

# The two curvatures

Neville Jackson

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## Abstract

There is published evidence that follicles curve during follicle development and that the presence of hard collagen in the lower dermis at this time interferes with the developing follicle downgrowth causing follicles to grow in a curve. There is also evidence of a strong association between fibre diameter, ortho/para cortical segmentation and general follicle size.

Conventional view of fibre curvature is that it is caused by differences in the ortho and para cortex. It is proposed that this may not be correct, and that both fibre curvature and microstructure difference between ortho and para cortex are caused by the fibre growing inside a curved follicle.

It is proposed that follicle curvature has two components. Firstly, all follicles in all breeds of sheep are slightly curved and the degree of this component of curvature is related to fibre diameter. Secondly, if a sheep has the type of collagen that is associated with wrinkles, it also has some additional follicle curvature which is caused by collagen interfering with follicle development.

Some data and analyses are presented to support this 'two curvatures' hypothesis. In order for the two curvatures hypothesis to have a feasible mechanism it is necessary to assume that follicle curvature causes fibre curvature. We are able to present some data to support this auxiliary assertion.

## 1 Introduction

Some time ago there was a wool industry which possessed a reasonable working definition of wool quality that was universally understood among producers, traders, and processors. They even went so far as to put a number on it, and to link it to spinning performance. Quality numbers or 'Counts' ranged from 100's to 32's, the number referring to the number of hanks of yarn (each 560 yards long) which could be spun from 1 pound (0.454Kg) of clean wool, at the spinning limit. The concept is obviously tied to particular processing technologies. What is of interest here is the way quality number was assessed. It was a visual appraisal of crimp frequency, with a correction for abnormal handle.

Then it was found that fibre fineness (ie diameter) was a major determinant of spinning performance and softness or handle. There was a period of agonising

over the relationship between crimp frequency and fibre diameter. We show some of these investigations in Figure 1 because they are relevant to our current arguments regarding curvature.

Notice that the crimp/diameter relationship is quite steep at low crimp frequencies, but flattens out as one approaches the higher crimp frequencies of fine Merino wools. We are going to argue that the crimp/diameter relationship was historically quite satisfactory for non Merino wools, and that quality numbers as originally used for British sheep breeds were probably an adequate diameter indicator and therefore did indeed relate to spinning performance. It is the Merino wools for which the quality number system breaks down. We will present new data making this clear; the above published material has an inadequate range, and is just what originally pointed us to the concept of crimp frequency relating to diameter for coarse wools but not for Merino.

Eventually measured fibre diameter replaced subjective quality numbers as a descriptor of wool sold in Australia, and elsewhere. The industry settled down to a period of about 20 years using fibre diameter alone. Then Paul Swan's thesis appeared defining fibre curvature and establishing a basic measurement method for fibre snippets and showing the importance of measurement conditions in ensuring that the fibre was relaxed for measurement (Swan(1993) [12]). Fibre specification eventually became a dual parameter affair, with fibre diameter and fibre curvature both specified, but there is some doubt regarding the validity of the measurement conditions for fibre curvature with both Laserscan and OFDA measurement methods.

In the middle of these market specification upheavals, sheep breeders also moved from quality numbers to fibre diameter, acknowledging that breeding of fine Merinos towards higher and higher quality numbers had not led to finer fibre diameters. Breeders also became interested, following the work of Nay(1966) [9], in follicle curvature. Follicle curvature was shown to be genetically correlated with staple crimp frequency, wrinkle score, and bulk compression measurement. The curvature of a follicle was always thought to be the same thing as the intrinsic curvature of a properly relaxed fibre, because it corresponded to the curvature with which the fibre emerged from the follicle. This was never proven. A formula converting follicle curvature scores to intrinsic radius of curvature was established by Jackson and Watts(2016) [8].

The focus of this document is on what causes follicles and fibres to be curved. There are two schools of thought on causation

**classic view** fibres curve because of their internal structure. In sheep like fine Merinos with a bilateral ortho/para cortical structure, the paracortex is always on the inside of the curve. It is asserted that the paracortex contracts more during keratinization and thus causes the fibre to curve. The follicle passively follows what happens to the fibre. In coarser woolled sheep without bilateral cortical structure this is less clear, but Hynd et al. (2009) [5] assert there is asymmetry in mitotic activity and keratinisation.

**follicle view** fibres curve because they form inside a curved follicle. The spatial environment in which the bulb cells differentiate influences their develop-

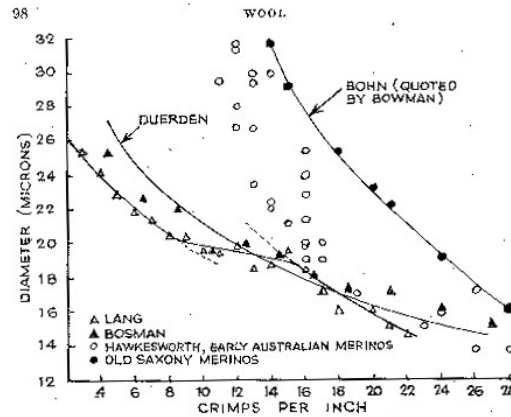


Fig. 5.3 The relationship between fibre diameter and staple crimp in merino wools as summarised by Roberts and Dunlop

(a) Reviewed by Roberts and Dunlop

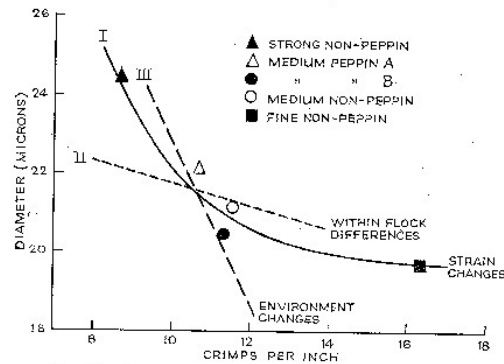


Fig. 5.4 Summary of fineness-crimp relations for Australian strains of merino studied by Roberts and Dunlop. Curve I represents the changes in diameter per unit change of crimp as different strains are studied in the same environment. The slope of line II represents the rate of change of diameter with crimp within any one age group in one flock of one strain. The slope of line III represents the change of fineness associated with unit change of crimp resulting from changes of environment upon any one flock of one strain

(b) Roberts and Dunlop's own data from CSIRO Strain Trial

Figure 1: Crimp frequency fibre diameter relationships from Roberts and Dunlop(1957) [11]. Figures reproduced from Onions(1962) [10]

ment leading to a different internal structure on the inside and outside of curves and a curved fibre shape. The observed differences in internal fibre structure are just a side-effect of forming inside a curved follicle, and are not the cause of curvature. To find the cause of fibre curvature we have to look for what causes follicles to curve.

This document takes the follicle view and attempts to uncover the causes of follicle curvature. It emerges that there is more than one causal factor, and that all are related to skin development, not to fibre structure.

## 2 Causation and association

Everyone understands that observing a correlation does not prove causation. So what experiments and analyses can one do to establish causation? There are several ways, and we list them

- Do a designed experiment. If the factors studied are the only difference between treatment groups, and there is proper randomization, then one can conclude the factors are responsible for the differences observed.
- Establish a time sequence. If A occurs before B, then it is not possible for B to cause A.
- Find a mechanism. If there is a feasible way in which A could cause B, then it is at least possible for A to cause B. Theories about how things work are very useful here.
- Strong correlation. There has to be some association observable between cause and effect. Observing association is a necessary step to establishing a cause, but it is not definitive.
- Regression with chosen independent X values. This is like a designed factorial experiment.
- Repeatability. If a relation is causal it will always be present.
- Coherence. If a proposed causal relation fits in with other things known and generally accepted in an area, it is likely to be causal. If it is in disagreement, one has to be careful.

Behind most of these points is the concept of confounding. Designed experiments attempt to study factors in isolation. In the real world, especially in biology, we are often forced to study traits varying simultaneously. Causal analysis in this situation is difficult. One approach is to fit a model corresponding to one's theory of causation and to show that it is a good fit to the data.

### 3 Which comes first follicle or fibre curvature ?

Evidence on the time sequence of follicle and fibre curvatures is not readily found. There is a photomicrograph in the classic study of Hardy and Lyne (1956) [3] which shows developing follicles in vertical section before the fibre growth has commenced. This photomicrograph is important so we reproduce it here in Figure 2

The fibre does not start to form before stage F4 and does not emerge from the follicle until stage F8. The first three photomicrographs, ie before stage F4, and the developing follicles show some curvature, especially in the second Figure. The fourth Figure shows branching follicles at day 102 . This is hardly convincing evidence. The degree of curvature is slight. It is suspected that the Hardy and Lyne used a strong woolled Merino, as this would have been easier material to study vertical sections.

### 4 Follicle curvature and collagen

As part of a study of association of collagen amount and type with wrinkle, it was observed that sheep in two groups chosen as wrinkle-free or wrinkled differed in amount and type of collagen in the lower dermis (Watts et al. (2020) [13], but also differed in follicle curvature. The group means for follicle curvature, and for fibre diameter, are shown in Table 1

Table 1: Means for follicle curvature, fibre diameter and integrated collagen optical density for wrinkled and wrinkle-free groups of sheep

	Wrinkle-free	Wrinkled
Follicle curvature (score 1-7)	2.16	4.44
Fibre diameter (micron)	17.26	18.15
Integrated collagen density (OD)	280851	362991

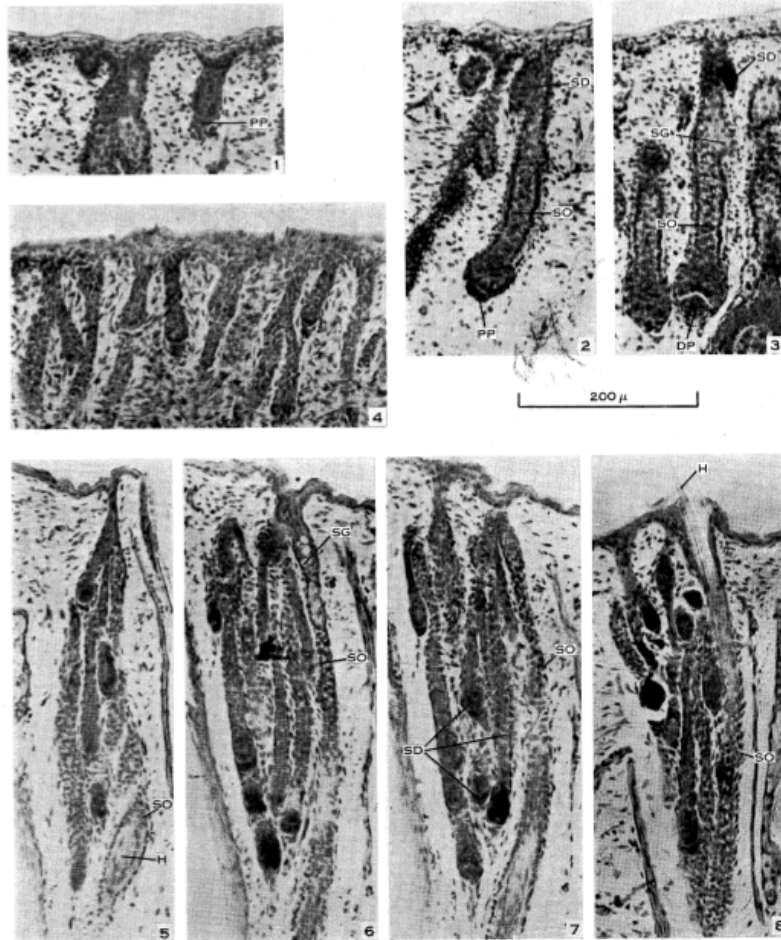
The groups were chosen to differ in wrinkle. It has been proposed that the observed collagen difference is the cause of the difference in wrinkle (Watts et al. (2020) [13]). We are wondering whether the collagen difference is not also the cause of the difference in follicle curvature.

What we propose is that presence of hard collagen in foetal skin during follicle development causes developing follicles to bend. There is visual evidence of this occurring. Dreyer et al. (1983) [2] published a photomicrograph of Karakul sheep foetal skin in vertical section at 128 days. We reproduce it here in Figure 3

We quote Dreyer et al

”The impression gained was that owing to the vigour of the follicle bulb, the constituent collagen fibres of the hypodermis were displaced in some cases, but no real piercing of that tissue took place. In other cases it would appear theat the follicle bulb and the papilla

## DEVELOPMENT OF WOOL IN MERINO SHEEP



(a) Plate I from Hardy and Lyne(1956) [3]

## EXPLANATION OF PLATES 1 AND 2

All figures are of sections through skin from the trunk of Merino foetuses. The staining is with haemalum, eosin, and picric acid, except Plate 1, Fig. 4, which is without picric acid. DP, dermal papilla; G, stratum germinativum; H, hair; HN, hair cone; P, periderm; PP, pre-papilla; S, stratum spinosum; SD, derived secondary follicle; SG, sebaceous gland; SO, original secondary follicle.

(b) Caption from Hardy and Lyne(1956) [3]

Figure 2: Follicles at some early stages of development



**Figure 14b** Deflected follicle bulbs on hypodermal layer. Pipe curl. Vertical section. Tail position. 128 days pre-natal. Magn. 114 $\times$ . a. Follicle bulb. b. Hypodermis.

Figure 3: Photomicrograph of foetal skin from Dreyer et al. (1983) [2] showing follicle bulbs deflecting on contact with the collagen layer. Karakul sheep at 128 days

were undergoing some degree of flattening due to growth pressure on the barrier layer.....This barrier effect could also explain the deflection of the bulb to any side as it reacts to the force exerted by downward growth”

This clearly establishes that the dark stained collagen layer in Figure 3 acts as a barrier to downward growth of follicles. If the follicles continue to grow, they must deflect sideways, and this will result in a curved follicle.

## 5 Follicle curvature without collagen

All follicles in non-Merino breeds of sheep have a slight degree of curvature, and their fibres or staples have a range of crimp frequencies less than one up to about 4 crimps per cm. We may have to exclude Downs wool breeds, here because they have very curved and tangled follicles, and I suspect they have hard collagen induced follicle curvature like Merinos.

We have to consider what causes the curvature of follicles in sheep which do not have hard collagen? The first thing to note is it appears to be quite strongly related to fibre diameter. There are data supporting this in Figure 1 and in the subsection below.

Follicles have an inherent asymmetric design. They have a thicker inner and outer root sheath on the ental side (side to which the muscle is attached in primary follicles), and this side is usually the outside of the curve. The bulb sometimes deflects toward this side. Larger follicles tend to be less curved, hence the connection between curvature and fibre diameter, because larger follicles tend to grow larger fibres (Henderson(1964 a [4])).

### 5.1 Data supporting proposal that curvature relates to diameter in non-Merino breeds, but not in Merino

The breed survey data of Carter(1968) [1] offer some support. There are no follicle or fibre curvature measurements, but there is crimp frequency and diameter. So we shall look at the crimp/diameter relationship across breeds in particular comparing non-Merino with Merino data. Figure 4 plots breed means of fibre diameter against crimp frequency

There is a clear straight line relationship for crimp frequencies up to about 4 crimps per cm. In the Merino range ( 4 to 8 crimps per cm) there is no relationship at all, and there is one outlier Downs wool breed mean in that range.

These data have limitations. There are not enough replicate points. We are using crimp frequency as a proxy for follicle curvature. Each point is a mean of about 20 sheep sampled from one flock representing the breed. The only positive is that it extends Figure 1 into the non-Merino breeds.



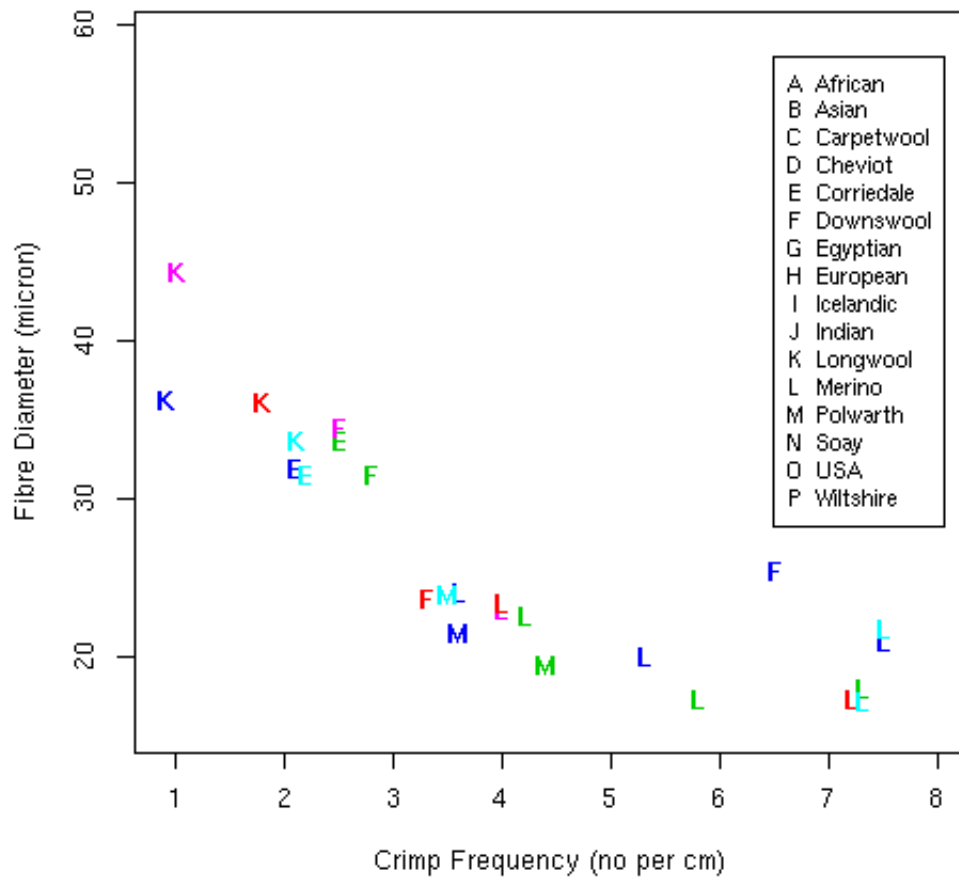


Figure 4: Crimp frequency fibre and diameter breed means from Carter(1968) [1]. Each point is mean of about 20 sheep from one flock representing a breed.

## 6 Can we separate two causes for curvature?

We are proposing that there is one follicle curvature, that all sheep have, that is related to fibre diameter and follicle size, and that there is a second follicle curvature that only Merinos have, that is caused by presence of hard Type I collagen in the lower dermis.

Can we separate these *two curvatures* by analysing data? I propose that we can use regression analysis to remove the diameter related part of follicle curvature variation, and then study the remaining variation and see if it relates to collagen measurements.

### 6.1 Does diameter corrected follicle curvature relate to collagen measurements?

The only available data that include collagen measurements, follicle curvature and fibre diameter are from the collagen/wrinkle experiments reported by Watts et al. (2020) [13]. Taking all available data from this experiment, we look first at the regression of follicle curvature on mean fibre diameter. This is shown in Figure 5

Figure 5 shows all data points, the regression line ( $Fc = 7.68 + 0.621 * D$ ) and the product moment correlation (0.61). So part of the follicle curvature of these sheep is clearly diameter related. The problem is this observed relationship is positive - the finer fibre diameter are *less* curved. According to our hypothesis (which is supported by the Carter(1968) [1] data), this relationship should be negative.

THIS IS A SERIOUS ISSUE WHICH PUTS A QUESTION OVER THE HYPOTHESIS THAT PART OF FOLLICLE CURVATURE IS DIAMETER RELATED. IT WAS THOUGHT THAT THE CARTER DATA IN Figure 4 SUPPORTED A DIAMETER-RELATED EFFECT ON CURVATURE. THAT MAY BE WRONG. WE NEED TO PAUSE AND DO 2 THINGS : 1. LOOK AT A LARGER DATA SET ( THE PRESENT SMALL DATA SET MAY BE BIASED FOR SOME REASON) and 2. THINK WHETHER OUR INTERPRETATION OF Figure 4 IS CORRECT

THE FOLLOWING SECTION DETAILING AN ANALYSIS WHICH DEPENDS ON THE CURVATURE/DIAMETER RELATIONSHIP HAS BEEN PUT INTO TINY FONT, INDICATING THAT IT MAY BE WRONG OR INAPPROPRIATE.

We remove this diameter related part of follicle curvature by computing the residuals for follicle curvature in Figure 5. We call these residuals  $Fc|D$  (follicle curvature adjusted for diameter) and the computed residuals are shown as a histogram in Figure 6

So this new variable ( $Fc|D$ ) has nearly as big a range as  $Fc$  and has a reasonable normal-looking distribution (this was tested with residual plots). The mean is zero because they are relative to the mean curvature at a given diameter.

We can now look to see if this remaining variation in  $Fc|D$  is related to collagen measurements. This relation is shown in Figure 7

So  $Fc$  adjusted for  $D$  does not relate to collagen. There are only 17 points because this work was incomplete when Jim Watts passed away. Only 17 sheep had  $Fc$  and  $D$  and Collagen measurements.

It is worth looking at the residuals from the fit in Figure 7 to see how much variation in  $Fc$  still remains, unexplained by either  $D$  or Collagen. We can do this by looking at variances. Variance of  $Fc$  was 1.91. Variance of  $Fc$  adjusted for  $D$  was 1.30. Variance of  $Fc$  adjusted for both  $D$  and Collagen was 1.04. So we have explained about half the variance of  $Fc$  using  $D$  and Collagen. The remaining half is probably measurement error, that is errors in scoring  $Fc$  and also errors in the  $D$  and Collagen measurements used for adjustment.

There are issues with this analysis

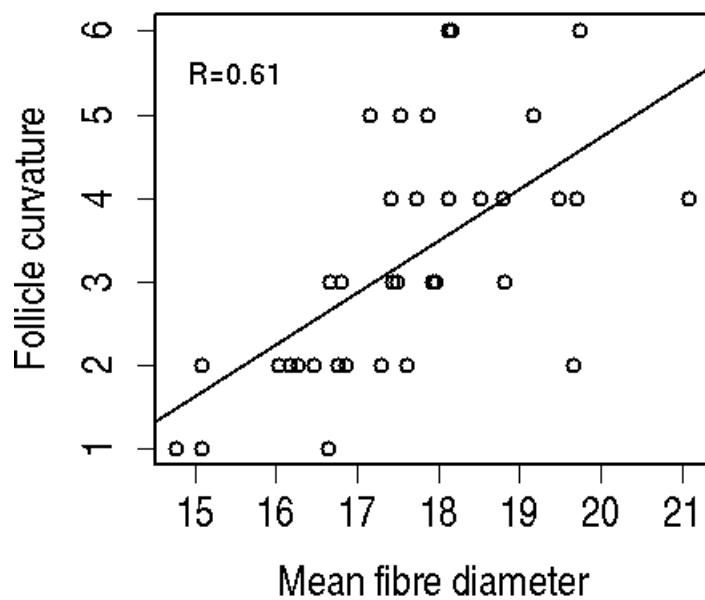


Figure 5: Scatterplot of follicle curvature against mean fibre diameter for 35 sheep in the trial of Watts et al. (2020) [13]. Line is the fitted regression ( $Fc = 7.68 + 0.62 * D$ ), and correlation is shown as  $R = 0.61$ .

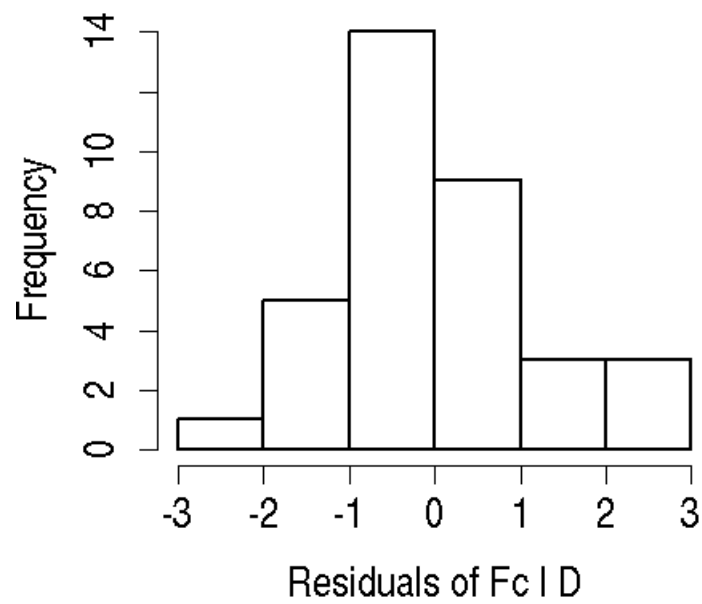


Figure 6: Histogram of residual variation in follicle curvature after adjusting for regression on mean fibre diameter

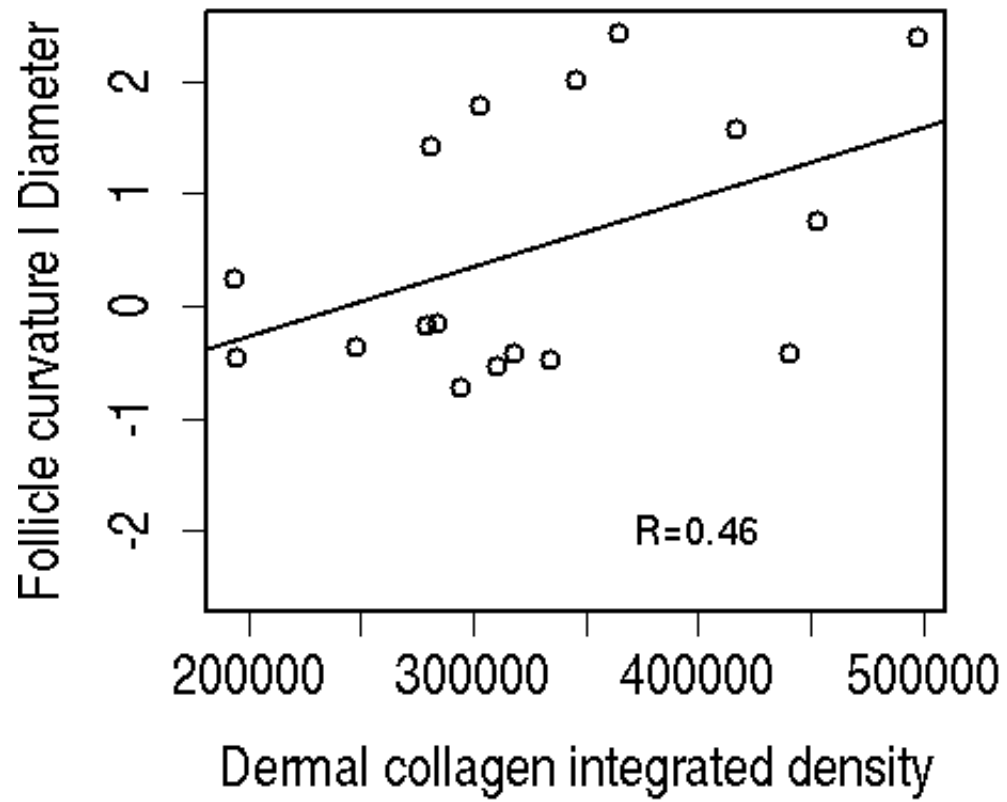


Figure 7: Scatterplot of follicle curvature adjusted for diameter against integrated dermal collagen optical density for 17 sheep in the trial of Watts et al. (2020) [13]. Line is the fitted regression ( $Fc|D = -1.49 + 6.17e-06 * Collagen$ ), and correlation is shown as  $R = 0.46$ .

- the data are from a designed experiment in which sheep were chosen from 2 commercial flocks to represent extremes of wrinkle-free or wrinkled. The analysis did not fit Flock or SkinType effects. This would have removed most of the variation, especially in collagen density.
- the stepwise adjustment is not the conventional way of analysing effects of 2 variables on a third variate. We do it stepwise first, so we can grasp what is happening.
- there is insufficient data
- the diameter effect on follicle curvature is positive . We are proposing that in general it should be negative.

### 6.1.1 Lets do it all again using multiple regression

Just to show that the conclusions from the stepwise analysis of previous section are OK, we do a multiple regression of follicle curvature on fibre diameter and collagen optical density. The result is summarised in Table 2

Table 2: Multiple regression of follicle curvature ( $Fc$ ) on mean fibre diameter( $D$ ) and integrated collagen optical density ( $C$ ) for 17 sheep from Trial2 of Watts et al.(2020) [13].

	Coefficient estimate	Std. Error	T value	Pr(>  t )
(Intercept)	-1.177e+01	4.678e+00	-2.515	0.0247 *
D	7.859e-01	2.894e-01	2.716	0.0167 *
C	5.188e-06	3.589e-06	1.446	0.1703

The regression on  $D$  is significant, that on  $C$  is not, but it is at least positive. To interpret this multiple regression equation we need to convert the coefficients to standardized partial regression coefficients. The standard deviations for  $D$  and  $C$  are  $\sigma_D = 1.0645$  and  $\sigma_C = 85844$ . We multiply the coefficients in Table 2 by these to get the standardised partial regression coefficients  $\beta_D = 0.8366$  and  $\beta_C = 0.4454$ . The proportions of variance explained are therefore the squares of these  $\beta'$ s, ie .6998 and .1983. These sum to .8982, so we have explained 89% of the variance of  $Fc$  and the remainder ( $1 - .8982 = .1018$ ) shows 10 percent of the variance unexplained.

This is not exactly the same as the stepwise analysis of the previous section, and the reason is that more than 17 observations were used for the first step ( regression of  $Fc$  on  $D$ ).

One can express the outcome of this multiple regression analysis as a path diagram (Wright(...) [?]). The path diagram is shown in Figure 8

Figure 8 is just an illustration of how the present data supports the hypothesis that there are diameter-related and collagen-related parts of follicle curvature.

The big issue is that the standardized partial regression for diameter is positive, where we are proposing that it should be negative if all other effects are averaged out properly. We therefore have to shelve this analysis, and try to do something on a larger and more typical Merino dataset.

## 6.2 Follicle curvature and fibre diameter in Merinos

The relationship of follicle curvature with fibre diameter can be checked from published estimates. Table 3 presents published estimates of phenotypic, genetic and environmental correlation. Standard errors can be obtained from the sources, they are a distraction here.

Table 3: Published estimates of phenotypic, genetic and environmental correlation between follicle curvature score and mean fibre diameter

Reference	Phenotypic correlation	Genetic correlation	Environmental correlation
Jackson Nay and Turner (1975) [7]	0.26	0.32	0.22
Jackson(2017) [6]	0.35	0.13	0.62

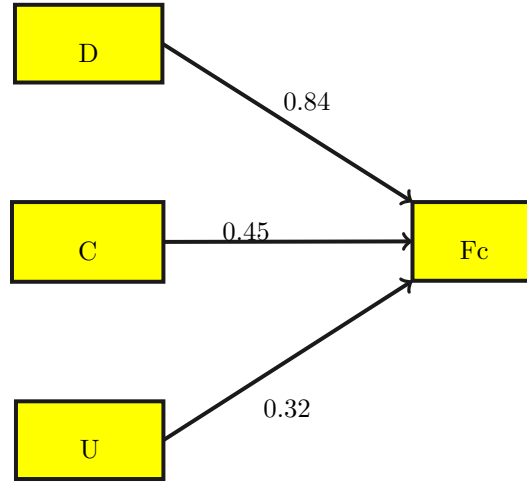


Figure 8: Path diagram expressing diameter ( $D$ ) related effects on follicle curvature, collagen ( $C$ ) related effects on follicle curvature ( $Fc$ ), and other undefined effects ( $U$ ). The labels on each arrow are standardised partial regression coefficients. The square of each coefficient indicates proportion of variance explained. There may be correlations among ( $D.C.U$ ) but these are not shown

The correlations are all positive. So we conclude the small dataset above is not atypical or biased. Follicle curvature really does have a positive relationship with mean fibre diameter in Merino sheep.

Now what about diameters of primary and secondary fibres? Estimates of correlations of follicle curvature with  $D_p$  and  $D_s$  are given in Table 4

Table 4: Estimates of phenotypic, genetic and environmental correlation between follicle curvature score and mean fibre diameter of primary and secondary fibres (Jackson(2017) [6])

Traits	Phenotypic correlation	Genetic correlation	Environmental correlation
Fc x $D_p$	-0.02	-0.32	0.25
Fc x $D_s$	0.33	0.72	0.03

This is more complicated. At least at the genetic level, follicle curvature is negatively correlated with  $D_p$ , but positively correlated with  $D_s$ . So our hypothesis of a  $D$  related curvature component works for primary fibres, but not for secondary fibres. That partly explains Carter's data shown in Figure 4 - In the non-Merino breeds where there is this negative crimp frequency x diameter relation, primary fibres are a much larger proportion of the fibre population. It may be that the negative relationship obtained for primary fibres also applies to So (secondary original fibres), because, as with primary fibres, So fibres form

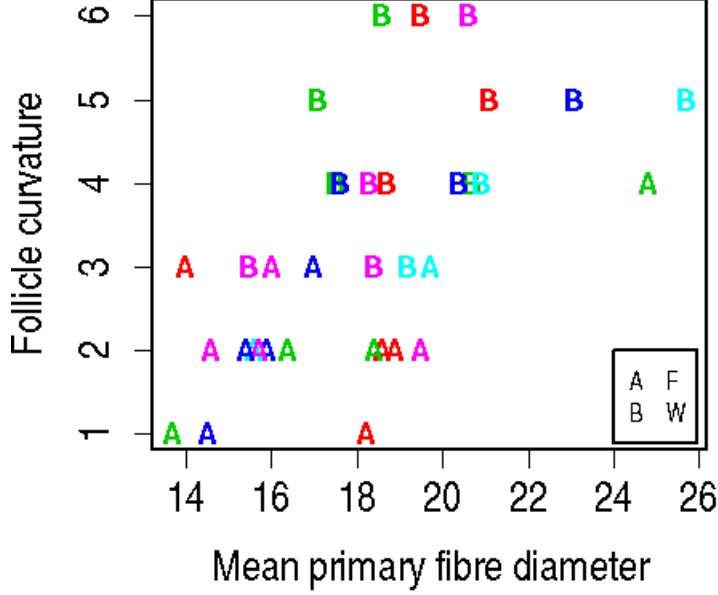


Figure 9: Scatterplot of follicle curvature against mean primary fibre diameter for 35 sheep in the trial of Watts et al. (2020) [13]. The correlation is  $R = 0.59$ .

at initiation sites. P and So fibres would be all the fibres in non-Merino breeds.

It is conceivable that follicle curvature in Sd fibres is different, and that would explain why Merinos have a different Fc x D relationship. One way in which curvature of Sd follicles could be different is that Sd follicles are formed at the same time as collagen is formed, at around 100 days of gestation. So collagen may only interfere with the curvature of Sd fibres.

#### 6.2.1 Does Dp corrected follicle curvature relate to collagen measurements?

We attempt to repeat the above rejected analysis, using Dp to remove the follicle size effect on follicle curvature, instead of D.

Table 9 shows follicle curvature plotted against primary fibre diameter for the data from the collagen/wrinkle experiment of Watts et al.(2020) [13].

The correlation is positive, and almost identical to the correlation of Fc x D. So this dataset is different from the large datasets from which published estimates of correlation were reported in Section 6.2.



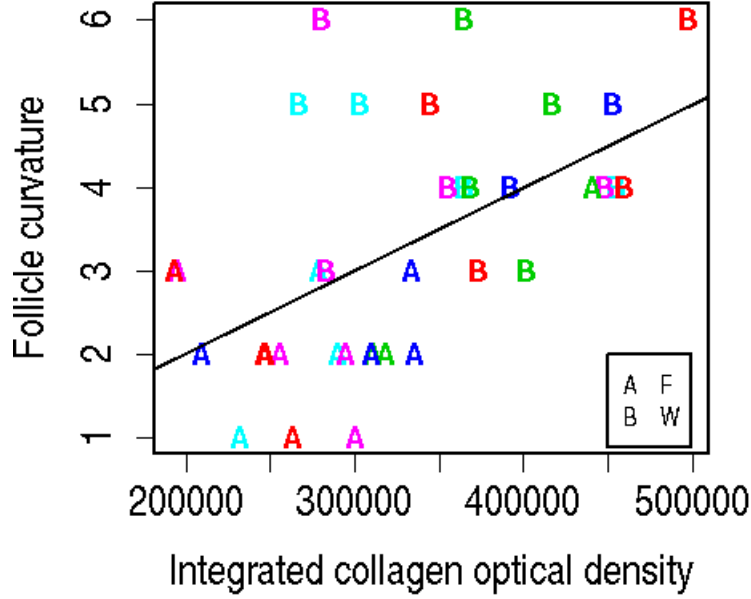


Figure 10: Scatterplot of follicle curvature against integrated collagen optical density for 35 sheep in the trial of Watts et al. (2020) [13]. Line is the fitted regression ( $Fc = 0.96 + 0.00584 * C$ ), and correlation is  $R = 0.55$ .

We can not proceed with the use of  $D_p$  to adjust  $F_c$  in this small dataset.

### 6.2.2 Can we do the stepwise analysis in reverse order, adjusting follicle curvature first for collagen?

This is a last ditch desperate approach. We are trying to prove that collagen affects follicle curvature. The diameter effect on follicle curvature is the nuisance relationship which should be adjusted out. But that is proving difficult, so we can try adjusting out the collagen effect on curvature, and see what variation remains.

Figure 10 shows the plot of follicle curvature against collagen measurement.

The correlation is positive (0.55), as expected. The regression line was  $Fc = 0.9601 + 5.843e-03 * C$ .

### 6.3 Follicle curvature analysis in a large Merino dataset

There are plenty of large follicle curvature datasets on Merinos. The problem is none of them have collagen measurements. What we propose to do is to use wrinkle score as a *proxy* for collagen. Either raw wrinkle score, or perhaps wrinkle score adjusted for S/P ratio (this would hopefully represent the part of wrinkle reflecting collagen amount and type).

## 7 Mechanisms

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