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Bulk and its structural basis: A review

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ABSTRACT

Loose wool bulk has been identified as a desirable objective characteristic associated with superior end-product performance in many of the present uses of wool. These are specifically, improved appearance retention of carpets and improved insulation of knitting yarns and loose wool batts. Breeds have been shown to differ in their ability to produce high bulk wools. Loose wool bulk is strongly inherited in the adult fleece, it is not however expressed in the lamb fleece and subsequently cannot be used as a selection criteria until hogget shearing. Fibre crimp appears to be the major factor associated with bulk. Crimp formation in Merinos is related to follicle structure, cell mitotic activity and cellular differentiation within the follicle bulb resulting in the production of different cortical cell types. At this time it is not known if a similar situation applies to crossbred wool type sheep. The identification of a suitable measurable structural characteristic would facilitate the selection of high loose wool bulk crossbred wool type sheep at a young age.

Keywords Loose wool bulk, measurement, fibre structure, follicle morphology, sheep breeds.

INTRODUCTION

Loose wool bulk is a property of wool associated with *springiness*, *loftiness*, and *filling power* (Elliott *et al.*, 1986). Loose wool bulk is of major importance to manufacturers of yarns used for knitting and the manufacture of carpets. Yarns made from wools exhibiting a high loose wool bulk characteristic, or from blends of wool incorporating wools with high loose wool bulk, will appear to have a greater effective yarn thickness and subsequently have a greater *apparent value* to the prospective consumer. High bulk yarns enhance carpet cover, which is the property exhibited by pile yarns to "hide" the backing fabric (Carnaby *et al.*, 1984). Carnaby and Elliott (1980) found that differences observed in bulk among different wools were also present in the yarns from those wools, r= 0.89. It was also observed that differences in loose wool bulk of more than 1.5 cm^3/g have a significant influence on yarn bulk with yarn bulk differences of greater than 15% being visually apparent.

MEASUREMENT OF BULK

In view of the commercial significance of yarn bulk in the carpet industry, it is highly desirable to be able to identify and quantify differences in loose wool bulk early, before processing begins. A variety of methods have been identified that would provide a numerical measure of bulk. These methods are based on a measurement of the bulk-compression characteristics of wool (Dunlop *et al.*, 1974; Chaudri and Whiteley, 1968). The two most widely used methods for measuring loose wool bulk are based on the principles of volume and pressure. The Wool Research Organisation of New Zealand (WRONZ) loose wool bulkometer (Bedford *et al.*, 1977), based on the work of Dunlop *et al.* (1974), estimates the specific volume (cm^3/g) of a 10g sample at a fixed pressure of 10 gf/cm^2 (0.98 kPa). This is in contrast to the resistance to compression method of Chaudri and Whiteley (1968) which estimates the load required to compress a sample of known mass (1g) to a fixed volume (9.98cc). Comparative studies of the 2 methods have shown that the rankings of wools tested by either method are highly correlated, r=0.86 (Dunlop *et al.*, 1974), and r= 0.96 (Chaudri and Whiteley 1968).

The WRONZ loose wool bulkometer has provided useful information to a wide range of users, however it has not proven to be useful for application in commercial testing. Commercial testing facilities are set up to handle cored samples rather than the full length samples utilized by the present system. A procedure has been investigated that would provide a loose wool bulk value derived from a core residue (van Luijk, 1987). The same physical system is utilized with the exception of a smaller diameter cylinder (50 mm vs 80 mm). A smaller sample is also utilized, 2.5 g vs 10 g. To be a viable alternative, the core bulk test method must duplicate the loose wool bulk test. Van Luijk (1987) compared the two measurement methods and obtained highly correlated results (r = 0.95), indicating that the core bulk test is a viable alternative test method. Investigations by other researchers have shown similar results, r = 0.86 and r = 0.89, respectively (Swan and Mahar, 1990; Sanderson and Burling-Claridge, 1991).

Techniques for measuring bulk in yarns (Ross *et al.*, 1977) and carpets (Carnaby and Thomas, 1978) have also been evaluated. Ross *et al.* (1977) found that compressing a hank of yarn in a channel at a pressure of 10 gf/cm^2 gives satisfactory comparisons of bulk between yarns. Carnaby and Thomas (1978) used glass beads (370 µm diameter) to estimate the total volume of void space in a 10 cm^2 sample of carpet. The value for the void space can be used in conjunction with the pile mass per unit area to compare the *apparent value* or *cover* of yarns of different bulk. Image analysis techniques (Wood and Hodgson, 1989) have also been utilized to measure carpet texture. The texture of a carpet results from the regular arrangement of short yarn segments, either as loops or cut-pile tufts in the pile. Changes in texture during wear occur by reductions in the clarity of individual tufts and from crushing or matting of the pile. This method objectively evaluates the effects that bulk has on the visual effect of wear on tufts and pile in carpets.

About 60% of the wool types grown in New Zealand are commonly used for the manufacture of carpets. This wool is grown predominantly by the Romney, Perendale and Coopworth breeds and is collectively referred to as Romcross wool. Romcross wools are widely used in the carpet industry because of their ability to improve blend colour and increase yarn strength while achieving good spinning performance (Ince, 1979). Romcross wool is however criticized by overseas wool processors because it lacks bulk and has poor resilience, so that the pile of carpets made from it flattens quickly (Dunlop *et al.*, 1974). Typical loose wool bulk values for fleece wool from numerous New Zealand breeds range from a low of 16 cm3/g to a high of 39 cm3/g (Elliott *et al.*, 1986), (Table 1).

TABLE 1 Range of loose wool bulk, greasy fleece weight and heritability of loose wool bulk for some New Zealand sheep breeds.

Breed	Loose wool bulk (cm^3/g) Range	Loose wool bulk (cm^3/g) Heritability	Greasy fleece weight (kg) Range
Southdown	30-39		2.0-2.5
Suffolk	30-39		2.5-3.0
Dorset	27-35		2.0-3 0
Cheviot	25-35		2.0-3.0
Merino	24-33	0.57-0.80[1]	3.5-5.0
NZ Halfbred	25-32		4.0-5.0
Corriedale	22-35		4.5-6.0
Perendale	21-33	0.42-0.70	3.5-5.0
Borderdale	18-28		4.5-6.0
Drysdale	20-26		5.0-7.0
Romney	18-24	0.34-0.35	4.5-6.0
Coopworth	17-24		4.5-6.0
Border Leicester	17-21		5.0-6.0
English Leicester	16-20		5.0-7.0
Lincoln	16-19		5.0-7.0

References: Bigham *et al.*, 1985; James *et al.*, 1990; Sumner *et al.*, 1989; Watson *et al.*, 1977.

[1]Relates to resistance to compression.

INHERITANCE OF BULK

Due to the apparent desirability of high bulk wools by the carpet manufacturing sector, an effort to evaluate the potential of within-breed improvement of loose wool bulk in Romcross sheep was initiated by Carnaby and Elliott (1980). Improving a character through breeding depends upon the ability to exploit existing variation between animals within a breed. Subsequent investigations have shown that the Romney and Coopworth breeds exhibit little variation in loose wool bulk but the Perendale showed large variations (Carnaby and Elliott, 1980; Bigham *et al.*, 1983; Bigham *et al.*, 1984; Elliott, 1981; Sumner *et al.*, 1989). Selection for bulk within the Romney or Coopworth breeds would prove difficult due to the lack of variation between animals. Selection within the Perendale breed for improved loose wool bulk could be feasible due to the

TABLE 2 Phenotypic and genetic correlations between loose wool bulk and other wool traits for Romcross wool and between resistance to compression and other wool traits for Merino wool.

Character	Phenotypic correlation		Genetic correlation	
	Loose wool bulk	Resistance to compression	Loose wool bulk	Resistance to compression
Greasy fleece weight	-0.03	0.13 to -0.03	-0.06 to 0.07	-0.35 to 0.02
Staple length	-0.50	-0.24 to -0.52	-0.47 to -0.35	-0.57 to 0.44
Fibre diameter	0.01	0.47 to -0.23	0.41 to -0.09	0.54
Follicle curvature	-	0.64 to 0.80		0.88

References: Bigham *et al.*, 1983; Bigham *et al.*, 1985; James *et al.*, 1990; Watson *et al.*, 1977; Whiteley *et al.*, 1978.

large phenotypic variation in bulk observed. The heritability and genetic correlations of loose wool bulk and other fleece characters are important if selection for bulk were to commence. Studies have shown that loose wool bulk and resistance to compression are highly heritable (Bigham *et al.*, 1983; Watson *et al.*, 1977; Bigham *et al.*, 1985; Sumner *et al.*, 1989) with the heritability values consistently higher in the Perendale (h^2=0.42-0.70) than the Romney breed (h^2=0.34-0.35). Phenotypic correlations have been estimated from hogget and ewe data collected from Romney, Coopworth and Perendale breeds (Bigham *et al.*, 1983; R.M.W. Sumner and M.L. Bigham, *pers. comms*) (Table 2). These correlations indicate a strong positive relationship between loose wool bulk and staple crimp, and a strong negative relationship with staple length. Greasy fleece weight and mean fibre diameter are weakly related.

Repeatability estimates between measurements of wool bulk for samples taken at lamb and hogget shearing are quite low (Sumner *et al.*, 1989), whereas repeatability estimates between measurement of samples taken after hogget shearing are high (Sumner *et al.*, 1986).

ENVIRONMENTAL EFFECTS ON BULK

Environmental effects on loose wool bulk have also been investigated. Sumner (1983) showed that despite a significant seasonal wool growth cycle for growth rate, fibre length, and fibre diameter, loose wool bulk did not exhibit a definitive seasonal trend. Loose wool bulk was also unaffected by frequency and time of shearing, pregnancy and lactation (R.M.W. Sumner unpublished). In the same trials loose wool bulk was unaffected by age between 1 and 5 years. Nutritional studies showed loose wool bulk of ewe hoggets of 6 breeds to also be unaffected by pasture allowance (Sumner *et al.*, 1981).

FIBRE FACTORS ASSOCIATED WITH BULK

Most of the investigations relating bulkiness to fibre characteristics have been done in Australia utilizing Merino sheep measuring bulkiness as resistance to compression. Resistance to compression is primarily a measure of the crimp structure of individual fibres. Fibre crimp, separate from staple crimp, has been shown to be an important aspect of wool quality playing a major role in the subjective determination of handle, a term used to describe the tactile properties of textile materials. The Australian studies aimed to relate softness of handle (and hence fibre crimp) to an easily measured objective parameter. Mean fibre diameter was generally thought to play a major role in the determination of softness or handle, the coarser the wool the harsher the handle. Studies by Shah and Whiteley (1971) and Ali *et al.* (1971) have shown that resistance to compression, in association with fibre diameter, accounts for the majority of variation in softness or handle. Low resistance to compression confers softness of handle to wools of a given fibre diameter. A study by Matsudaira *et al.* (1984), evaluated the relationship between fibre crimp and fabric quality through an objective method of evaluating fabric handle. They found that fibres removed from high-quality fabrics have a high crimp level with fibre crimp playing an important role in yarn extensibility, compressibility, and fabric extensibility which improved fabric quality. There was a strong correlation between fibre crimp and *numeri* (smoothness) (r = 0.89) and *fukurami* (fullness and softness) (r=0.86). This study indicated that highly crimped wools produce fabrics with higher levels of softness and smoothness. Fabric softness and handle as measured by Matsudaira have not been related to degree of resistance to compression, crimp number, and fibre diameter.

To date, there has been little data relating fibre characteristics with bulk in Romcross wools where the objective is to increase bulk. It is unknown at this time if the same factors which govern the presence of bulk in the Merino also act in Romcross types of sheep. This information would play an important role when attempting to increase bulk in breeds or lines of New Zealand Romcross wool type sheep.

Crimp form (either helical or planar) appears to be the major factor that influences the observed variation occurring in the resistance of different types of wool to compression (Chaudri and Whiteley, 1968; Whiteley and Balasubramaniam, 1974; Slinger and Smuts, 1976). Similar results are reported by Watson *et al.* (1977) after investigating effects of selection for resistance to compression in the Australian Merino. Planar types of crimp are best represented as a form of sine wave and are representative of low bulk wools, while the helical form is believed to be characteristic of high bulk wools (Chaudri and Whiteley, 1968). A discussion of the biological basis for crimp is necessary to understand the mechanisms through which fibre crimp imparts its effect on loose wool bulk.

Fibre crimp has been related to certain morphological features of follicles (Nay and Hayman 1969; Orwin and Woods 1983; Kaplin and Whiteley 1978):

1. Curved follicles produce fibres with a higher crimp frequency when compared to straight follicles;

2. Follicles producing fibres showing distinct short-term variation in fibre diameter and contour will exhibit changes in fibre direction as seen in highly crimped wools; and

3. The structure and composition of the cortical cells making up the cortex itself may be a causative factor of crimp.

Numerous authors (Whiteley *et al.*, 1978; Watson *et al.*, 1977; Chaudri and Whiteley, 1968) have substantiated that the majority of the variation in resistance to compression in Merino wools can be explained by follicle curvature, crimp and fibre diameter in decreasing order of importance. The importance of follicle curvature was assumed to be related to its effect on single-fibre crimp.

FOLLICLE FACTORS AFFECTING BULK

The relationship between crimp and follicle curvature is quite strong (r= 0.80) (Whiteley *et al.*, 1978). Studies on the composition of wools of high and low fibre crimp (Campbell *et al.*, 1972; 1975) support earlier findings (Chapman, 1965; Nay and Johnson, 1967; Nay and Hayman, 1969; Nay, 1970) that staple crimp is highly related to follicle shape and depth. Watson *et al.* (1977) and Whiteley *et al.* (1978) in later studies, further established the relationship between follicle curvature and resistance to compression. This observation may have biological significance from a viewpoint that since follicle structure develops at a relatively early age and is not influenced by level of nutrition (Nay and Jackson, 1973), it may be feasible to select animals with the propensity to produce high loose wool bulk fleeces at an early age. Whiteley *et al.* (1978) supported an earlier finding by Campbell *et al.* (1975) that because the correlation between staple crimp and follicle curvature is quite strong, follicle curvature and fibre growth rates are the major factors determining single fibre crimp.

FIBRE STRUCTURE

Auber (1952) pointed out certain characteristics of the follicle bulb which may play a role in defining fibre morphology. He hypothesized that crimp formation was associated with cyclic changes in the follicle. The mechanism was based on concepts of deflection of the bulb, curvature of the follicle and asymmetry of keratinization.

The morphological mechanisms causing bulb deflections have not been well defined, but may be related to a difference in mitotic activity in different regions of the deflected bulb (Schinckel, 1961, 1962; Fraser, 1964; Wilson and Short 1979; Williams and Winston 1987). These differences may in turn be associated with differences in cell types which make up the cortex, the major component of most wool fibres which is therefore likely to determine many wool properties.

It has been demonstrated that the cortex of a crimped Merino wool fibre consists of two distinct bilateral segments, the para-and orthocortices. These are situated respectively on the concave and convex sides of the crimp waves. This unique bilateral structural arrangement was thought to be responsible for crimp due to the different cortical cell types making up the cortex (Horio and Kondo, 1953; Mercer, 1953; Fraser and Rogers, 1953, 1954; Brown and Onions, 1961; Baird, 1963).

In further examinations of the cell types making up the cortex of wool fibres, the appearance of cortical cells which exhibited an intermediate staining characteristic were observed (Rogers, 1959a; Dobb *et al.*, 1961). Bones and Sikorski (1967), named these cells mesocortical cells. Subsequently the three cortical cell types (ortho, meso and paracortical) have been described on the basis of the size and distribution of their macrofibrils and the arrangement of the microfibril/matrix complex within them. Mesocortical cells exhibit intermediate characteristics between ortho and paracortical cells (Rogers, 1959b; Bones and Sikorski, 1967; Kaplin and Whiteley, 1978; Orwin *et al.*, 1984). Kaplin and Whiteley (1978) observed that the fine structure of the three cortical cell types differed primarily in the ratio of microfibril to matrix with paracortical cells exhibiting the lowest ratio. The obvious differences then between these cell types is the arrangement and relative proportions of microfibril and matrix proteins that constitute the fibre cortex. The average proportion of microfibrils in the paracortex is about 33-48% by volume, and in the orthocortex, 67-70% by volume (Dobb, 1970). With the association between crimp and bilateral structure of fibres, Brown and Onions (1961), supported by Baird (1963), likened a growing fibre to a bimetallic strip, whose dissimilar metals contract at different rates due to temperature change. Crimp in wool was considered to arise from differential longitudinal swelling of ortho and paracortical cells with the extent of fibre curvature dependent on the relative amount and distribution of each cortical cell type. Kaplin and Whiteley (1978) also observed that high-crimp Merino wools exhibited a higher content of high-sulphur proteins when compared to low-crimp wools, consistent with their observation that high-crimp Merino wool consists of orthocortical and paracortical cells, whereas low-crimp Merino wool consists of orthocortical and mesocortical cells with only a very small proportion of paracortical cells. Separation and isolation of ortho and paracortical cells from wool fibres with the subsequent extraction of their proteins has shown a somewhat greater content of high-sulphur proteins in the paracortex than in the meso and orthocortex respectively (Kulkarni *et al.*, 1971; Dowling *et al.*, 1990).

Bones and Sikorski (1967) suggest that the percentage of orthocortex remains constant whereas the amounts of para and mesocortex, and ultimately the sulphur content of the wool, are dependent on the amount and composition of the matrix protein. Studies conducted on Merino ewes which have been selected for high (6.8 crimps per cm) and low staple crimp frequency (2.6 crimps per cm) using ewes derived from a common genetic origin and maintained under similar environmental and nutritional conditions (Campbell *et al.*, 1972), have provided information that relates to the compositional differences observed between high and low crimp wools. The sulphur content of the low crimp wools was lower (3.18%) than the sulphur content of the high crimp wools (3.69%). This confirmed earlier observations by Thorsen (1958) and Snyman (1963) that the sulphur content of wool is proportional to the rate of crimping. Mowat *et al.* (1982) observed a difference in high-glycine-tyrosine (H-G-T) proteins compared to high-sulphur proteins in the matrix of orthocortical cells of different wools, including the high and low crimp Merino wools. H-G-T proteins have a higher proportion of hydrophobic amino-acid residues compared with high-sulphur proteins (Crewther, 1976). This suggests that orthocortical cells with a high ratio of H-G-T proteins to high-sulphur proteins contain less absorbed water before keratinization. These cells may therefore contract less during drying after keratinization than orthocortical cells which exhibit a low ratio of H-G-T proteins to high-sulphur proteins. Thus crimp frequency may be related to the relative amounts of the two types of matrix protein in the orthocortical cells and hence the relative proportions of the three types of cortical cells and their location in the fibre cortex.

CONCLUSIONS

Loose wool bulk or resistance to compression are two definitions of similiar properties of wool fibres. Loose wool bulk is a positive characteristic relating the desirability of a wool for knitting or carpet manufacturing. Resistance to compression, in the worsted industry, is a negative characteristic associated with a wools softness or handle. High resistance to compression values equate to a harsh handle, which is undesirable in the worsted fabric industry. Both of these terms relate to the single fibre crimp structure in a fibrous mass and its response to pressure.

Crimp has been shown to be the most important characteristic of wool fibres in relation to loose wool bulk or resistance to compression. Crimp formation in the Merino breed has been related to follicle structure, cell mitotic activity, and cellular differentiation within the follicle bulb. These in turn lead to different cortical cell types. There has been little work to attempt to describe Romcross wools and the underlying mechanisms responsible for within and between breed differences in loose wool bulk. Are the mechanisms the same between the Merino and crossbred types of wool and if so are the factors such as follicle structure and cortical composition responsible for the demonstration of bulk characteristics? Answers to these questions will provide an improved understanding of the structural basis of bulk with a long term view of increasing the bulk of the New Zealand Romcross clip.

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