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# Divergent selection for total fleece weight in Angora rabbits: Correlated responses in wool characteristics

S.A. Rafat [a,b], H. de Rochambeau [a], R.G. Thébault [c], I. David [a], S. Deretz [c], M. Bonnet [c], B. Pena-Arnaud [a], D. Allain [a,*]

[a] INRA UR631, Amélioration Génétique des Animaux, BP 52627, 31326, Castanet Tolosan, France
[b] Department of Animal Science, Faculty of Agriculture, University of Tabriz, 51666, Tabriz, Iran
[c] INRA UE967, Génétique Expérimentale en productions Animales, Phanères, Le Magneraud, BP 52, 17700 Surgères, France

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**Abstract**

An experiment was carried out to study direct and indirect responses to selection in the Angora rabbit. There were two selection lines, one selected for high fleece weight and the other for low fleece weight. Data from 669 female rabbits born in 1994–2001 and having produced a total of 2923 harvest of wool were analysed to quantify the correlated responses to selection. By 2001, there had been eight cohorts of selection. The correlated responses analysed included compression, resilience, fleece quality traits (bristle and down length, average fibre diameter, comfort factor, bristle diameter) and secondary to primary follicle ratio (*S*/*P*). Genetic correlations were obtained by restricted maximum likelihood techniques. In response to selection, a positive difference of 0.92, 0.21 and 0.55 genetic standard deviation were observed for bristle length, comfort factor and *S*/*P*, respectively. No correlated response was observed on down length while negative differences of 1.00, 1.31, 0.38 and 0.50 genetic standard deviations were observed for compression, resilience, bristle diameter and average fibre diameter, respectively. Selection for increasing total fleece weight results in an increase of qualitative component traits of wool production in the French Angora rabbit. The quantitative traits were examined in the first (published) part of the paper.


*Keywords:* Angora rabbit; Bristle; Divergent selection; Down; Fibre diameter; Follicle; Wool

## 1. Introduction

Angora rabbit fibre is categorised in the luxurious especially fine animal fibre group along with mohair, cashmere and alpaca. After wool and mohair, Angora fibre production is the third largest fibre industry in the world. Angora rabbit production in France was estimated to be approximately 2000–3000 rabbits with an annual production of 2 tonnes of fibre in 2005 (personal communications with the Union of French Angora Rabbit Breeders).

Selection for total fleece weight was successful in sheep (Wuliji et al., 2001; Bray et al., 2005), in goat (Merchant and Riach, 2003; Bai et al., 2006) and in French Angora rabbit (Rafat et al., 2007). It is unclear, however, whether a higher fleece weight is associated with an increase in other fleece characteristics (length, diameter, compression and secondary to primary follicle ratio) of Angora rabbits. In sheep, Morris et al. (1996) found an unfavourable

* Corresponding author. Tel.: +33 561285171; fax: +33 561285353.
*E-mail address:* daniel.allain@toulouse.inra.fr (D. Allain).

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correlated response in mean fibre diameter when selecting for high fleece weight. In a companion paper, Rafat et al. (2007) presented results of a divergent selection experiment on total fleece weight in French Angora rabbits. The first results indicated that an important direct response on total fleece weight was obtained on the two divergent lines. A divergence of three genetic standard deviations on both total fleece weight and weight of the bristly wool was observed between the high and low lines after 8 years of selection. An increase in live body weight was also obtained by selection for total fleece weight. The objective of this paper was to evaluate the correlated responses to selection for fleece characteristics.

## 2. Materials and methods

### 2.1. Animals

The animals came from a divergent selection experiment on total fleece weight described by Rafat et al. (2007). Studies were made on the wool production of 669 female Angora rabbits born between 1994 and 2001 under a divergent selection program to assess direct and correlated responses. There were 3567 animals in the pedigree file. The aim of the selection experiment was to obtain two divergent lines for total fleece weight. The selection criterion was the total fleece weight of the does measured for the third and later harvests. The selection method was based on a BLUP procedure using a repeatability animal model. The management, reproduction and housing conditions of these animals have been previously described (Allain et al., 1999; Rafat et al., 2007).

### 2.2. Traits

The rabbits were plucked for the first and second times at the ages of 8 and 21 weeks, respectively. Thereafter they were plucked at regular intervals every 14 weeks until the 12th harvest. The data of the 3rd to 12th harvests for each cohort were utilised in this study. At each harvest, total fleece weight (TFW) was recorded. The live body weight (9LW) was measured 9 weeks before each harvest. At the fifth and seventh harvests from cohorts of 1994 to 2000, and at the 3rd to 12th harvests from the last cohort born in 2001, the following variables were recorded: compression, resilience, the length of bristles (BL) and downs (DL) measured on locks taken from the haunch. The first two measurements were used to judge the quality of the fibre (Allain et al., 1999). Compression and resilience were measured according to the method of de Rochambeau et al. (1991).

On animals born in 2001 and issued from the last selected cohort, additional biological samples were made at the fifth and the seventh harvests (Table 1). Two wool samples were taken from the haunch. The first sample including all kinds of fibre was obtained to determine average fibre diameter (AFD) and comfort factor (CF, percentage of fibres ≤30 μm) according to the Optical Fibre Diameter Analyser (OFDA) methodology (IWTO-47, 1995). The second sample was obtained by extracting bristles by hand from a total lock in order to determine bristle diameter (BD) according to the cross section methodology (Allain and Thébault, 1996). Skin samples were taken from the back by biopsy 5 weeks after the fourth and the sixth harvest to determine the primary to secondary hair follicle ratio within the hair follicle group. Details of the methodology of skin histology and $S/P$ ratio measurement are described by Rougeot and Thébault (1983). Because of the shrinkage of skin specimens during histological procedures, there is a strong case for using the relative density of primary and secondary follicles expressed by the $S/P$ ratio to overcome the difficulties of making an accurate estimate of total population of wool follicles (Abouheif et al., 1984).

### 2.3. Statistical analysis

#### 2.3.1. Testing of fixed effects

The least squares method of the GLM procedure (SAS, 2001) was utilised to determine the significance of the fixed effects and covariate. TFW was analysed with a model that initially included year and season of birth, harvest season, harvest number and reproduction as fixed effects and 9LW such as a covariate. BL, DL, compression and resilience were analysed with the same

Table 1
Number of records ($N$), means and standard deviation (SD) of the means for the studied traits

| Trait | Unit | $N$ | Means | SD |
|---|---|---|---|---|
| Total fleece weight [a] | g | 2923 | 213.27 | 56.60 |
| Bristle length [b] | mm | 1171 | 101.93 | 9.41 |
| Down length [b] | mm | 1170 | 67.04 | 8.78 |
| Compression [b] | mm | 1165 | 26.52 | 2.64 |
| Resilience [b] | mm | 1165 | 60.08 | 5.33 |
| Bristle diameter [c] | μm | 149 | 46.41 | 3.45 |
| Average fibre diameter [c] | μm | 157 | 14.91 | 0.94 |
| Comfort factor [c] | % | 157 | 97.85 | 0.83 |
| Secondary to primary follicle ratio [c] | – | 102 | 48.18 | 10.32 |
| Live weight before wool harvest [a] | g | 2923 | 3802.1 | 473.99 |

[a] This trait was measured at all fleece harvests of all cohorts.
[b] This trait was measured at all harvests of the last cohort, and fifth and seventh harvests from previous cohorts.
[c] This trait was measured at the fifth and seventh harvests of the last cohort.

Table 2
Significance levels of fixed effects for the studied traits[a]

| Traits | Fixed effects | | | | | Covariate |
|---|---|---|---|---|---|---|
| | Year | Harvest number | Birth season | Harvest season | Reproduction | 9LW |
| TFW | *** | *** | *** | *** | *** | *** |
| BL | *** | * | * | ** | ns | |
| DL | *** | *** | ** | ** | ns | |
| Compression | *** | ** | ns | *** | ns | |
| Resilience | *** | ** | ns | ** | ns | |
| BD | | | | * | | |
| AFD | | | | * | | |
| CF | | | | * | | |
| *S/P* | | | | * | | |

[a] TFW: total fleece weight; BL: bristle length; DL: down length; BD: bristle diameter; AFD: average fibre diameter; CF: comfort factor; *S/P*: secondary to primary follicle ratio; 9LW: live weight at age of 9 weeks before wool harvest.
*** $P<0.001$; ** $P<0.01$; * $P<0.05$; ns: non-significant.

model without the covariate. BD, AFD, CF and *S/P* were analysed with a model including the harvest season effect (Table 2).

### 2.3.2. Estimation of genetic parameters and breeding values

The estimates of variance components for different variables were obtained by using VCE, a multivariate restricted maximum likelihood (REML) variance component estimation program with an animal model (Groeneveld, 1998). Genetic parameters were estimated according to a multivariate analysis including the nine traits studied: TFW, BL, DL, compression, resilience, BD, AFD, CF and S/P. The following multivariate linear mixed model was used:

$$\mathbf{y}_i = \mathbf{X}_i\mathbf{b}_i + \mathbf{Z}_i\mathbf{a}_i + \mathbf{W}_i\mathbf{p}_i + \mathbf{e}_i$$

where

$\mathbf{y}_i$ ($\mathbf{K}_i$) is a vector of $\mathbf{K}_i$ observations collected for the *i*th trait,

$\mathbf{b}_i$ ($\mathbf{f}_i$) is a vector of fixed environmental effects for the *i*th trait consisting of:

- a covariate effect of 9LW on TFW,
- year effect (8 levels; from 1994 to 2001) on TFW, BL, DL, compression and resilience,
- harvest number effect (10 levels; from the 3rd to the 12th harvest) on TFW, BL, DL, compression and resilience,
- birth season effect (4 levels) on TFW, BL and DL,
- harvest season effect (4 levels),
- reproduction effect (three levels: females which had litters and females which had been inseminated or not) on TFW.

$\mathbf{a}_i$ ($N$) is a vector of direct genetic effect for the *i*th trait; $N$ is the total number of animals in the pedigree,

$\mathbf{p}_i$ ($N_i$) is a random vector of permanent environment to all observations from a given animal for the *i*th trait; $N_i$ is the number of animals measured for the *i*th trait,

$\mathbf{e}_i$ ($\mathbf{K}_i$) is a random vector of residual for the *i*th trait.

$\mathbf{X}_i$, $\mathbf{Z}_i$ and $\mathbf{W}_i$ are known design matrices.

Table 3
Heritability (bold) and genetic correlations ± standard deviations from multiple-trait analysis for the studied traits[a]

| | TFW | BL | DL | Compression | Resilience | BD | AFD | CF | *S/P* |
|---|---|---|---|---|---|---|---|---|---|
| TFW | **0.35±0.03** | 0.37±0.07 | 0.20±0.08 | 0.05±0.08 | −0.07±0.08 | 0.16±0.06 | 0.02±0.07 | 0.12±0.09 | 0.04±0.10 |
| BL | | **0.15±0.02** | 0.75±0.09 | −0.15±0.10 | −0.04±0.12 | 0.55±0.09 | 0.04±0.13 | 0.34±0.14 | 0.07±0.16 |
| DL | | | **0.06±0.02** | 0.12±0.12 | 0.30±0.14 | 0.80±0.09 | 0.39±0.19 | −0.12±0.17 | −0.46±0.19 |
| Compression | | | | **0.10±0.02** | 0.84±0.06 | 0.39±0.09 | −0.10±0.13 | 0.38±0.14 | 0.14±0.16 |
| Resilience | | | | | **0.08±0.02** | 0.72±0.09 | −0.13±0.15 | 0.17±0.17 | 0.05±0.18 |
| BD | | | | | | **0.39±0.05** | 0.07±0.12 | 0.01±0.17 | −0.18±0.15 |
| AFD | | | | | | | **0.32±0.08** | −0.63±0.12 | −0.88±0.11 |
| CF | | | | | | | | **0.15±0.05** | 0.86±0.11 |
| *S/P* | | | | | | | | | **0.17±0.06** |

[a]TFW: total fleece weight; BL: bristle length; DL: down length; BD: bristle diameter; AFD: average fibre diameter; CF: comfort factor; *S/P*: secondary to primary follicle ratio.

Breeding values for all the traits were obtained as solutions from the best linear unbiased prediction analysis of the last covariance matrices at convergence. Then the means of the estimated breeding value (EBV) for all traits were calculated per cohort of animals born the same year and per divergent selected line.

## 3. Results and discussion

### 3.1. Genetic parameter estimates

Table 3 shows the heritability estimates of, and genetic correlations between total fleece weight and wool characteristics. Heritability estimates for BL, DL, compression and resilience were smaller than those reported earlier in Angora rabbits (Allain et al., 1996a). Genetic correlations between the total fleece weight and both bristle and down length were low to moderate and positive. The genetic correlation between bristle and down length was high and positive. Heritability estimates for BL, DL, compression and resilience were low to moderate, ranging from 0.06 to 0.15. All these results were in agreement with earlier observations (Allain et al., 1996b). In cashmere goats, Bai et al. (2006) reported a significant positive correlation between fleece weight and fibre length.

High and positive genetic correlations were observed between compression and resilience. These two important fleece characteristics are used to determine fleece bristlyness. Bristly fleeces from Angora rabbits are valued because of their ability to produce a fluffy yarn used for certain luxury knit products. Bristly fleeces compress more and relax less than woolly ones (de Rochambeau et al., 1991).

Heritability estimates for BD, AFD, CF and *S*/*P* were moderate to high. The heritability of *S*/*P* in the present study was low compared to estimates by Abouheif et al. (1984) in sheep and Ma et al. (2005) in cashmere goats, but in agreement with the lower value of the estimate by Mortimer (1987) in Merino sheep. The high and positive genetic correlation of CF with *S*/*P* and the high and negative genetic correlation between AFD and S/P suggest the possibility of using either AFD or CF instead of *S*/*P*. Measurement of AFD and CF by OFDA methodology is rapid, easier and less expensive than the measurement of the *S*/*P* ratio from a skin sample after a histological treatment. Up to now, there are no literature available describing genetic parameters of fibre diameter and hair follicle density in Angora rabbits.

### 3.2. Genetic correlated responses on other fleece traits

The means of breeding value estimates per year of birth are plotted in Fig. 1 for BL, DL, compression and resilience. Response on total fleece weight and correlated responses on other fibre traits observed on the 2001 animal cohort. In response to the divergent selection experiment on total fleece weight, positive differences of 0.92, 0.21 and 0.55 genetic standard deviations were observed for bristle length, comfort factor and *S*/*P*,

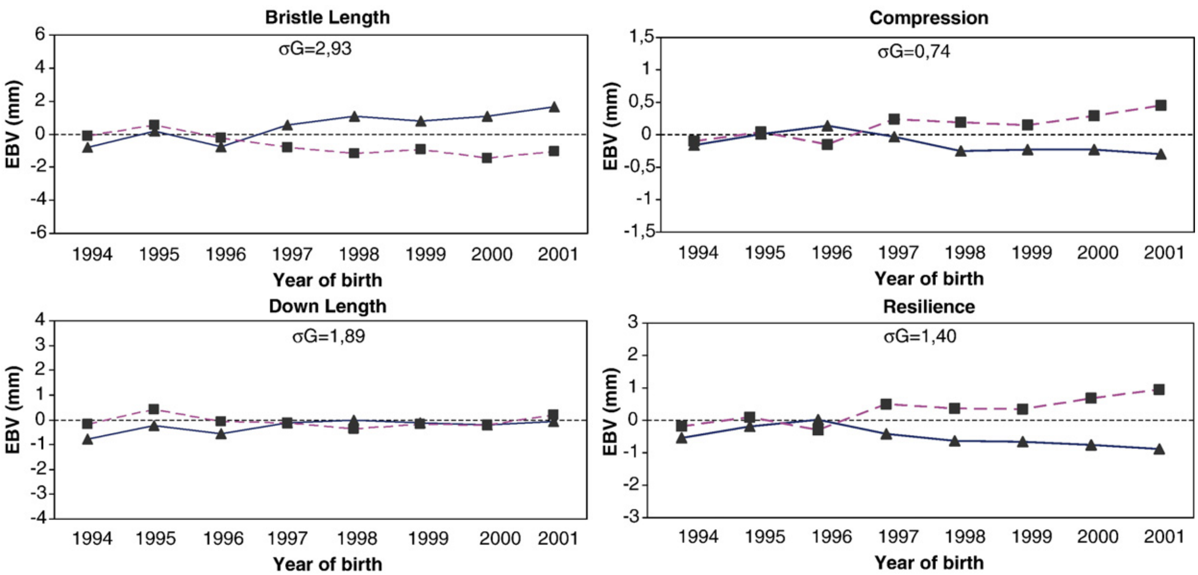


Fig. 1. Change of mean breeding value estimates (EBV) of bristle length, down length, compression and resilience, over the 8 years of selection for both the high (▲) and low (■) lines. Genetic standard deviation ($\sigma_G$) is given for each trait.

respectively. There was no effect on down length while negative differences of 1.00, 1.31, 0.38 and 0.50 genetic standard deviations were observed for compression, resilience, BD and AFD, respectively. No results about correlated responses to selection on total fleece weight or on fleece characteristics in Angora rabbits have been published. It is important to observe that selection for total fleece weight has a general beneficial effect on fleece quality. A high quality fleece having a good aptitude to produce a fluffy yarn is characterised by a high weight of first class quality, high fleece homogeneity and long bristles (Thébault and de Rochambeau, 1988). These characteristics were observed in the high line as described previously for weight of first class quality and fleece homogeneity (Rafat et al., 2007) and in this study for length of bristles. Thus, selection for total fleece weight results in an improvement of the quality of the fleece. Similarly, Bai et al. (2006) suggested that selection for cashmere weight is very effective in the cashmere goat, which has led to the slow genetic progress of fibre length due to its genetic correlation with cashmere weight. In another study, Redden et al. (2005) concluded that selection for increased mean cashmere weight results in a reduction in fleece quality and value.

Compression and resilience were also affected by selection and a decrease in both traits was observed in the high line. Similarly, a gradual decline in resistance to compression was noted over 9 years of selection of good quality wool or finer wool in Merino sheep (Ventner, 1980). Resistance to compression is related to fibre crimp and fibre diameter (McGregor, 2006). In our study estimates of genetic correlations were positive between BD and both compression and resilience.

## 4. Conclusion

Selection for total fleece weight significantly increased bristle length, secondary to primary follicle ratio and comfort factor and decreased compression, resilience, bristle diameter, and average fibre diameter. These changes resulted from moderate to high genetic correlations between total fleece weight and bristle length, and between fibre dimensions (BL, DL, AFD, and BD) and secondary to primary follicle ratio, comfort factor, compression and resilience. Thus, selection for increasing total fleece weight results in an increase of both quantitative and qualitative traits of wool production in the French Angora rabbit. Measurement of total fleece weight is simple and easy at the farm level. Selection for this trait has positive effects on fleece characteristics such as bristle length, follicle population and fibre diameter.

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