ECHANICAL PROPERTIES OF MEAT

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Introduction

The tenderness of meat, and its texture in general, are important factors in the consumer's choice. In the absence of any direct ssification of the muscles, the potential tenderness of meat is judged on the basis of anatomical criteria, such as the type of muscle and the ade of carcasses. However, these criteria do not provide a sufficiently clear indication of this potential, which is of great importance, for ef in particular, since it dictates not only the commercial value of the meat but also the manner in which it will be treated (the type of oking required, whether it will be tenderised, or processed). Consequently, it is of great interest to find a reliable means of accurately essing meat tenderness. This property can vary greatly between animals and also depends on rearing and slaughtering methods and on w the meat is processed and marketed. There are thus large differences in the tenderness of commercially available meat, even in muscles the same category as still shown recently by MORGAN *et al*., (1991). In addition, new developments in production and transformation hniques, such as the breeding of leaner animals, the use of anabolic substances, drastic refrigeration conditions and a more rapid mercialisation, have, to varying degrees, had a harmful effect on meat tenderness (SMULDERS *et al*., 1991).

Tenderness can be defined as the ease, perceived by the consumer, with which meat structure is disorganised during mastication. hough tenderness cannot be strictly defined in physical terms it involves the aptitude of meat to be sheared, compressed and ground ing consumption and therefore depends directly on the mechanical properties of the muscles. Hence mechanical methods were widely d to determine tenderness. The various devices developed have been described in several detailed reviews (SZCZESNIAK and RGESON, 1965 ; STANLEY, 1976 ;VOISEY, 1976 ; HARRIS and SHORTOSE, 1988). For a long time, studies dealt mainly with the el of correlation observed between results obtained with mechanical methods and those from sensory analysis. This approach had wbacks since the correlation coefficients between the results of sensory and mechanical analyses varied greatly and sometimes were not nificant depending on the experimental conditions and the factors responsible for variation in texture. Numerous reasons have been gested to explain these results. For some authors (VOISEY, 1976) the discrepancies observed were due to the fact that the mechanical s, which are generally empirical, were performed under conditions that were ill managed and far removed from those of sensory analysis. ost tests, the samples were submitted to complex strains under the effects of shearing, compression and traction which varied according xperimental conditions with far lower strain rates than those encountered during mastication (BOURNE, 1977 ; TORNBERG *et al*., 5 ; PRÖSCHEL and HOFMANN, 1988). The major problem, however, is that texture is a multidimensional sensory characteristic that not be reduced to a single mechanical parameter as was attempted in most tests used. Furthermore, the mechanisms of mastication are o complex and are governed by parameters of load, strain and strain rate that are not known (CHRISTENSEN, 1984 ; TORNBERG *et al*., 5).

Despite these criticisms, a recent survey (CULIOLI et LEPETIT, unpublished) involving 82 organisations, belonging to both the lic and private sectors, and working in the fields of meat production, quality control and processing, showed that the most widely used %) mechanical method is the Warner-Bratzler test, an empirical technique developed more than 60 years ago (WARNER, 1928). This , which has a 80% satisfaction rate, remains the main reference. It is used in parallel with sensory and consumer panels to determine eptability thresholds for meat (SHACKERFOLD *et al*., 1991). The main other methods used to characterise the mechanical properties of at are compression tests (36%), tensile tests (27 %), made under conditions established by STANLEY *et al*.,(1971) and BOUTON and RRIS (1972c), penetrometry (25%), multi-blade shearing (KRAMER, 1951) and bite tests (10 %) (VOLODKEVICH, 1938). Most tests determining meat tenderness, therefore, have been in use for quite some time and little work has been done in recent years to devise new s. Research has focused on a more analytical approach based on tests performed in closely controlled conditions and having a twofold ective : (i) to determine the structural causes of meat toughness and suggest possible treatments to offset defects in texture and (ii) to have ller understanding of the mechanisms and structures involved in the phenomenon of rupture caused by mastication.

The mechanical properties of meat are closely related to the characteristics of its structural components such as the extent of ageing, length of the sarcomeres, pH and water retention in the myofibrillar structure, the amount of collagen, its cross-linking state and hence its rmostability, and the spatial distribution of the connective tissue. The aim of this review is to examine the information yielded by chanical studies on the structural characteristics which influence meat tenderness.

Structural peculiarities of muscle tissue

Meat is a composite material. It is made up of several structural elements which taken together confer on the whole properties that parately the different components do not possess. Muscle tissue can be considered as a collection of cylindrical muscle fibres, representing out 85 % of the volume, joined together by connective tissue whose mechanical resistance is provided by collagen and elastin fibres.

The muscle fibres, 10 to 100 μm in diameter and up to several centimetres in length, make up the contractile system : they contain rge numbers of protein filaments orientated either in the direction of the axis or perpendicularly. Their internal structure has been described n detail by LAZARIDES (1980), STANLEY (1983), LOCKER (1984) and SQUIRE *et al.,* (1987). The connective tissue can be separated morphologically into three separate but interlinked entities : epimysium, the outer sheath of the muscle ; perimysium, connecti surrounding the bundles of muscle fibres ; and endomysium, which encloses each muscle fibre. The last has been described as feltwork of fibrils with no clear overall directional pattern (BORG and CAULFIELD, 1980 ; ROWE, 1989). However, SWATLAND observed that under stress these fibrils can become orientated either perpendicular or parallel to the muscle fibres. In contrast, ROWE ; 1981) has shown that, in the perimysium and the epimysium, the majority of collagenous fibres are wavy and form a well-ordere cross lattice at an angle to the myofibre axis. Collagenous fibres show a maximum waviness in rest length meat and any chang sarcomere length of raw meat induces a change in the waviness and orientation of these fibres. Elastin is found only in the epimysi the perimysium (ROWE, 1986), generally in far smaller amounts than collagen except in certain muscles such as *Semitendino* *Latissimus dorsi*, which have a special function in locomotion (BENDALL, 1967). Elastin forms a branched network and is comp large fibres (Φ~ 5-10 μm) orientated parallel to the muscle fibres and other finer fibres (ϕ~1-2μm) orientated more or less like the fibres (ROWE, 1986). The main difference between collagen and elastin fibres is that the former are very rigid and inextensible elastin fibres are much more extensible and less rigid. They have a modulus of elasticity of 10^9 Pa and 10^6 Pa, respectively (VIID 1982). In addition, unlike collagen fibres, which are greatly denatured and contracted by heating, elastin is very thermostable an mechanical behaviour is not affected by thermal treatments.

Although the present review concentrates mainly on the fibrous structures of meat, mention should also be made of the role pl water, the major constituent (~ 75 %) divided up between the intra (90 %) and extra-cellular (10 %) compartments (cf. reviews of OF al., 1989 and of HONIKEL, 1989), and by the lipids. The intramuscular lipid fraction through its rheological properties and its effect on the collagen network in particular has a beneficial influence on tenderness (KOCH *et al.*, 1989). For meat to be pal minimum content of 3 % of lipids is needed. Reconciling nutritional and sensory requirements, some authors have even defined a wi acceptability between 3 and 7.3 % of intramuscular lipids (SAVELL and CROSS, 1988).

The structural elements of muscle tissue are therefore mainly filamentous, and orientated. As a result meat is anisotropic i.e. different physical properties according to the direction considered. This anisotropy has effects not only on mechanical properties but electrical (SWATLAND, 1980) and thermal properties in the frozen state, (HILL *et al.*, 1967). It also influences the flow of water (LOCKER and DAINES, 1974 ; LAROCHE, 1982 ; OFFER *et al.*, 1989). As regards mechanical properties, anisotropy results as from the internal organisation of the muscle fibres as from the organisation of the connective tissue surrounding the fibres. As a cons of anisotropy, to establish relations between the mechanical characteristics of meat and the properties of its different structur necessary to identify not only the direction of the applied strains but also that of all the strains in the tested sample. In certain mus direction of the muscle fibres can be considered as the sole axis of anisotropy. However, in flat muscles or in muscles whose tendon direction is not the same as the direction of the muscle fibres there is at least one other axis of anisotropy (LOCKER and DAINES, ROWE, 1977) because the perimysial sheets are orientated preferentially in one direction. In addition to anisotropy, another im structural feature determining the behaviour of meat is that certain orientated elements of the structure are in a wavy state which modified by technological treatments, such as cooking. Consequently, during mechanical tests each structure undergoes different depending on how wavy it is.

The composite and anisotropic nature of meat makes it difficult to analyse its behaviour. However, these structural features hav been used in devising mechanical tests to specifically stress a given structure. Another difficulty in analysing meat lies in the fact th variations in connective tissue distribution and sarcomere length exist within each muscle and induce a large variability in the me properties (SEGARD et al., 1974). From the statistical relationship between the number of replicates and the precision i determination DRANSFIELD and McFIE (1980) recommend to use at least 7-10 replicates for the measurement of meat me properties.

3 - Influence of measuring conditions on the mechanical behaviour of meat

Among the numerous factors playing a role in mechanical test, dimensions of samples analysed and the rate of strain substantially influence the results of the measurements. STANLEY *et al.*, (1971) applied loads in tensile experiments on raw meat pa the myofibres and observed that the breaking strength decreased as the sample length increased. His explanation was that a fibre br weakest point, which is more likely to occur the more the sample length increases. This phenomenon is known as "weak-lin (MORTON and HEARLE, 1969). In addition, LEWIS and PURSLOW (1990) reported that when a sample of cooked meat was perpendicular to the muscle fibres, the breaking stress increased with the thickness of the sample in the direction perpendicular to the fibres. This is because the probability of an intact perimysial ribbon being included in the specimen increases with specimen th When no perimysium strands are present in the samples, the breaking stress is supported by the perimysial-endomysial junction stress necessary to produce perimysial-endomysial separation is lower than that needed to break perimysium strand. In shearing tes (1971) showed that shear stress was proportional to the thickness of the sample up to a limit of 1 cm in meat. At greater thickness stress reached a plateau value, owing to the difficulty of concentrating all the stress along a shearing plane in a product that is com thick. This difficulty is not restricted to meat samples and has also been encountered in tests with spun protein fibres (LAR SALÉ, 1976), but nevertheless depends greatly on the products tested and the measuring geometry (CULIOLI and SALÉ, 1981).

The mechanical behaviour of meat is complex , with a viscoelastic contribution, and its mechanical properties therefore depend on rate at which strain occurs. However, the influence of strain rate in meat is only slight, whatever the test used. In tensile tests, on raw at, for example, an increase in strain rate from 5 to 25 % per minute resulted in an increase of only 20 % in the resistance measured at d point (LOCKER and WILD, 1982). Furthermore, breaking strength in tensile tests with cooked meat did not significantly vary when strain rate was within the range of 2 to 10 % per minute, whether strain was applied parallel or perpendicular to the muscle fibres RSLOW, 1984). During sinusoidal compression of raw meat, the influence of test frequency on the maximum stress was slight and eased when the maximum strain increased. At 20 % strain, an increase in frequency by a factor of 100 produced an increase in strength factor of 2, whereas at 80 % strain the increase was only 1.2 (LEPETIT and SALÉ, 1985). In the same testing conditions, KAMOUN CULIOLI (1988) showed on cooked meat that whatever the cooking temperature, the compression ratio and the directions of strains, the ss at maximum strain rate increased only by a factor of 1.2 to 2 when the frequency increased by 100. But because of earlier ruptures at rates, the maximum stress was not influenced or might even slightly decrease. The influence of strain rate has also been studied in aring performed in harmonic range at low strains. An increase in frequency by a factor of 100 also produced an increase by about 2 in the plex and elastic moduli in a frequency range of 10^{-3}-10 Hz (ALARCÓN-ROJO, 1990).These results show that it is important to clearly ne the testing conditions for strain rate. However, because the influence of this factor is limited, even in a range including masticatory ditions, analysing the mechanical properties at high strains would not lead to improvements in sensory-instrumental relations, unlike it been suggested.

Analysis of muscle fibre properties from mechanical behaviour of meat samples.

Tensile tests

Several kinds of deformation (compression, shearing, traction) have been investigated to analyse muscle fibres. When the rmations are applied parallel to the myofibre axis in a tensile test, the resulting stresses can be transmitted by the sole internal ponents of the myofibres without the participation either of their membranes or of the connective tissue. Thus, tensile tests have been ely used to study the mechanical properties of muscle fibres. These properties can be determined either by following the stress or strain eloped in isometric and isotonic tests or by analysing the relations between stress and strain in tests in which these two parameters vary ultaneously.

With isometric tests it is possible to monitor the active properties of myofibres during *rigor* onset and their passive properties after r (JUNGK *et al*., 1967 ; BUSCH *et al*., 1967 ; LACOURT, 1972 ; KHAN, 1974). These tests have the advantage of not applying any in that might modify the kinetics of the phenomenon studied. However, y yield no information on the mechanical properties of meat (moduli, osities, breaking strength) as the samples are not submitted to any strain. pite this, some authors (KHAN, 1974) have established relations between ximum tension developed at *rigor* and shear force determined *post rigor*.

Isotonic tests have also long been used to follow the variation in the chanical properties of the myofibrillar structure during *rigor mortis* onset d ageing. When a muscle is submitted to isotonic tension in the direction of fibres, it extends and then recovers all or part of the subsequent ormation once the load is released. The variation in extensibility during onset of *rigor mortis* has been studied with varying loads : 5-25 g/cm^2 URRIE and WOLFE, 1979), 40-70 g/cm^2 (BENDALL, 1973), and up to 0 g/cm^2 (HONIKEL *et al*., 1983). Greater stresses destroy the structure of muscle, which does not regain its initial length after load release. wever the test conditions (stress applied, sample slack length) may have an ect on mechanical evolution *post mortem*. DRANSFIELD *et al*.(1986) ng a cycle procedure between two stress values (0.1 N/cm^2 and 0.3 to 2.1 cm^2) showed that the greater the upper limit of the stress was the sooner st *rigor* remanent extension occurred. Cyclic low deformation tests applied n raw *post rigor* meat must be used with caution to follow ageing.They can obably induce a fatigue of the material at low strains (LEPETIT, 1992). They are more adapted to study rigor onset.

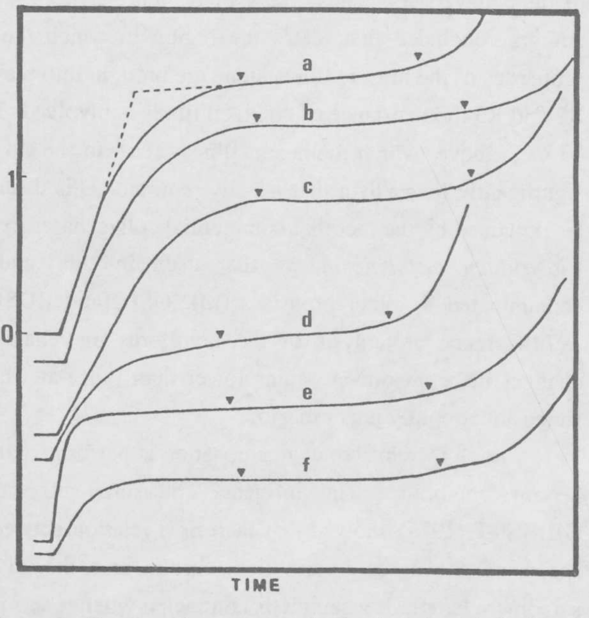

Figure 1 : Tension-time curves obtained at rigor (a,b,c) and after ageing during 1 day at 15°C (d,e,f). Deformation rates : 25.0 (a,d), 10.8 (b,e) and 5.4 (c, f) % / min. ▼ : 50 and 100% extension. (From Locker and Wild, 1982).

It is more common to analyse stress-strain relations obtained in monotonic extension tests. BOUTON et al. (1975c) showed that an itial yield and a final yield can be defined on these curves and attributed to myofibre and connective tissue resistances, respectively. OCKER and DAINES (1975b) determined a yield point using another procedure consisting in a stepwise increase in load. In these nditions the samples suddenly reach a point at which extension continues without further loading. LOCKER and WILD (1982) observed hat this point varies during ageing of meat . Using an automatic loading system (Yieldmeter) they obtained yield point at an extension of 0 % (fig.1). Tension-time curves showed a well defined plateau in the case of aged meat and more specially at low extension rates. During ageing the yield point decreased by a factor close to 10, from 1.2 to 1.4 kg/cm^2 at *rigor mortis* to a minimum value of 0.1 to 0.2 k the case of aged *Sternomandibularis* muscle. These authors recommended using the yield point value as an index of ageing. Ho use of the method was called into question in the case of meat that had undergone cold shortening (LOCKER and WILD, 1984), wh yield force values similar to those of normal meat. In fact, this is not contradictory since the toughening caused by cold shorteni detected once the meat is cooked and is not directly linked to a lack of ageing. In contrast, the yield point of a muscle that has set i a stretched state is greater than that of a normal muscle. The yield point value increases in particular when the muscle has underg rigor extension greater than or equal to 1.4. Correction to bring the yield point back down to the same number of fibres per surfac unit decreases but does not cancel the effect of stretching. The marked increase in the yield point observed in high pre-rigor extens was attributed by these authors not to a modification of the myofibrillar structure but to the involvement of the connective tissue (L and WILD, 1982). An initial yield was also determined by CURRIE and WOLFE (1980) in the pre-rigor phase but at a higher ext varied during rigor mortis onset in relation to extra-cellular space. This yield in the pre-rigor state is probably a different event f initial yield and, according to LOCKER and WILD (1982), corresponds to some kind of failure just before the breaking of the network.

The limit strain from which the collagen fibres are put in tension has been widely studied. According to MAGID and LAW the viscoelastic properties of myofibres are mainly involved up to a 1.8 strain. LOCKER and LEET (1975) showed that isolated m without any collagen can be stretched by a factor 4, whereas connective tissue limits their deformation to a factor 2. When th waviness of collagen fibres in a rest length sample was taken into account, it was shown (LEPETIT, 1991) that the fibres are the put under tension at 1.65 strain. As all the collagen fibres are not in the same wavy state, some are put in tension at a lower str specifically measure the properties of myofibres, mechanical tests should be performed at a much lower strain than 1.65. However m can also influence the mechanical properties of meat determined at high strains. STANLEY *et al.* (1971) showed that breaking str energy at rupture decrease during ageing, and hence reveal the mechanical properties of the muscle fibres. But the action of a co was observed to reduce the breaking strength of meat samples, indicating that the connective tissue is also involved in this m parameter (EINO and STANLEY, 1973).

To determine more accurately the strain at which myofibres and collagen fibres simultaneously bear stress during a ten SACKS *et al.*, (1988) analysed the effect of a collagenase treatment on the stress-strain curves obtained with extension parallel to the fibres. The authors divided up the curve into three distinct areas (fig.2) : a first region, R1, between 0 and 13 % of deformation ; R2, up to 70 % and a final one, R3, where there is rupture. None of the mechanical parameters characterising R1 was affected by of the collagenase whereas those of R2 and R3 were modified. The authors concluded that R1 is the region in which the mechanical properties of the muscle fibres alone are brought into play whereas in R2 and R3 the resistance of collagen fibres is involved. The strain of 13 %, above which collagen fibres start to be in tension, is significantly lower than that usually reported. This discrepancy may be explained by the fact that commercial collagenases extracted from *Clostridium histolyticum*, as that used in this study, may be contaminated by other proteases (MIYOSHI and ROSENBLOOM, 1974). Hence proteolysis of the myofibres may have caused the changes in behaviour at strains lower than those at which collagen fibres are normally under tension.

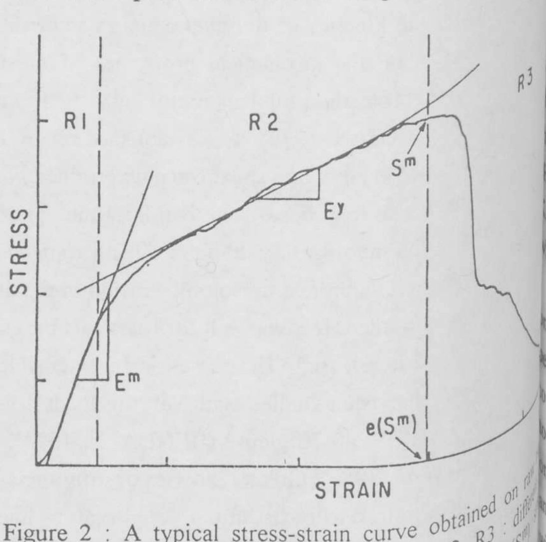

Figure 2 : A typical stress-strain curve obtained on ra tensile test parallel to muscle fibres. R1, R2, R3 : diff regions ; E^m, E^y : moduli ; S^m : maximum stress ; e(S^m S^m. (From Sacks *et al.*, 1988).

Even if myofibre characterisation is performed at low strains, certain conditions can influence measurement. DAVEY and GILBERT (1977) showed that there is a relation between the initial shape of the force-deformation curves and the distribution of sarcomere length. If a sample is contracted when it sets in rigor, only some of the fibres are involved in the contraction while the others are simply crimped (VOYLE, 1969). Consequently, only the fibres bear the initial stress, and this affects the modulus measured at low strain. Crimping of the fibres can also occur in certain m set in *rigor* in a state of extension. Some muscles present *post rigor* contraction when the forces maintaining the muscle in released. This phenomenon, described by ROWE (1982a, b), is due to the elastin fibres of the connective tissue (LEPETIT, muscles which have undergone such a *post mortem* contraction, myofibres are crimped and are not involved in the mechanical re low strains. So the relation between the mechanical resistance at low strains of a raw meat sample and that of its myofibres is evident to establish.

Ageing influences not only the breaking strength of myofibres but also their viscoelastic properties which can be stud relaxation tests. STANLEY *et al.* (1971) has shown that the parameters characteristic of relaxation curves obtained on ra modified during ageing. The amplitude of the force decrease, in particular, is higher for aged than for rigor meat. SACKS

NER *et al*. (1974), MAGID and LAW (1985) have proposed mathematical equations to model the force-time relationships.

Tensile methods can still be used to follow the variation of the mechanical properties of the muscle fibres after meat has been cooked. e-deformation curves can always be analysed in terms of initial yield and final yield (BOUTON *et al*., 1975c ; LOCKER and CARSE, 6 ; LOCKER *et al*, 1983 ; RAO and GAULT, 1990). The initial yield can however become simply an inflexion point on the curves and even be undetectable after cooking at temperatures higher than 70°C (LOCKER and CARSE, 1976). The interpretation of initial and yields in structural terms is more ambiguous than in the case of raw meat. The extent to which the collagen network is contracted nds on the cooking temperature, and the effect of this network on the mechanical properties of the sample varies according to the gen cross-linking state. However, LOCKER *et al*., (1983) showed that cooking conditions in which collagen was largely solubilised eased the breaking strength from 4-5 kg/cm2 to 1.8 kg/cm2, while the initial yield was not affected. These authors concluded that ective tissue plays no part in initial yield point. The decrease in initial yield of cooked meat is however far less than the drop in the yield t of raw meat.

The peak force determined on cooked meat, although dependent on the resistance of connective tissue, fell by about one third after ng (PURSLOW, 1991). This is due to the fact that the modifications in myofibre strength during ageing changed the mode of rupture RSLOW, 1991). In unaged cooked meat, owing to the high resistance of myofibres, the endomysial-perimysial junction is the first ture to fail at the boundaries of muscle bundles and so the ruptures cannot be transmitted from one bundle to the next. Bundles then fail idually and the collagen is the last structure to break and this induces high breaking strength. In contrast, cracking of fibre bundles is first rved in aged meat. Rupture is then transmitted perpendicularly to the myofibre from one bundle to the next because the perimysial-mysial junction is intact and fibre bundles and perimysium fail simultaneously. As a consequence the breaking strength is much lower and rs at lower extensions. The elucidation of the mechanisms of rupture shows that, in cooked meat unlike in raw meat, there is no direct tion between the initial and final yields and the resistance of the myofibres and connective network. The relation may depend on the ective strength of each structure, which varies, in particular with ageing time and cooking conditions.

Compression tests

The first studies on the behaviour of meat in compression were made with devices with non flat compression surfaces, which made strain pattern complex. However, these tests, usually called bite tests (Volodkevich tenderometer, (VOLODKEVICH, 1938), MIRINZ derometer (MACFARLANE and MARER, 1966), have been used to study myofibre strength in cooked meat (DAVEY and GILBERT, 4 ; RHODES et al., 1972 ; DRANSFIELD *et al*., 1980-81). It was shown in early studies (STEINER, 1939, as quoted by BATE SMITH BENDALL, 1949) using the device of Volodkevich that compression measurements could provide evidence of meat ageing. STEINER 39) observed that the load-displacement curves varied greatly according to the direction of the compression, along or across the grain, and re influenced by cooking. When samples were tested across the grain, STEINER (1939) concluded that muscle fibres and connective tissue th contribute to resistance, while only the latter is involved in the resistance of samples tested along the grain. SEGARDS *et al* (1974) lysed the mechanical behaviour of meat in compression, in a test in which the deformation was applied parallel to the myofibre axis. They owed that, at 20% compression, raw M. *Psoas major*, which is the most tender muscle, has the highest apparent modulus of elasticity while e tough *Biceps femoris* muscle has the lowest. Although not specified in their study it is likely that expected variations in sarcomere length HOSTETLER *et al*., 1972) should be taken into account to understand the different behaviours of the two muscles. SEGARS and APSALIS (1976) emphasised the role of transverse strain during compression tests and developed a two-dimensional mechanical model hich takes into account that transverse strain.

Tranverse deformations play an important role in most mechanical tests. When a sample which is not fully compressible is stressed in ne direction, it deforms not only in the direction of the applied strain, but also in two other directions, called free strain directions, erpendicular to that applied strain. This makes the analysis of the mechanical behaviour of an anisotropic product complex because ,according o the strain direction occurring in the sample, different mechanical properties are involved. In compression tests, it is easy to limit the strains o certain directions by using a cell with two lateral walls. When a sample is compressed in such a cell it can deform laterally in one direction nly and the resulting deformation is called free strain. By varying the directions of applied and free strains the whole mechanical behaviour of an anisotropic sample can be detailed. With such a cell and with a product which has only one axis of anisotropy, three basic configurations have been defined, each one referring to a defined couple of applied and free strains (LEPETIT, 988.) These three configurations are (fig.3) :

Longitudinal : - applied strain perpendicular to muscle fibres and free strain parallel to muscle fibres

Transverse : - applied and free strains perpendicular to muscle fibres

Axial : - applied strain parallel to muscle fibres and free strain perpendicular to muscle fibres.

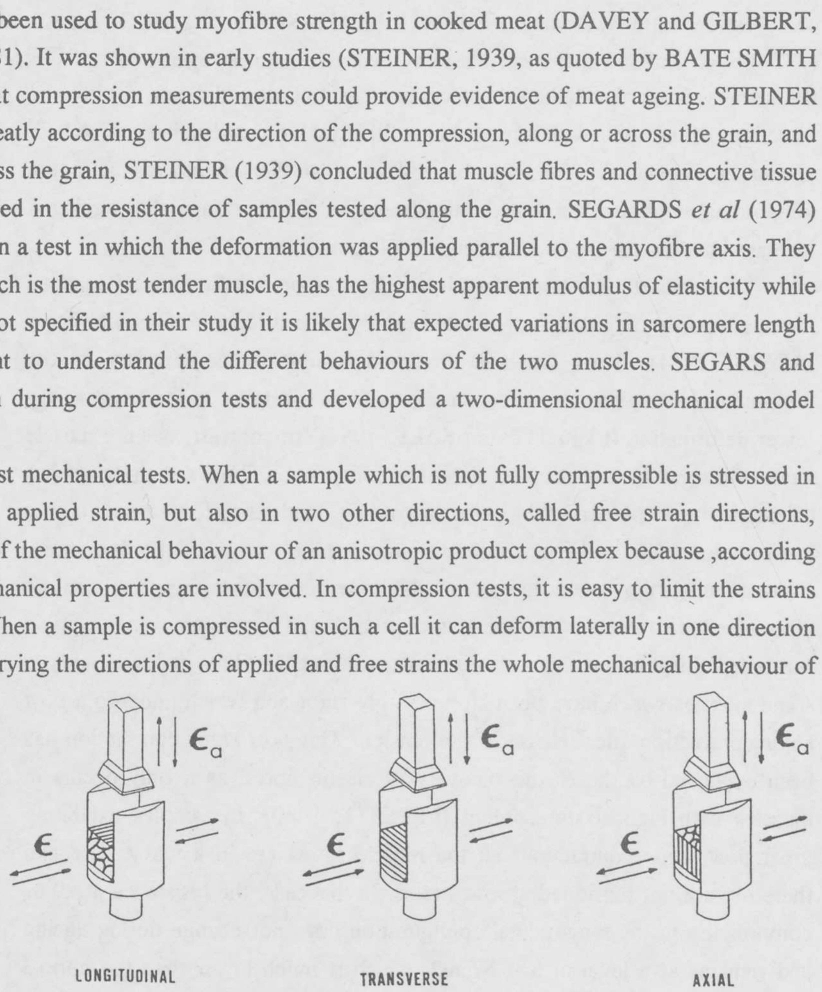

Figure 3 : Schematic representation of the 3 configurations of the compression test. ε_a : applied strain ; ε : free strain. (From Lepetit, 1988).

The behaviour of meat samples has been analysed with this cell fitted on a sinusoidal compressive device (SALÉ *et al.*, 1984). W device, according to PELEG (1978), the deformation law of tested samples is the same whatever the sample height, which is not the classical testing machines, which use a defined and constant displacement rate of the probe.

In a study using these different configurations on raw meat, it was shown that, whatever the configuration, there is a compression ratio at which sample elasticity reaches a maximum (LEPETIT, 1988, 1989). This ratio takes different values according configurations used and has been called longitudinal, transverse or axial critical compression ratio. These critical compression correspond to the strains at which all the fibres of the collagenous tissue are put under tension as a result of the free strain. For rest samples the longitudinal critical compression ratio (LCCR) is about 40%. At compression ratios below LCCR, the collagenous fibres partially unfold and do not produce any resistance linked to their mechanical properties. In the longitudinal configuration and for compressions lower than the LCCR, the maximum stress reached during one compression cycle is not related to the connective network resistance but depends on myofibre strength (LEPETIT and SALÉ, 1984 ; 1985). At 20 % compression, which is well below the LCCR, resistance rapidly increased during *rigor mortis* onset and decreased during ageing (LEPETIT and SALÉ, 1984, LEPETIT *et al.*, 1986 ; LEPETIT and CULIOLI, 1987).These mechanical changes are in close link with biochemical events occurring in the myofibrillar structure (fig.4). Moreover, after ageing the resistance measured at 20 % compression is similar (8 - 10 N/cm2) for all muscles in a normal contraction state (fig.5), (LEPETIT and SALÉ, 1984 ; 1985). Ageing can occur in cold-shortened meat which gives the same limit value of resistance as normal meat (LEPETIT, 1989). This is in agreement with the results of LOCKER and WILD (1984) on the yield point of raw meat determined in a tensile test. A 20% compression ratio was also used by TAKAHASHI and SAÏTO (1979), who showed that meat elasticity decreases during ageing in the same way as the detection of connectine, but they did not specify the directions of the applied and free strains of the test. If meat has been stretched, ageing can always be followed by resistance at 20% compression in the longitudinal configuration, but the limit value of the resistance after ageing is increased because of the involvement of collagen fibres.

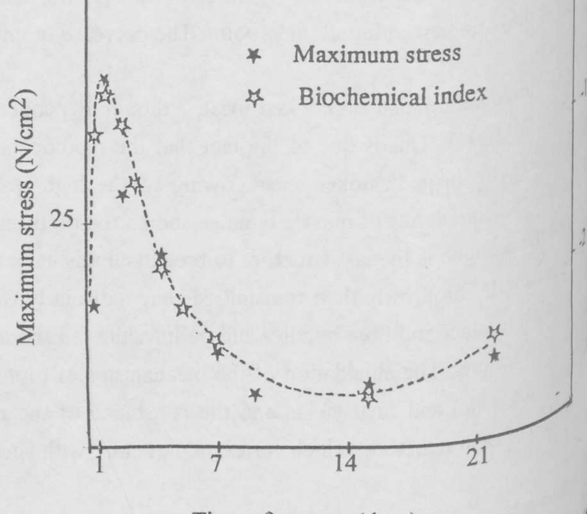

Figure 4 : Variations during storage in the maximum stress (20 % compression ratio, measured in the longitudinal config and in the biochemical index of ageing (☆). M. *Longissimus* (From Lepetit and Salé, 1984).

If a muscle has been stretched before *rigor mortis*, the collagenous fibres are partly unfolded and oriented more in the direction of muscle fibres (ROWE, 1974). Thus when a stretched sample is compressed in the longitudinal configuration, the collagenous fibre will take up the tension at a lower deformation (LEPETIT and SALÉ, 1987). In contrast, when a muscle has set in *rigor* in a contracted state, the collagenous fibres are stretched but oriented more perpendicularly to myofibres and therefore need higher compression ratios to be put under tension in the direction of the free strain. Consequently, the strain range in which myofibre characteristics can be determined decreases when meat is stretched and increases when meat is shortened. Elastin fibres can also interact with muscle fibres at low strains in some muscles which have been stretched pre-rigor and which undergo a *post rigor* contraction after release of the tension. This *post rigor* contraction has been explained by the elastic recovery of elastin fibres, as it only occurs in muscles with high elastin content (LEPETIT, 1989). In samples exhibiting great *post rigor* contraction, all the muscle fibres are in a wavy state and therefore are not tensioned at low strains. In this case, the resistance at 20 % compression in the longitudinal configuration does not change during ageing and remains at a level of 3-4 N/cm2, which is much lower than the normal limit strength of muscle fibres. Although this phenomenon is unusual, it must be detected in order to avoid any misinterpretation of the data. The strain range in which the specific characteristics of myofibres can be measured

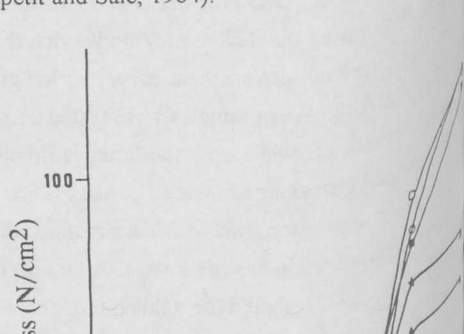

Figure 5 : Variation in maximun stress with com ratio. Longitudinal configuration. Sarcomere leng standard deviations in brackets :

□ *Pectoralis profundus* : 2.04^b (
■ *Biceps femoris* : 1.74^a (
○ *Semitendinosus* : 2.03^b (
✶ *Triceps brachii* : 1.79^a (
▲ *Semimembranosus* : 1.99^b (
● *Longissimus dorsi* : 1.86^{ab} (
☆ *Psoas major* : 3.26^c (
(From Lepetit and Salé, 1985).

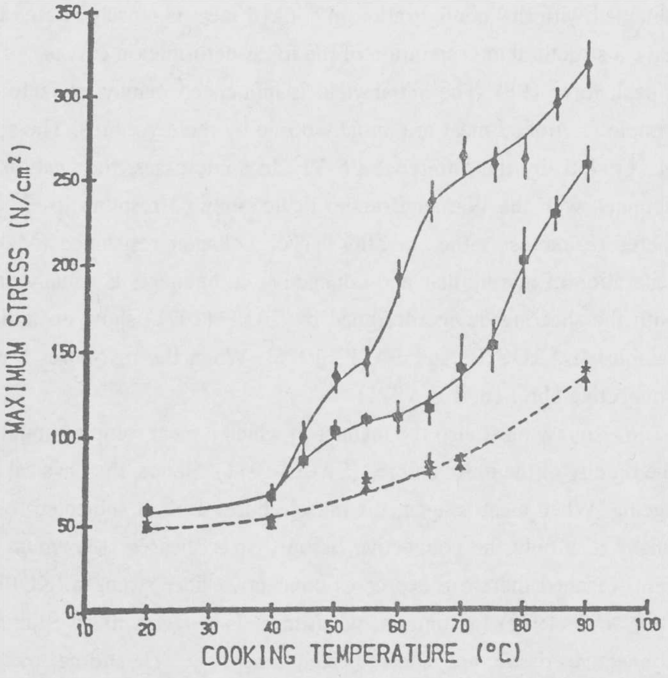

Figure 6 : Variation in maximum stress (σm) with cooking temperature. *Semimembranosus* muscle analysed in the longitudinal (——) and transverse (---) configurations at rigor (◆; ★) and after ageing (■, ▲). Core cooking length 30 minutes. Compression ratio 0.8. (From Kamoun and Culioli, 1989).

pendently of those of collagen and elastin fibres had been mined theoretically (LEPETIT, 1991).

The transverse and axial configurations, although presenting mum elasticity at a strain for which collagen fibres go into tension, e been shown to be unsuitable for the determination of myofibre acteristics, as the resistance measured in these configurations do not ge significantly during ageing (LEPETIT, 1982 1988 1989 ; PETIT and CULIOLI, 1987).

The behaviour of cooked meat has also been studied in pression tests. RHODES *et al.*, (1972) analysed the load-mation diagrams obtained during linear compression using a ified version of the device of Volodkevich that induced a zone of pression between two blunted wedges. The compression was pendicular to the muscle fibres and the sample was held between two llel walls thereby avoiding deformation perpendicular to the muscle : these conditions correspond to the definition of longitudinal guration mentioned above. In these conditions, load-deformation es present an initial peak at about 50-75 % which reflects erentially muscle fibre characteristics. This parameter has been used antify meat ageing (DRANSFIELD *et al.*, 1980-1981).

In sinusoidal compression, it has been shown that, as with raw at, low strains in the longitudinal configuration can be used to sure muscle fibre strength in cooked meat samples (KAMOUN and LIOLI, 1988), but only at temperatures which do not contract gen fibres. When collagen does contract, resistance at low strains, in contrast, depends on muscle collagen content. When strain is high, ss-strain curves show a rupture which can be more or less distinct. This rupture occurs for strain that decreases during *post mortem* time in 45 and 75 % range. Stress at break decreases *post mortem*, particularly when cooking temperatures are around 65°C (fig.6). However, it is uenced by the connective tissue (KAMOUN and CULIOLI, 1989). In contrast, the stress measured in the transverse configuration did not ge during ageing denoting the resistance of connective tissue (fig.7). The authors suggested using the ratio of the maximum strains ieved in the two configurations as an index of ageing for cooked meat. This ratio is independent of collagen content, and consequently of type of muscle, and approaches a value of 1 in meat aged for a long time. However, this index may be influenced by the contraction or etched state of the muscles as the number of fibres (myofibres and connective fibres) taking up the tension in the longitudinal test and the sverse test varies in opposite directions when the contraction state changes.

It is difficult to understand the mechanical behaviour of cooked meat because cooking modifies its compressibility. It is widely epted that raw meat, like muscle, is incompressible (Poisson ratio μ = 0.5) in the strain range corresponding to that of physiological strain. wever, SEGARDS *et al.*, (1977) showed that, at 20 % strain, meat cooked to 63°C became slightly compressible (0.20 < μ < 0.26), in ich case the value of the Poisson ratio will determine the extent of the free strain appearing in a mechanical test in response to a strain posed. It would be necessary therefore to know both the imposed and e strains to determine how the different elements or structures of a mple are stressed (SEGARDS and KAPSALIS, 1976).

3 *Shear tests*

Studies on meat shearing are the most numerous in the field of at research. Almost all have been made with the Warner-Bratzler vice (WARNER, 1928) and have dealt mainly with cooked meat. The ults obtained with this device often serve as a reference in mparative studies even though the mechanical significance of the rameters measured are not clearly established and have been widely iticised (VOISEY, 1976). As in tensile and compression tests, the ientation of the strains imposed in relation to the myofibres influences e shear force values (MURRAY *et al.*, 1983). The most commonly ed configuration is that in which the shearing plane is perpendicular to e muscle fibres. BOUTON and HARRIS (1972a), PAUL *et al.*, 973), CROSS *et al.*, (1973) have shown that the maximum force

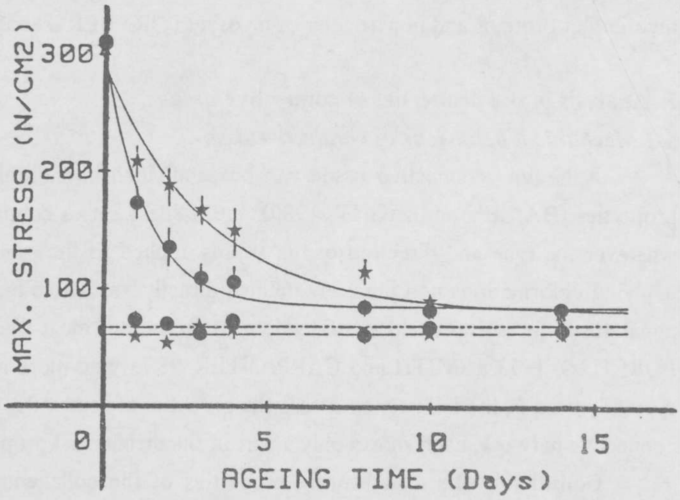

Figure 7 : Variation in maximum stress (σm) with ageing time at 6°C. *Semimembranosus* (★) and *Longissimus* muscles (●) core cooked 30 min. at 65°C. Longitudinal (——) and transverse (----) configurations. (From Kamoun and Culioli, 1989).

obtained with this configuration in cooked meat is closely related to the myofibrillar component of the meat. But BOUTON *et al.*, (gave a structural interpretation of the force-deformation curves. As in tensile or compression tests these curves present an initial yield (a peak force (PF). The initial yield is influenced mainly by factors affecting myofibrillar structure, suggesting that the strains appli sample of cooked meat are initially borne by the myofibres. The strength of the connective fibres can be assessed according to BOU *al.*, (1975b) by the difference PF-YF. In some cases, the analysis of peak force alone can lead to false conclusions ; the maximum obtained with the Warner-Bratzler device may correspond to either the initial or the final yield depending on how the meat is coo therefore express either myofibrillar or collagen resistance (MØLLER, 1980-1981). Moreover in the case of cold-shortened m separation of myofibrillar and connective components is usually difficult (BOUTON *et al.*, 1975c). The diagrams obtained on cook with the shearing device designed by SALÉ (1971) show no initial yield or peak force, and stress reaches a plateau at the rupture samples (LAROCHE and SALÉ, 1976). When the myofibres are rigid, as in cooked meat, there is simultaneous shearing of musc connective fibres (SALÉ, 1971).

In raw meat also the manner in which a meat sample submitted to shear strain between a blade and two knives is deformed dep the rigidity of the muscle fibres (SALÉ, 1971). Hence, the physical significance of a mechanical parameter measured during a test chang ageing. When meat is aged, the muscle fibres are not subjected to shearing : their content is gradually pushed away from the stress a finally it is only the connective tissue that is sheared. Maximum force (Fm) reached therefore expresses connective fibre strength (KOPP and BONNET, 1982) In contrast, when meat is in *rigor*, muscle fibres and connective tissue are sheared simultaneously. The force measured increases more rapidly but reaches a lower maximum value, characteristic of the couple myofibres-connective tissue (fig.8). The energy (W) expended to achieve rupture decreases during ageing but depends on collagen content. Conversely, the ratio W/(Fm x e)), which includes the initial thickness (e) of the samples and reflects the shape of the diagrams, is independent of the connective tissue and can be used to make a quantitative measurement of ageing (SALÉ and VALIN,1970).

Shearing tests made on compliant composite products such as raw or cooked meat are therefore complex operations highly dependent on experimental conditions and difficult to interpret in structural terms. This could explain why results varied according to the system u particular the fact that the shear stress of raw meat in different tests (SALÉ and VALIN, 1970 ; BOUTON and HARRIS, 1972b) was fo be lower than that of isolated muscle fibres, i.e., completely devoid of collagen fibres (MARSDEN and HENRICKSON, 1977).

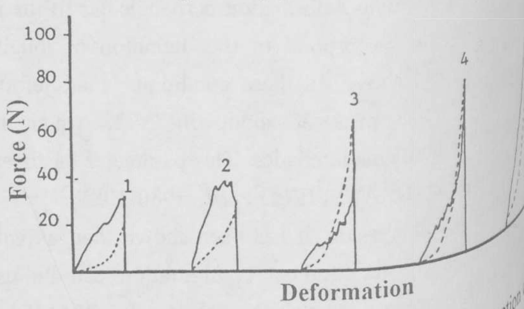

Figure 8 : Influence of ageing on the force-deformation c obtained in shearing. M. *Longissimus dorsi* (1), *Psoas maj* *Semitendinosus* (3), *Pectoralis profundus* (4) and *Tr* *brachii caput laterale* (5). (——) 1 day and (---) 8 day *mortem*. (From Salé, 1971).

Shear tests have also been used to analyse the viscoelastic properties of meat with low shear rheometers. In this technique, samp submitted to very low sinusoidal stress or strain between two parallel plates, making it possible to continuously monitor rheological be without causing destruction of the samples. The method has been used to study raw meat properties (ALARCÓN-ROJO, 1990 perform thermal scanning analysis on meat slices (BOHLIN *et al.*, 1987 ; TORNBERG and PERSSON, 1988). Rheological paramet as complex, storage, loss moduli and loss tangent characterise the viscous and elastic parts of rheological behaviour. They are difficult to interpret in terms of the respective properties of myofibres and collagen fibres. They are influenced neither by myofibre or nor by ageing (ALARCÓN-ROJO, 1990), although a large increase in rigidity from 55°C up to 60°C seemed to reflect the gel myofibrillar proteins and in particular of myosin (TORNBERG and PERSSON, 1988).

5- Analysis of the properties of connective tissue

5-1 Mechanical behaviour of connective tissue

Although connective tissue can be subdivided into different levels of organisation, which have their own chemical and properties (BAILEY and LIGHT, 1989), the tissue forms a continuum throughout a meat sample and unlike muscle fibres can be whatever the type and direction of the strains applied to the samples. Thus it is possible to yield information on the connective applying deformations non precisely defined directly, on whole muscle. This has led to the development with various degrees of s apparatuses for the prediction of tenderness from raw meat measurements (HINNERGARDT and TUOMY, 1970 ; HANSEN PURCHAS, 1973 ; SMITH and CARPENTER, 1973, and more recently SHORTHOSE *et al.*, 1988 ; PHILLIPS, 1992). However currently used in the industry to assess the potential of tenderness of muscles. Although different types of deformation can be used connective network, each shows only a part of the mechanical properties of this tissue.

Considering the load bearing properties of the collagenous network in connective tissue, PURSLOW (1989) suggested network acts as a mechanism to prevent both over-stretching and over-contraction of muscle by providing rapidly very considerable at some limit strains. Thus, connective tissue would be the limiting factor in the rupture of meat, whatever the internal or external the two levels of organisation involved in meat texture, the perimysium plays the major role in mechanical properties whereas end acts at a more subtle level (LIGHT *et al*, 1985). Most studies on the mechanical properties of connective tissue have focused on th gen, which is the most determinant factor but some showed that h elastin and the ground substance could have an influence, albeit to a er extent (CROSS *et al*., 1973 ; BAILEY and LIGHT, 1989).

Isometric tension tests have been used to analyse the heat-aviour of collagen. They have been made mainly on collagen ctures such as the tendons, skin and isolated epimysial fibres. They sist in measuring the tension developed during continuous heating, erally in a neutral isotonic medium, up to boiling temperature. The ximum force per unit section area and the temperature at which this ce occurs have been related to the heat stable molecular cross links of collagen and to its thermal solubility (KOPP and BONNET, 1987). s method has also been used on meat samples : similar tension files were observed but with the maximum tension reached at the ximum heating temperature. The value of this maximum tension is arly related to the amount of collagen (KOPP, 1977) but is also uenced by its cross linking state (KOPP, 1976). Although isometric sion tests provide valuable information on collagen cross-linking e, particularly in the low thermal solubility range (KOPP and NNET, 1987), tests carried out on meat should be interpreted with caution since maximum tension is influenced by the contraction state of e muscle (ROCHDI *et al*., 1983) : muscles which set up in rigor in a stretched state exhibit higher tension, owing to the organisation of the nective network. Moreover, these tests do not mimic what actually happens during the cooking of meat as samples are not allowed to ely contract. These conditions of restraint directly influence the mechanical properties of connective tissue (SNOWDEN *et al*., 1977) and e denaturation of collagen (ROCHDI *et al*., 1985). To have a precise idea of the mechanical properties of intramuscular connective tissue in oked meat, LEWIS and PURSLOW (1989) recommended performing the mechanical tests directly on perimysium excised from a cooked mple.

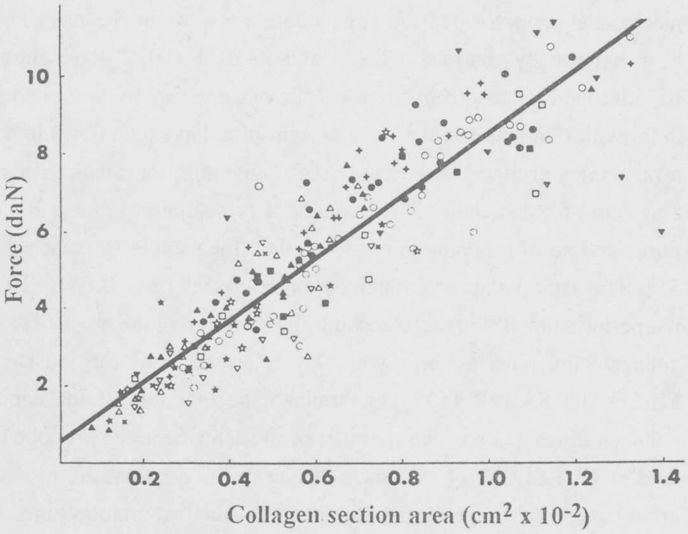

Figure 9 : Maximum shear force versus section area of sheared intramuscular collagen. 7 *Pectoralis profundus* and *Rectus abdominis* muscles. (From Kopp and Bonnet, 1982).

previously mentioned, in tensile tests in which deformation is plied parallel to muscle fibres, whether on raw or cooked meat, the eaking parameters depend on the properties of both the connective ue and muscle fibres (STANLEY *et al*., 1971 ; 1972). vertheless tensile tests perpendicular to muscle fibres (adhesion t) have been proposed as a means of evaluating the specific perties of connective tissue (POOL, 1967 ; BOUTON *et al*., 72c ; PENFIELD *et al*., 1976). They allow stresses to be nsmitted throughout the sample by the connective tissue only : the eaking strength measured in that test does not vary during post-or tenderisation (BOUTON *et al*., 1972b). In this test, as in others, e strength of the connective tissue is closely dependent on the ntraction or stretched state of the sample , whether this state is hieved by changing the sarcomere length of raw meat (BOUTON al, 1974) or by thermal contraction during cooking (BOUTON *et* , 1976). In fact, any change in the contraction or stretched state oduces a change in not only orientation and waviness but also in e number of collagenous fibres per unit of area under load. oreover, for a given length ratio of a meat sample, which represents e deformation of a sample compared to its rest length state in uscle, the state (orientation and waviness) of the collagenous fibres pends on how this length ratio has been reached, by pre-rigor or st-rigor deformation or by thermal contraction. Therefore, the eometrical state of the fibres in the final network must be known efore their properties can be determined from a measurement of the echanical properties of the connective network performed on a eat sample. The consequence of pre-rigor deformation on the

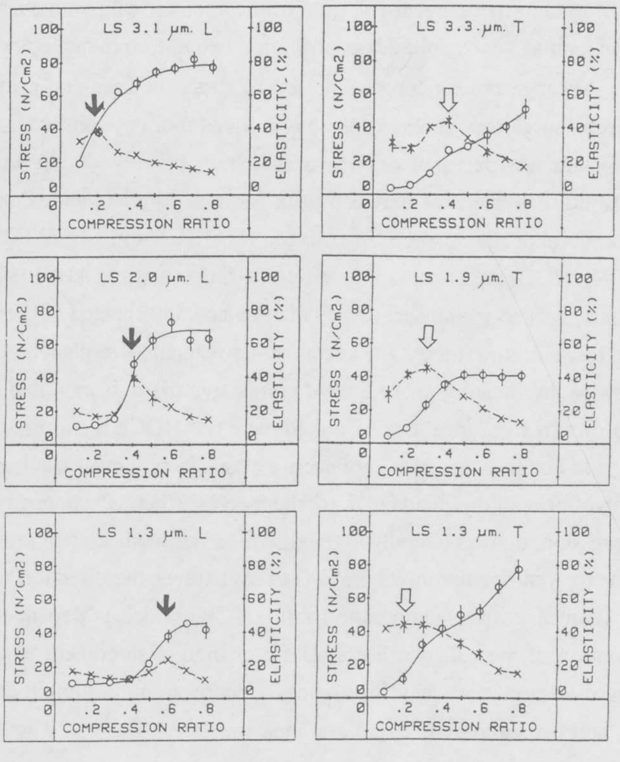

Figure 10: Influence of compression ratio on maximum stress (○) and elasticity (×) in the longitudinal (L) and transverse (T) configurations for a *Semimembranosus* muscle. LS : sarcomere length (μm). An increase in LS induces a decrease in the longitudinal critical compression ratio (🡇) and an increase in the transverse critical compression ratio (⇩). (From Lepetit, 1989).

mechanical properties of the collagenous network in the raw state have been extensively analysed. FIELD and FABER (1970) have shown that the mechanical anisotropy of the endomysium can be described by the deformation of a somewhat slack system of collagenous fibres in a helical arrangement around the muscle fibres. These authors calculated that such a system of collagenous fibres results in a maximum volume for muscle fibres and so in a minimum tension, when their angle to muscle fibres is 55° The same value was obtained experimentally by ROWE (1977) for the perimysium. Taking into account the variation in the angle between the collagen and muscle fibres with the deformation of the muscle fibres, FIELD and FABER (1970) determined the modulus of the endomysial collagen fibres and showed that it is of the same order as that obtained on tendon. PURSLOW (1989) showed that in the perimysium, in which the arrangement of the collagen fibres, unlike in the endomysium, can be clearly observed, there is a great variation in the angle between the collagen and muscle fibres on both sides of the theoretical value determined for a given sarcomere length. Considering the volume fraction of perimysium in muscle, PURSLOW (1989) predicted the stress produced by collagen fibres in tensile tests parallel to the muscle fibres on pre-rigor meat and concluded that the stiffness of the perimysium was negligible up to about 3.8 µm. As there is a direct relationship the limit sarcomere length in tension and the limit sarcomere length in contraction, this result implies that collagen fibres can be str contraction only at sarcomere lengths lower than 0.9 µm. The results of a study that considered both the waviness of the pe collagenous fibres in rest length meat and the usual limit of 1.1 µm for sarcomere length in cold-shortened meat showed that the con of collagen is negligible in a narrower range, between 1.1 µm -3.3 µm (LEPETIT, 1991). This is in agreement with the results of DAV DICKSON (1970), which give higher values of tensile stress of meat from 3.2 µm–3.3 µm than those predicted by the model of PU (1989). In fact ,there is a distribution of the geometrical parameters of collagenous fibres around a mean value, which makes it difficult precise limit at which collagen contribution becomes non negligible.

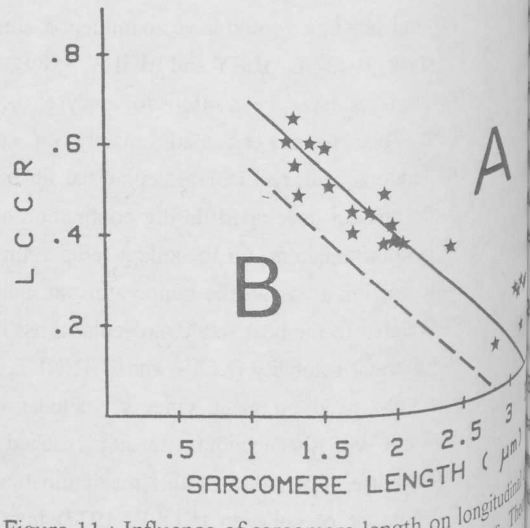

Figure 11 : Influence of sarcomere length on longitudinal compression ratio (LCCR). M. *Semimembranosus*. The curve (——) ; Curve vertically shifted by 0.15 (experimental points ; (A) strain range where collagenous are under tension or broken ; (B) strain range for mus strength measurement. (From Lepetit, 1991).

Shear tests have long been used to study the breaking properties of meat mainly with the Warner-Bratzler device. In such a s has been shown that sample rupture is induced more by tensile strains than by shearing strains (VOISEY, 1976). HARRIS and SHOR (1988) later restricted this conclusion to raw or only slightly cooked meat. The resistance of connective tissue is usually deter measuring the difference between peak force and initial yield. Indeed that difference is not affected by ageing of meat and varies in th manner as expected changes in collagen (HARRIS and SHORTOSE, 1988). Shear strength of raw meat samples has been studied by and BONNET (1982) using a specific shearing system (SALÉ, 1971). These authors showed that the maximum shear force of raw m is linearly related to the section of collagen actually sheared (fig.9), but that the degree of collagen cross-linking does not affect the m shear force of raw meat. An accurate assessment of collagen strength by this method can be obtained only if myofibre strength otherwise the shearing procedure of connective tissue is modified (SALE, 1971). It is therefore not suitable for determining collagen s either on raw rigor meat or on cooked meat (LAROCHE and SALÉ, 1976).

In compression tests, connective tissue in raw meat can be analysed at high strains only, whether the free strains are in the direc the myofibres or perpendicular to them. Nevertheless, connective tissue is the structure preferentially strained if the sample can compression, deform laterally in the direction perpendicular to muscle fibres (LEPETIT, 1982 ; 1989, LEPETIT and CULIOLI, 1987 similar to what occurs in adhesion tests .Whatever the direction of free strains the connective network is put under tension at a com ratio (named critical compression ratio, CCR) which is dependent on sarcomere length as a result of variations in both the wavines orientation of the collagen fibres. But a change in sarcomere length has an opposite effect according to the direction of the free stra increase in sarcomere length produces a decrease in the longitudinal CCR and an increase in the transverse CCR (fig. 10). The long CCR and the sarcomere length are linearly related (fig. 11). These results have been confirmed by ABUSTAM *et al.* (1987) who stu variation in the correlation coefficient between maximum stress reached during compression of raw meat and collagen content. Wha free strain direction, these authors showed that the correlation coefficient increases in a sigmoid fashion with the maximum strain during the test, becomes significant from 0.3-0.4 strain range and reaches a maximum value (~0.8) in destructive conditions. After maximum stress at a high strain can still be related to collagen content (CULIOLI *et al.*, 1990) but the correlation coefficient then lower values closely dependent on the thermal stability of the collagen and on cooking conditions. In cooked meat the collagen netwo under tension at lower compression ratios because of the thermal contraction of collagen (KAMOUN and CULIOLI, 1988) but determination of the CCR has not been performed yet and is made more difficult owing to the large increase in myofibre strength concomitant decrease in that of the perimysium (LEWIS and PURSLOW, 1989). Connective network strength can be more determined when meat samples completely break. Hence tensile and shear tests are more suitable than compression and bite tests, in w cult to reach rupture in reproducible conditions. However, even in tensile tests rupture of connective network in cooked meat follows a plex pattern which depends on the direction of the applied strain with respect to the myofibres and on the respective strengths of ofibres and collagen fibres (PURSLOW, 1991). Tensile tests along the myofibres is ten fold higher than that measured across the fibres, ich indicate a participation of myofibres in the former case. Although in compression the ratio between longitudinal and transverse stresses lso linked to the myofibre strength, this ratio is much lower than that obtained in tension (KAMOUN and CULIOLI, 1989). In tensile tests oss the myofibres the first event seen is the opening up of cavities between fibre bundles involving the peri-endomysial junction RSLOW, 1985). Then the cavities join up and finally perimysial strands rupture. The breaking strength is determined by the amount and stance of perimysium. The maximum stress reaches values in the 30 to 60 kPa range whether or not intact strands of perimysium are sent in the sample tested (LEWIS and PURSLOW, 1990).

Effect of the organisation of the connective network on the mechanical properties of meat.

Although it was first suggested many years ago that the pattern of the perimysial network has an effect on meat tenderness (BRADY, 7) it is the least studied of the different characteristics of connective tissue that influence the mechanical properties of meat. Yet, in raw at, it may contribute to the 30 to 40 % variance in the mechanical resistance of the connective tissue not due to the level of collagen tent (DUMONT, 1985 ; 1988). Furthermore, this pattern is a criterion in the professional assessment of muscles based on the coarseness eir grain determined subjectively by passing the thumb over a muscle section (HAMMOND, 1952).

The connective network, by its mechanical action, is directly involved in muscle development. It dictates the shape of the muscle and it deforms during contraction. The pattern of the network varies widely between muscles and also between animals (SCHMITT *et al.*, 9) and so is dependent on genetic type. In double muscle animals there are large bundles and very thin connective sheets (BOCCARD *et* 1967 ; DUMONT and SCHMITT, 1973), while crossbreeding of Bos indicus with Bos taurus produces a coarser-grained meat RMAN, 1982), and offspring of male Angus, Hereford and Shorthorn have finer-grained meat than that of male Charolais, Brangus and hman (DAMON *et al.*, 1960).

There have been conflicting results on the relation between the size of the muscle bundles bordered by the connective sheets and the derness of the meat. Some workers associated large bundles with a finer structure and greater tenderness (BRADY, 1937) while others erved a negative relation between these features (COOPER *et al.*, 1968). These discrepancies can be partly explained by the complexity the structural organisation (fig.12) and the different levels of structuring should therefore be taken into account ,(DUMONT, 1985).

The influence of the connective network organisation on the mechanical properties of meat has been evidence in the studies of WE (1977). This author studied the mechanical behaviour of raw scle slices subjected to tensile stress perpendicular to the axis of myofibres and observed that the direction of the stress in relation the orientation of the connective lamellae directly affected the ent of deformation in creep test and the moduli measured during sion tests. The orientation of the lamellae depends on the shape, e and orientation of the muscle bundles and varies within a same scle and between muscles (ROWE, 1977 ; SIRET *et al.*, 1990). rt of the variability in mechanical properties between muscles and ween samples from the same muscle might thus be due in part to e distribution of the perimysium which could also be responsible r the low correlations obtained between measurements made on fferent samples of raw and heated meat. Finally, it is likely that the acture behaviour of cooked meat is also influenced by the ganisation of the connective network.

The influence of the connective network organisation on the echanical properties of meat has been confirmed by the studies of UMONT (1988). This author showed that the relation between the ear strength measured on raw meat and the collagen content of the uscles depends on the type of muscle and animal. He suggested ing the ratio F/C, in which F is the mean shear force on raw meat nd C the collagen content expressed by the ratio hydroxyproline itrogen/total nitrogen, as a structuring factor of the connective etwork on which the mechanical properties of meat partly depend. He has also shown (DUMONT, 1983) that the linear density of the onnective network (the number of lamellae per length unit) in raw meat measured, considering all the structural levels, according to the onger axis of large stained histological sections cut perpendicular to the myofibres is closely related (r = 0.89) to the maximum shear force.

Figure 12 : Different levels of organisation of the perimysial network. Muscle section (a). Primary (b), secondary (c), tertiary (d), quaternary (e) and principal (f) bundles. (From Schmitt *et al.*, 1979).

By taking into account just the main sheet of the network, ABUSTAM *et al.* (1987) obtained similar results in a compression test. Ho no conclusive results have emerged from the various studies on the incidence of the perimysium distribution on mechanical pro because variations in the network are always accompanied by related variations in collagen content (ABUSTAM *et al.*, 1987) collagen thermal solubility (NORMAN, 1982) whose respective impacts have not been determined. Furthermore, the relations betw mechanical measurements and the characteristics of the network are often restricted to linear density, just one of the 26 descriptors d by DUMONT (1985). The thickness of the main and secondary sheets, in particular, should also be taken into consideration. These come up against the problem of obtaining a perfectly distinctive perimysial network in which the different myofibre bundles c identified. Although the connective network and its constituents can be closely studied on stained histological sections, even by au image analysis (SCHMITT and DUMONT, 1969 ; SCHMITT *et al.*, 1979 ; TOTLAND *et al.*, 1985), the same method cannot be easi to study whole sections of muscles. Consequently, a technique for obtaining whole muscle sections was designed (SCHMIT DUMONT, 1980), but with which it is difficult to totally identify the perimysial network so that analysis is often restricted to the bundles.

5-3 Application of ultrasound methods to the structural analysis of connective tissue

Ultrasound techniques have been used for some time in the meat production sector to determine simultaneous fat thickne muscular development in the live animal (KEMPSTER *et al.*, 1979 ; GLODEK, 1984) and more recently in meat processing to assess content of carcasses (MILES *et al.*, 1990). These methods are based on the analysis of the propagation velocity of the ultraso influenced by the composition of the muscles, and particularly by their fat content, or on the measurement of the distance betw ultrasonic transducer and a fat-lean meat or fat-bone interface acting as a specular reflector to the ultrasonic waves. Other ultrasound techniques have also been used to study muscle tissue, such as subjecting tissue to ultrasound pulses and analysing the diffusion ge When an incident ultrasonic wave encounters local modifications in density and compressibility in the sample studied due to stru small dimension compared to the wave length, it is diffused in numerous small waves in all directions. The signals thus diffused inte the surface of the transducer and give rise to images presenting a random graininess or mottling . This phenomenon, which is "speckle", is well-known in echographic imaging (BURCKHARDT, 1978 ; WAGNER *et al.*, 1983). Statistical analysis of this speckl of the specular reflection of the ultrasounds on structures of greater size than the wave length, characterised by impedance ruptures, pr information on intramuscular fat content and its distribution (HAUMSCHILD and CARLSON, 1983 ; BRETHOUR, 1990) and heterogeneity of the meat as influenced by the presence of connective sheets (ABOUELKARAM *et al.*, 1992). These ultrasound meth non-destructive and hence could be used to characterise and classify muscles. However, they do not provide so detailed a descriptio pattern of the connective sheets as the direct analysis of the network. Furthermore, they are not able, for the present, to distinguish b the respective contributions of the fat deposited in the connective structure and the collagen fibres, which have opposite effects on tex

The methods used to analyse the ultrasonic signals diffused could be adapted for the study of the mechanical properties of They could be used as a complement to current methods, most of which determine the overall behaviour of the product tested but are to provide information non destructively on the distribution of the mechanical properties within the sample. By coupling a static mec deformation with a high frequency (i.e. ultrasonic) mechanical deformation OPHIR *et al.* (1991) devised a method of determining el profile within a product. They correlated couples of ultrasonic lines from a sample at rest and from the same sample mechanically and showed that it is possible to determine local strain and consequently, as the applied stress is known, the values of local elastic rigid zones within the sample, not normally seen by direct observation of echographic images, can thus be detected. When applied to slab, this method clearly revealed the differences in mechanical behaviour between fat and lean tissue. OPHIR *et al.* (1991) have su that the method could be used for the quality control and grading of meat. However, the resolution, which depends among other th the wavelength used, the characteristics of the signal and the mechanical contrast in the tissue, would have to be sufficiently fine.

6 - Conclusion

For a long time, research on the mechanical properties of meat focused mainly on the development of devices for evalu texture of cooked meat. As they generally gave a force value determined under various deformation conditions, no universal me assessing texture was established . About 20 years ago, there was a change in direction, and studies concentrated on a critical a current methods advocating a more fundamental approach to determine which structures are in fact stressed during mechanical te which conditions.

It was shown that the application of tests in well-defined conditions of deformation and the determination of several para the force-deformation curves could yield information on the mechanical properties of the connective tissue and the myofibres. I possible to analyse the variations in the characteristics of these structures as affected by different factors, both biological and tech This can be done successfully in raw meat because of the peculiar structural features of the collagen fibres. In cooked meat the two are closely linked and their mechanical properties usually interfere to induce the overall mechanical behaviour. Thus it is still di cooked meat to determine with certainty and in all cases whether the variations in a mechanical parameter are the result of chan strength of the myofibrillar structure or in the connective structure itself or in the association myofibres-connective network.

Much still remains to be done in the prediction of cooked meat texture from measurements on the muscle. It will require non destructive methods to determine both collagen and myofibre strength. While a non destructive assessment can be made of the latter on muscle samples of well-defined geometry in which anisotropic factors are under control, the method has yet to be applied to a muscle, or a portion of muscle, in which anisotropy is less easily controlled. Although the collagen content of a sample of raw meat can be determined mechanically, it is not at present possible to do so in non destructive conditions. Moreover, the extent of cross-linking of the collagen cannot always be assessed mechanically in raw meat. The influence of the distribution of the perimysial network on the mechanical properties of meat is not yet fully known, and methods to characterise this network need to be developed. Research efforts should be devoted to providing the meat industry with a method capable of assessing as essential a characteristic of its raw material as tenderness.

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