No attempt was made to distinguish or separate fur fibers from guard hair. Thus, the information presented in the histograms (Figures 2 and 3) represents a random sample of fibers from the flank of the animals.

The fibrous body covering produced by the furless grandsire ("Fuzz") of all the rabbits in this study consisted of relatively small quantities of both guard hair and fur ranging in color from white to fawn to brown. The fiber diameter distribution for this animal is shown in Figure 2 (data in Table 1). For contrast, a histogram of the fiber from a typical furred animal is shown in Figure 3 (data in Table 1). The small amount of fiber produced by Fuzz was shorter, coarser, less variable in fiber diameter, and contained a greater percentage of fibers >30 μm, and a similar amount of crimp compared with fibers produced by furred rabbits of the F_2 generation. In contrast, the mature Fuzz (presumably a class 2 rabbit) produced less fiber per unit area than the younger F_2 furless rabbits (age approximately 10 wk) whose hair was shorter, finer, more variable in fiber diameter, and greater in prickle factor and curvature than that of their ancestor.

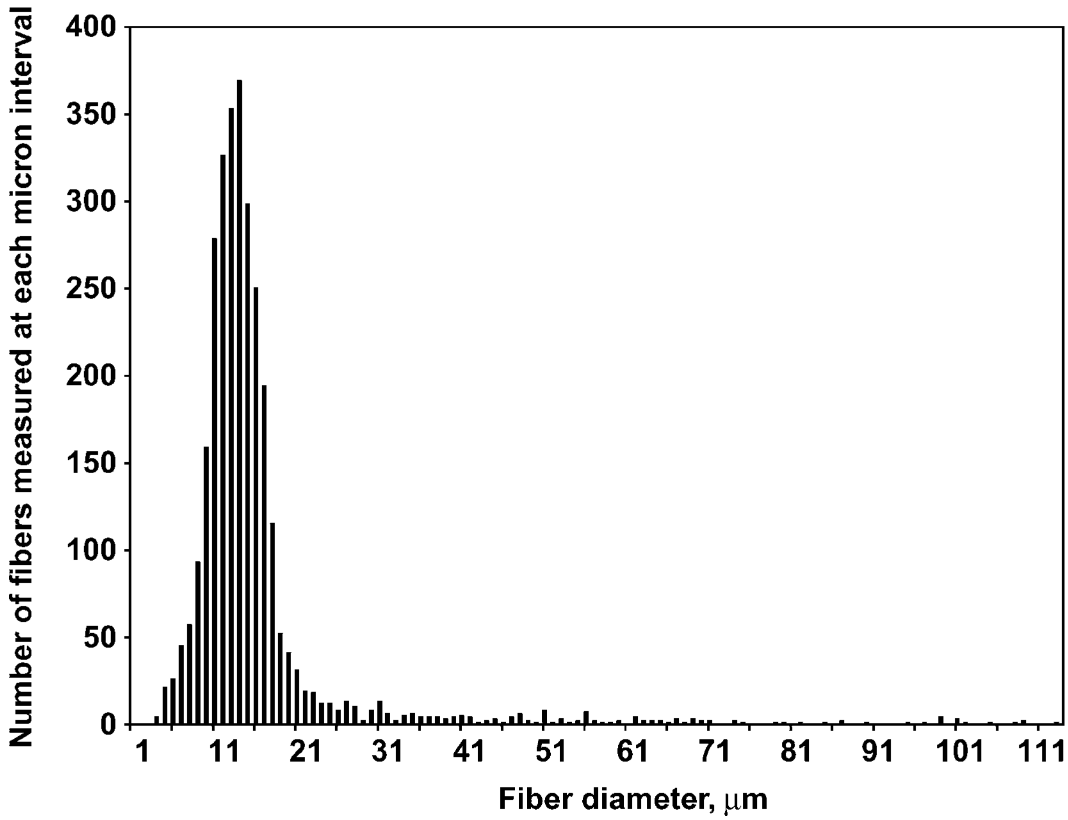

Figure 3. Frequency distribution of fiber diameter for a typical furred rabbit. The fiber sample was taken from the side of the rabbit at the cranial–caudal midpoint.

Statistical Properties and Comparisons for BW and Fiber Characteristics

As a group, at the end of the 42-d growth performance studies, furless rabbits were 9% heavier (1,941 vs. 1,783 g; $P < 0.01$) than normally furred rabbits (Table 1). One explanation is that less fur production leaves more nutrients available for growth. In addition, Jackson et al. (2006) reported that furless rabbits had lower core body temperatures and respiratory rates than furred rabbits and that these values were associated with greater feed intake. Contrary to these results, in an earlier report on rare furless rabbits, Kislovsky (1928) observed that BW of furless kits were generally lower than furred littermates at d 29 of age, and their description more closely matched our class 1 rabbits. In addition, Kislovsky (1928) reported that all furless kits died by 1 mo of age. However, the time of year in which these observations were made was not mentioned in this report from Russia. It is possible that this was not the same genetic mutation as in our population.

Fiber grown per unit area of skin by furless rabbits was 11% of that grown by normally furred rabbits (1.74 vs. 15.83 mg/cm^2; $P < 0.01$). The average staple length of fibers grown by furred rabbits was longer (2.56 vs. 1.54 cm; $P < 0.01$) and the average fiber diameter was finer (14.5 vs. 15.8 µm; $P < 0.01$) than those produced by furless rabbits. The proportion of guard hairs to fine fur in Fuzz' F_2 grand-progeny was much greater in furless than in furred rabbits, as indicated by the prickle factor (i.e., % of fibers >30 µm: 11.3% for furless, 3.5% for furred rabbits). Thirty microns is considered to be a reasonable cut-off between fur and hair populations, based on Figure 2 and the work of Boucher et al. (1996). Variability of fiber diameter (SD and CV), prickle factor, average fiber curvature and variability (SD) of curvature were all lower ($P < 0.05$) in furred vs. furless rabbits. Thus, all but the curvature results led to the conclusion that the fibers of the furless rabbits are composed of a greater ratio of coarse guard hair to fine fur fibers than that of the furred rabbits. This being the case, the curvature data indicate that the fine down of furless rabbits must contain more crimp than down fibers in their furred contemporaries.

Table 2 contains least squares means (and SE) for BW and fiber characteristics for furred and 3 classes of genetically furless rabbits. Although furless rabbits as a group were heavier than furred rabbits (Table 2), class 3 rabbits had greater BW than classes 1 and 2. Because the rabbits were raised on wire floors, a plausible explanation is that, assuming that furless class 3 rabbits had more fur on the footpads, more frequent feeding activity may have positively affected BW compared with class 1 and 2 furless rabbits. However, because furless rabbits were not sorted into pens by class, it was not possible to test this hypothesis. Having the

Table 2. Least squares means (±SE) for BW and fiber characteristics of furred and classes of genetically furless rabbits

	Class[1] (n)			
Trait	0 (26)	1 (11)	2 (17)	3 (9)
BW, g	1,772 ± 60	1,817[b] ± 82	1,981[b] ± 69	2,075[a] ± 93
Weight of fiber per unit area,[2] mg/cm^2	15.6 ± 1.1	0.4 ± 1.8	1.4 ± 1.6	6.2 ± 2.6
Staple length, cm	2.5 ± 0.1	1.0[b] ± 0.2	1.8[a] ± 0.1	2.1[a] ± 0.2
Average fiber diameter, μm	14.4 ± 1.0	16.3 ± 1.5	15.1 ± 1.2	16.3 ± 1.7
SD of fiber diameter, μm	9.7 ± 1.0	12.8 ± 1.5	13.6 ± 1.2	13.4 ± 1.8
CV of fiber diameter, %	66.3 ± 3.3	78.6 ± 5.1	90.6 ± 4.1	81.2 ± 6.0
Prickle factor, %	3.5 ± 1.7	13.1 ± 2.5	10.1 ± 2.0	10.3 ± 3.0
Average fiber curvature, deg/mm	38.5 ± 2.2	44.8 ± 3.4	50.0 ± 2.7	47.4 ± 4.0
SD of fiber curvature, deg/mm	35.5 ± 1.9	45.1 ± 2.9	46.3 ± 2.3	41.6 ± 3.4
CV of fiber curvature, %	92.6 ± 2.5	103.7[a] ± 3.7	92.6[b] ± 3.0	88.7[b] ± 4.2

[a,b]Means in the same row for furless columns (classes 1, 2, and 3) not sharing a common superscript letter differ ($P < 0.05$). Statistical comparisons between furred and furless rabbits are presented in Table 1. In this table, means for furred and classes of furless rabbits were obtained from the same analysis.

[1]Fur classes: 0 = furred rabbit; furless classes 1 = <1 g; 2 = 1 to 5 g; and 3 = >5 g in actual or estimated total fur weight.

[2]Results from yr 1 data only, involving 17, 8, 7, and 5 furred and class 1, 2, and 3 furless rabbits, respectively.

least amount of fiber, class 1 rabbits also had the shortest fiber and were the most variable in terms of fiber curvature CV. Other fiber traits did not differ among classes of furless rabbits despite numerical differences. It is also important to note that all 3 classes of furless rabbits exhibited fine fur and coarse guard hairs unlike those described by J. Hammond (Cambridge Univ., UK), in his notes to Castle (1933), that appeared to grow only long guard hairs all over their bodies. In a detailed histological study of these rabbits, Drapeau (1933) showed that the external absence of under hair was due to a failure of these fibers to erupt from their follicles, a result of premature keratinization that affected the sebaceous glands and the inner epithelial sheath. Interestingly, the fine fur fibers were growing into the surrounding connective tissue where they subsequently atrophied.

Total Estimated and Actual Fur Weights

Estimated and actual mean shorn fur weights from yr 1 and 2, respectively, are summarized by fur class in Table 3. Generally, good agreement was present between the means of the estimated (yr 1) and actual (yr 2) values, although it was not appropriate to statistically compare estimated vs. actual fur weight means. For the furred rabbits, actual fur weight was less than the estimated mean value. For the furless classes of rabbits, estimated and actual mean values were of similar magnitude. As expected, for both estimated and actual fur weight means, furred rabbits had substantially more total fur than furless rabbits ($P < 0.01$). Estimated fur weight means were comparable for class 1 and 2 rabbits, whereas only class 1 differed from class 3 rabbits. For actual mean fur weight, both class 1 and 2 rabbits were similar, but both differed from class 3 rabbits ($P < 0.01$). In addition, the estimated range in fur weights (11.9 to 38.8 g) was greater than actual values (16.8 to 26.1 g) for furred rabbits. Conversely, the estimated range for class 3 furless rabbits (5.79 to 9.40 g) was somewhat smaller than the actual range (6.98 to 11.87 g). Nevertheless, the formula used to estimate body surface area (Jelenko et al., 1971), and hence estimated fur weight, appears to reasonably correspond to actual fur weight values for furred and furless rabbits. In retrospect, a useful study would be to take a similar small fur sample (as in yr 1), but followed by an entire shearing of the body coat of the same animals, to determine the reliability of predicting total fur weight based on measurement of a small sample.

Correlations Among BW and Fiber Characteristics

Furred Rabbits. The significant correlation between BW and staple length was negative for furred rabbits (Table 4). Presumably, a preponderance of shorter fibers reduces heat stress, which indirectly increases growth rate. The magnitude of this correlation was greater than, but in the same direction as, that reported by Allain et al. (1996) for Angora rabbit does and Lupton et al. (1990) for Angora goats. In contrast, the BW vs. staple length correlation for Rambouillet sheep was close to zero (Lupton et al., 2003). Other significant correlations included the positive relationships between average fiber diameter and the 2 measures of fiber diameter variability (SD and CV) and prickle factor and the negative correlation with average fiber curvature. Other strong, positive correlations occurred between the SD and CV of fiber diameter and prickle factor and a lower but significant correlation with coefficient of variation of fiber curvature. These correlations (with the exception of average fiber diameter vs. average fiber curvature) were similar to those reported for sheep (Lupton et al., 2003) and Angora goats (Pfeiffer

Table 3. Statistical properties of estimated (actual) total fur weight (g) in normal furred and genetically furless rabbits from yr 1 of the experiment[1]

			Furless[2]					
Item	Furred		Class 1		Class 2		Class 3	
n	17	(2)	8	(3)	7	(10)	5	(4)
Mean fur weight, g	26.0[c]	(23.0[c])	0.27[a]	(0.64[a])	2.67[ab]	(2.07[a])	8.20[b]	(8.68[b])
SEM	±1.42	(±1.48)	±2.03	(±1.30)	±2.17	(±0.94)	±2.74	(±1.17)
SD	8.22	(6.60)	0.19	(0.15)	0.96	(1.09)	1.75	(2.21)
CV, %	31.4	(30.8)	83.2	(70.5)	33.8	(38.4)	22.1	(25.0)
Minimum fur weight, g	11.9	(16.8)	0.08	(0.06)	1.26	(1.72)	5.79	(6.98)
Maximum fur weight, g	38.8	(26.1)	0.69	(0.35)	4.33	(4.85)	9.40	(11.87)

[a–c]Least squares means, compared separately for estimated and actual fur weight, in the same row not sharing a common letter in their superscripts differ ($P < 0.01$).

[1]Total fur weight was estimated from yr 1 data, based on fur density (mg/cm^2) from a small sample taken on the body coat (approximately 20 cm^2), multiplied by estimated total body surface area in cm^2 = $(0.0014W + 8.6104)W^{0.667}$, where W represents BW in g; Jelenko et al. (1971).

[2]Classes 1, 2, and 3 of furless rabbits consisted of <1, 1 to 5, and >5 g in estimated or actual total fur weight, respectively.

et al., 2004). Finally, there was a strong positive correlation (r = 0.90) between weight of fiber per unit area and total fur weight, as has also been reported for sheep (Ponzoni and Fenton, 2000). However, in our experiment, this high correlation may reflect a part-whole relationship because weight of fiber per unit area was used to estimate total fur weight values before statistical analyses.

Furless Rabbits. The correlation between BW and staple length was significant and positive for furless rabbits, the opposite of that for furred rabbits. There appears to be a relationship unique to furless rabbits. Interestingly, all of the correlations between BW and fiber diameter related traits were in the opposite direction to those observed for furred rabbits. A strong and positive correlation was present between BW and average fiber curvature indicating that the heavier furless rabbits were associated with a greater proportion of down fiber compared with guard hair (because curvature of guard hair is very low). The prevalence of finer fibers may have protected the rabbit from extremes in ambient temperature, thereby lessening the depression of feed intake. The nature of these correlations warrants further research.

More of the correlations shown in Table 4 were significant for furless rabbits than for furred rabbits. Significant correlations that were similar in magnitude and direction for both types of rabbit included: average fiber diameter vs. SD of fiber diameter (+), prickle factor (+), and average fiber curvature (–); SD of fiber diameter vs. prickle factor (+) and CV of fiber curvature (+); average fiber curvature vs. SD of fiber curvature (+); and fiber density vs. total fur weight (+). With the exceptions of average fiber diameter vs. average fiber curvature and SD of fiber diameter vs. CV of fiber curvature, these correlations were generally greater than, but in the

Table 4. Correlations between traits for furred (above diagonal) and genetically furless (below diagonal) rabbits[1]

Trait[2]	BW	SL	AFD	SDFD	CVFD	PF	AFC	SDFC	CVFC	WFPUA	FURWT
BW	—	−0.60[3]	0.23	0.25	0.27	0.20	−0.11	0.15	0.40	−0.24	0.19
SL	0.56	—	−0.08	−0.23	−0.28	−0.19	−0.11	−0.29	−0.25	0.46	0.19
AFD	−0.42	−0.23	—	0.92	0.80	0.94	−0.60	−0.34	0.51	−0.22	−0.18
SDFD	−0.48	−0.21	0.95	—	0.97	0.98	−0.44	−0.17	0.54	−0.13	−0.06
CVFD	−0.04	0.26	−0.39	−0.10	—	0.93	−0.38	−0.11	0.53	−0.01	0.08
PF	−0.43	−0.25	0.99	0.98	−0.27	—	−0.44	−0.17	0.53	−0.19	−0.15
AFC	0.80	0.26	−0.58	−0.72	−0.28	−0.63	—	0.86	−0.13	−0.30	−0.32
SDFC	0.77	0.07	−0.48	−0.63	−0.35	−0.52	0.97	—	0.38	−0.42	−0.34
CVFC	−0.21	−0.66	0.66	0.66	−0.22	0.71	−0.35	−0.11	—	−0.26	−0.11
WFPUA	−0.36	−0.06	0.66	0.62	−0.27	0.63	−0.19	−0.20	0.19	—	0.90
FURWT	−0.25	−0.03	0.53	0.49	−0.24	0.50	−0.03	−0.05	0.12	0.98	—

[1]Data from yr 1 only.

[2]BW = BW, kg; SL = average staple length, cm; AFD = average fiber diameter, μm; SDFD = SD of fiber diameter, μm; CVFD = CV of fiber diameter, %; PF = prickle factor, %; AFC = average fiber curvature, deg/mm; SDFC = SD of fiber curvature, deg/mm; CVFC = CV of fiber curvature, %; WFPUA = weight of fiber per unit area, mg/cm^2; and FURWT = total fur weight per animal, g.

[3]Correlations larger than ±0.53 and ±0.66 are significantly different from zero at $P < 0.05$ and $P < 0.01$, respectively.

same direction as, those reported for fine-wool sheep (Lupton et al., 2003). In fact, the 2 correlations involving fiber curvature are significant and positive for the sheep population as a whole but have declined in recent years for fine-wool sheep (~18 to 25 μm range) because breeders have increasingly selected these animals for greater wool production. In many cases, that selection has resulted in fibers containing less crimp. Correlations that were significant for furless rabbits only included (sign given in brackets when the direction was not the same for furred rabbits): BW vs. average fiber curvature [+] and SD of fiber curvature (+); staple length vs. CV of fiber curvature (–); average fiber diameter vs. CV of fiber curvature (+) and fiber density [+]; SD of fiber diameter vs. average fiber curvature (–), SD of fiber curvature (–), and fiber density [+]; and prickle factor vs. average fiber curvature (–), CV of fiber curvature (+), and fiber density [+]. Interestingly, only the last of these correlations is significant for fine-wool sheep (Lupton et al., 2003).

Conclusions

Statistical properties and comparison of several fiber characteristics (staple length, fineness, prickle factor, and curvature) and fiber production (per unit area of skin and per animal) generally show that, besides the lower fur weight per unit area, the overall shorter coat of furless rabbits is composed of a greater ratio of coarse guard hair to fine fur fibers than that of furred rabbits. These fiber properties may, at least partially, account for the lower core body temperatures and respiratory rates (recorded at 1400 during the hot summers of south Texas from 2002 to 2004) of furless compared with furred rabbits and, because of less physiological stress, could indirectly account for the greater feed intake and heavier BW, respectively, as documented by Jackson et al. (2006). However, these results were obtained from an F_2 generation in which linkage disequilibrium could be very high (i.e., the furless gene may have been linked to other genes from the founder sire, Fuzz, and the furred gene may have been linked to other genes from founder New Zealand White does). If true, several generations would be required to gradually mitigate such linkage associations. Hence, it would be useful to later repeat this experiment to confirm the present encouraging results.

Of relevance, rabbits evolved and soon propagated in areas around the Mediterranean, where a coat of body fur provided insulation that supported the practice of aboveground, nocturnal feeding when exposed to cold temperatures, whereas the instinctive behavior of burrowing allowed rabbits to escape from hot daytime temperatures. The conventional rearing of domesticated rabbits in hutches makes them vulnerable to heat stroke even when shade is provided. Moreover, fur from fryer rabbits is of negligible commercial value. These fur quality characteristics of furless rabbits are preliminary yet encouraging and are an important aspect of adaptation to arid and tropical regions where rabbit development projects have a great potential to alleviate human hunger and poverty.

IMPLICATIONS

Perhaps the greatest potential of the domesticated rabbit is as a source of food and income for impoverished farm families throughout the developing world. One major constraint, however, is that the body coat of fur contributes to the species' vulnerability to heat stroke and decreased fertility and growth that can occur when reared in arid and tropical environments. This study examined and compared fiber characteristics of genetically furred and rare furless rabbits. Coats of furless rabbits are composed of shorter fibers having a greater ratio of coarse guard hairs to fine fur fibers compared with their furred contemporaries. Furless rabbits produced about 90% less fiber per unit area of skin than furred rabbits. These results, along with those from a series of experiments that have demonstrated less heat stress and greater feed intake and growth rates in furless rabbits, hold promise for the suitability of furless rabbits for meat production in arid and tropical environments.

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