THE MECHANICAL PROPERTIES OF THE LARGE BOWEL IN HEALTH AND DISEASE

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Ch.M
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1983

I N D E X .

Abstract.

The mechanical properties of the large bowel have been largely neglected to date. A method was established using the rat colon to mechanically test colonic tissue. The method involved 10 mm rings of colon being tested mechanically at right angles to the long axis of the colon. Tests chosen to measure "strength" were burst strength and tensile strength. "Stretch" was measured by percentage elongation and width of the colon at burst. The internal diameter of the colon at zero stress and the thickness of the colon wall, at rest were taken as reference dimensions. Viscoelastic properties were measured by stress relaxation and hysteresis in the rat and stress-relaxation in the human.

Post-mortem material was the only practical source of non-diseased colonic tissue across the spectrum of age. The tests used were not affected significantly by death or time after death. Because colons required to be transported from Uganda to be tested in Edinburgh, a method of preserving mechanical properties during storage had to be devised. The method of choice was salt, mechanical properties as tested being well preserved for at least 35 days.

Twenty-two adult Edinburgh colons (age range 19 to 81) and 17 adult Kampala colons (age range 14 to 62) were studied. In addition, 10 Edinburgh children's colons (age range 28 weeks gestation to 4 years) and 3 Kampala children's colons (age range 36 to 40 weeks gestation) were tested. Segments from an ascending, transverse, descending and sigmoid colons were tested in each case.

The tensile strength of the human colon declined with age ($P < 0,05$). Once adult life was reached its capacity to stretch remained fairly constant, except in the sigmoid colon, where there was a fall in stretch capacity with age ($P < 0,001$). The diameter of the colon fell with increasing age in adult life ($P < 0,05$), this was most pronounced in the Edinburgh colon. Viscoelastic properties were unaffected by age. There were no consistent sex differences in mechanical properties.

The Kampalan colon had a significantly greater tensile strength than its Edinburgh counterpart ($P < 0,05$). The distal but not the proximal colon had a greater stretch capacity in the Kampala group ($P < 0,001$). The viscoelastic property of stress relaxation was similar in both groups. Children's colons were similar in the two race groups.

Comparing those colons with and without diverticular disease in the Edinburgh over 50 group, no differences were found in mechanical properties.

The results are discussed in the light of the few mechanical or structural studies previously reported for the colon and also mechanical studies of other tissues. Their relevance to the high incidence of diverticular disease in Edinburgh compared with Kampala is discussed, together with theories for the aetiology of diverticular disease.

Acknowledgements .

I am indebted to the guidance and supervision of Mr. A.N. Smith and Dr. M.A. Eastwood. Their enthusiasm and perspective were invaluable. The work could not have been completed in the time available without the generous support of Mr. I. Capperauld, Ethicon Research Laboratories, Sighthill Industrial Estate, Edinburgh who allowed me the use of facilities, providing technical assistance and guidance on numerous occasions. Dr. P. Lawrie and Mr. K. Anderson deserve a special thanks. The collection of specimens in sometimes difficult circumstances was only possible because of the co-operation of Dr. R.A. McCaulay, Department of Forensic Medicine, Edinburgh University; Dr. A. Bassutil, Department of Pathology, Western General Hospital, Edinburgh; Dr. D. Bain and Mr. A. Clancy, Department of Pathology, Royal Hospital for Sick Children, Edinburgh and Professor J.W. Mugerwa, Department of Pathology, Makerere University, Kampala, Uganda. Dr. R.A. Elton gave statistical help on numerous occasions and Dr. A.E. Williams allowed the use of his HP85 computer. Thanks too, to my wife Dr. Anne Watters for checking the manuscript and Miss E. Conner for typing the manuscript.

Introduction.

The structure of the bowel wall has been somewhat neglected in the study of colonic disease. The obvious muscle thickening and the demonstration of high-intraluminal pressures by some groups of workers have inspired many to regard diverticular disease as a disorder of function. Painter in his book (1975) discussed some of the theories of relevance to a structural disorder such as obesity, ischaemia and the site of entry of blood vessels. There is little evidence to support the roles of obesity and ischaemia but the relation of diverticula to entry sites of the blood vessels in the bowel wall is well recognised (Drummond, 1917). Slack (1962) described two rows of diverticula on each side of the colon emerging between the mesenteric and antimesenteric taeniae.

Diverticular disease becomes more common with increasing age in those communities which eat a western, low-fibre diet. It is primarily a 20th century problem in these communities (Painter and Burkitt, 1975). Preliminary mechanical tests on post-mortem bowel have shown a decline in tensile strength with age in all regions of the colon (Yamada, 1970). There has been no study of the mechanical properties of the colon in high- and low-fibre diet communities.

Parks and Connell (1969), Parks (1970) and Smith *et al* (1981) studied the pressure/volume curves obtained with balloon distension of the living colon. Balloon distension of the distal colon in diverticular disease did not produce the pressure change in response to increasing volumes that occurs in normal subjects. This phenomenon was not altered by surgical resection (Parks, 1970), myotomy or treatment with bran (Smith *et al*, 1981).

These results suggest there is a structural change in the bowel wall in diverticular disease. What is not known is whether this change is a primary or secondary change.

THE COLONIC WALL.

The colonic wall (Figure 1), as any biological tissue, is a composite structure of collagen, elastin, reticular fibres, cellular and nerve elements, as well as smooth muscle. These materials are embedded in a matrix of ground substance. The mechanical properties of the bowel wall are the product of the materials within it and their interactions with each other.

As can be seen in Figure 1, the colonic wall comprises four principle layers. The mucosa consists of columnar epithelium, lining the crypts which contain glandular and cellular elements. The submucosa is composed of a collagen network within a bed of ground substance and some cellular elements. Nervous elements of the myenteric nerve plexus are found here. The muscle layer consists of circular and longitudinal muscle. The circular muscle is arranged as a tight spiral so that the individual fasciculi are almost circular, whilst the longitudinal muscle is concentrated in three bands called taenia, whose individual fasciculi cross from one side of a taenia to the other over a distance of 200 mm or so (Pace, 1966). The longitudinal muscle thus forms a loose spiral. The longitudinal muscle is continuous around the outside of the circular muscle, and except where it is concentrated into the taenia, it is thin. The two muscle layers are connected at the edges of the taenia and there is a layer of connective tissue between them. The fourth principle layer is the serosa, which is essentially a peritoneal covering.

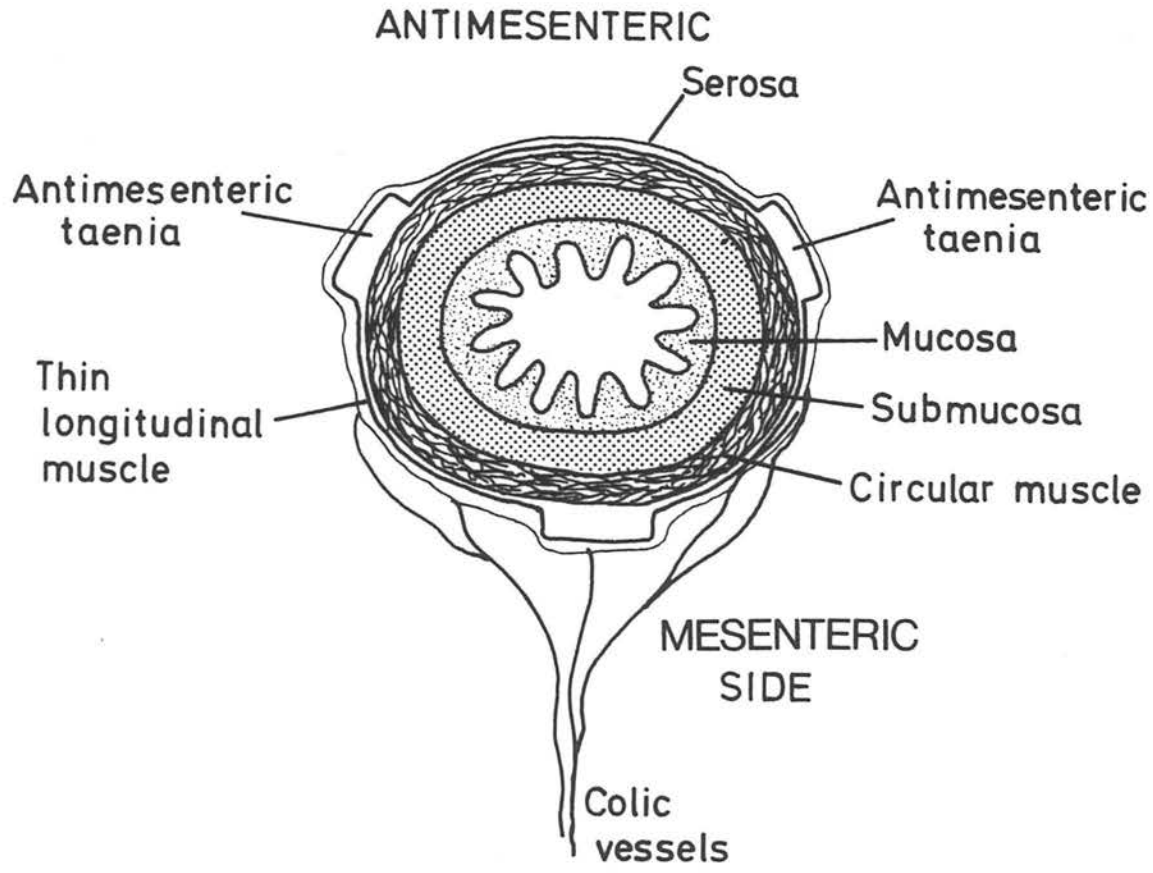


Figure 1 : Structure of the human colonic wall.

BIOMECHANICS.

Biomechanics is the study of the structure and function of biological systems by means of the methods of mechanics (Hatle, 1974). There are obvious difficulties in relating the result of mechanical tests to such a composite structure. One approach is to try to obtain the constituent materials in pure form and test them individually. Thus approximately 80% of the dry weight of tendon is collagen; the ligamentum nuchae of ungulates contains 80% elastin: and synovial fluid is a relatively pure form of protein-glycosaminoglycan complex which constitutes ground substance.

Another approach is to systematically remove the constituents of a composite structure, one by one, by enzymolysis and test what remains. Enzymolysis has the disadvantage of removing bonds between the constituent materials as well as the materials themselves, but is nonetheless a valid approach (Hoffman *et al*, 1973).

A third approach is to test the whole tissue and interpret the results in conjunction with the two previously mentioned approaches and with knowledge of the structural composition obtained from light and electron microscopic studies, and from microdissection of the tissue.

In this study we have adopted the third approach, that of testing the tissue as a whole. Information presently available from other methods of approach is limited with respect to the colon.

MECHANICAL DEFINITIONS.

Although mechanical descriptions of the behaviour of a material may be difficult when applied to biological tissues, these descriptions provide the

essential framework for communication and comparison.

Stress : Stress is load per unit area. Thus a 240 pound man standing on a brick twelve square inches in area exerts a stress of 20 pounds persquare inch. In English speaking countries stresses have traditionally been expressed in pounds per square inch, whereas the SI units are expressed as Newtons per square metre (Nm^{-2}).

At the molecular level the application of a stress means that the orientation of atoms is altered. Atoms are pushed together when a compressive stress is applied (the man standing on a brick) or pulled further apart when a tensile stress is applied (pulling on a rope).

Strength : Strength is the force or stress required to break a material. (ie. to pull apart the interatomic bonds). Strength may be measured in a number of ways: in tension or compression, by shear, torsion or bending. Tensile strength is the most relevant method of measuring strength in the colon, since the colon is subject to distending forces or stresses. Compressive strength is relevant to skin and bone whilst shear strength is relevant to the intima of blood vessels. The tensile strength of various commonly used materials is shown in Table I.

TABLE I. Approximate tensile strength of various substances (from Gordon, 1968).

Material	Tensile strength (Nm^{-2})
Commercial steel	400×10^6
Aluminium	70×10^6
Wood (spruce) along grain	100×10^6
Wood (spruce) across grain	3×10^6
Brick	5×10^6
Catgut	350×10^6
Silk	350×10^6
Tendon	100×10^6
Bone	140×10^6

Strain : Strain is the amount of stretch or elongation which occurs when a load is applied to an object and is expressed as a ratio of the original length. For example, if a rod 100 cm long stretches 1 cm under load then it is subject to a strain of 1/100 (0,01 or 1%). Because strain is a ratio it has no units.

Elasticity : A material is called elastic if the process of extension and recovery is reversible and can be repeated many thousands or millions of times. For example the 100 cm rod above when stretched extends to 101 cm, but on removal of the load will return to its original length of 100 cm. A good example of an elastic material is the spring of a watch coils and uncoils 18,000 times each hour.

Plasticity : A material is said to be plastic when it does not recover its original shape and dimensions on removal of a load. Plasticene and putty are plastic materials.

Young's modulus : A modulus is a figure which describes a property of a material. Young's modulus describes the elastic flexibility of a material. For an ideal elastic material, stress is proportional to strain so that graphically they may be plotted as a straight line (Figure 2). Thus for any material stress/strain is a constant (e), and this constant is termed the Elastic or Young's Modulus. That stress is proportional to strain is only an approximation for non-biological materials, though this relationship is reasonably accurate within a range of ±1% of the neutral or strain-free position. Young's modulus has the same units as stress, Nm^{-2}, or pounds per square inch.

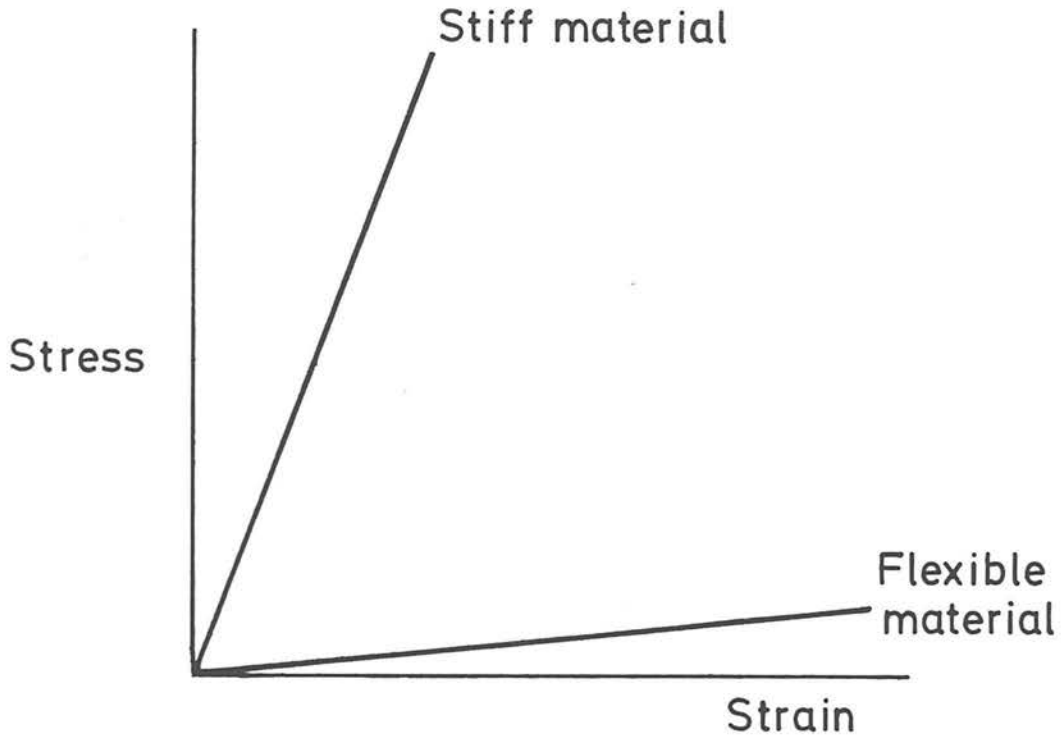
Stiffness : A material with a high Young's modulus (ie. a steep line on a stress/strain graph (Figure 2) is stiff, a good example being steel which allows strains at less than 1%. A material such as rubber is flexible, which allows strains over 100%. The Young's modulus for various materials is given in Table II.

TABLE II. Approximate Young's modulus (E) of various substances.

Material	E (Nm^{-2})	
Steel	210,000 $x10^6$	(Gordon, 1968)
Aluminium	73,000 $x10^6$	(Gordon, 1968)
Bone	21,000 $x10^6$	(Gordon, 1968)
Wood	14,000 $x10^6$	(Gordon, 1968)
Rubber	7	(Gordon, 1968)
Elastin	3 $x10^5$	(Wainwright *et al*, 1976)
Collagen	1 $x10^9$	(Wainwright *et al*, 1976)
Ground substance	1 -10	(Wainwright *et al*, 1976)
Smooth muscle relaxed	1 $x10^5$	(Caro *et al*, 1978)
Smooth muscle active	2 $x10^6$	(Caro *et al*, 1978)

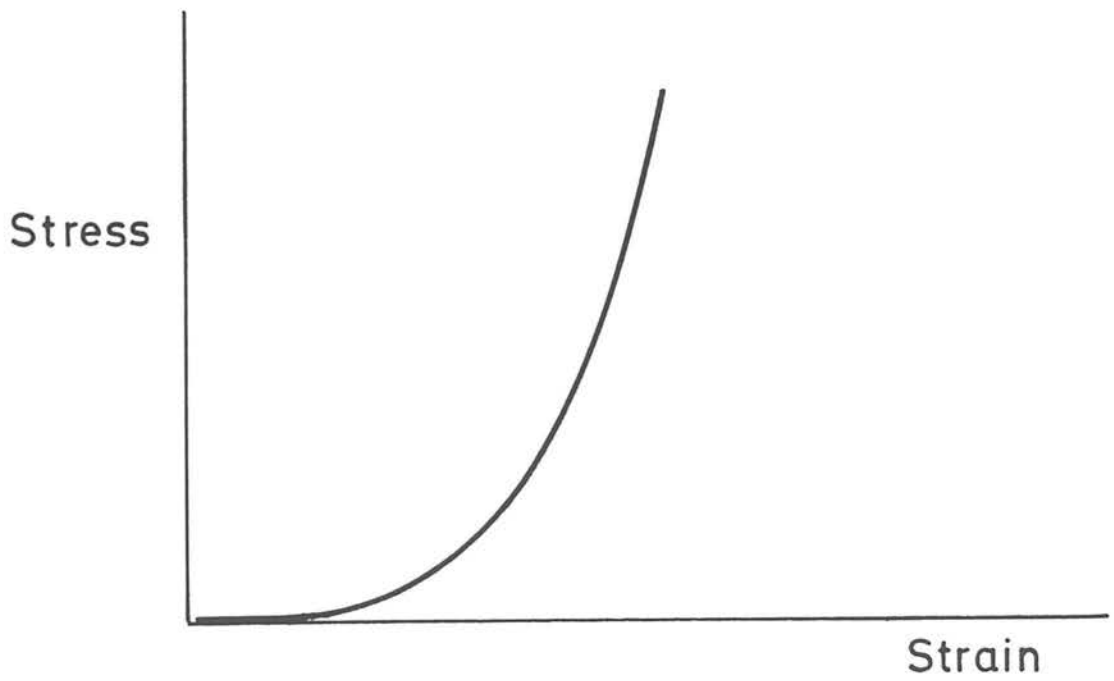
Stiffness is not the same as strength. A biscuit is stiff but weak, whereas steel is stiff but strong. Nylon is flexible and strong, whilst raspberry jelly is flexible and weak.

Viscoelasticity : Unfortunately composite biological materials do not have constant stiffness, and stress is therefore not proportional to strain. The stress/strain graph looks like that in Figure 3. Thus, it can be seen that the Young's or Elastic modulus will be different at whatever point one chooses to measure stress and strain. This would only present mathematical problems in describing the Elastic modulus in terms of a curve if the tissues were truly elastic, returning to their original dimensions when the stress is removed. Biological materials exhibit some plasticity in that they do not entirely return to their original dimensions. Plastic behaviour is typical of a viscous liquid and therefore biological tissue is said to be viscoelastic.



Stress - strain curve for truly-elastic material

Figure 2



A typical curve for a biological material. Stress is not proportional to strain.

Figure 3

The term viscoelastic implies some properties typical of a viscous liquid and some properties typical of an elastic solid. When a stress is applied to a homogenous engineering material such as steel (Figure 4a) there is a constant strain registered for as long as the stress is held. When the stress is removed the rod returns to its original length. When a biological material such as bowel, skin or blood vessel is stressed, strain lags behind stress (Figure 4b). On removal of the stress the biological material does not return to its original length.

Stress relaxation : If a constant strain is applied the amount of stress registered declines with time (Figure 5). This viscoelastic property is known as **stress relaxation.**

Creep : When a constant stress is applied, the biological tissue continues to elongate with time (Figure 6).

Hysteresis : This viscoelastic property refers to the failure of the tissue to return rapidly to its original dimensions on removal of a stress. After an elastic or steel rod has been stressed, the rod returns to its original dimensions at the same rate as if deformed on applying the stress, and thus no energy is lost in applying and relaxing the stress. This is why a watch spring can uncoil and coil 18,000 times an hour without losing energy. A viscoelastic material does not behave like this since on removing the stress, the stress/strain curve is steeper (Figure 7). This implies that energy has been lost in the deformation.

CONSTITUENTS OF BIOLOGICAL TISSUES.

Biological tissues are composite structures and therefore their mechanical

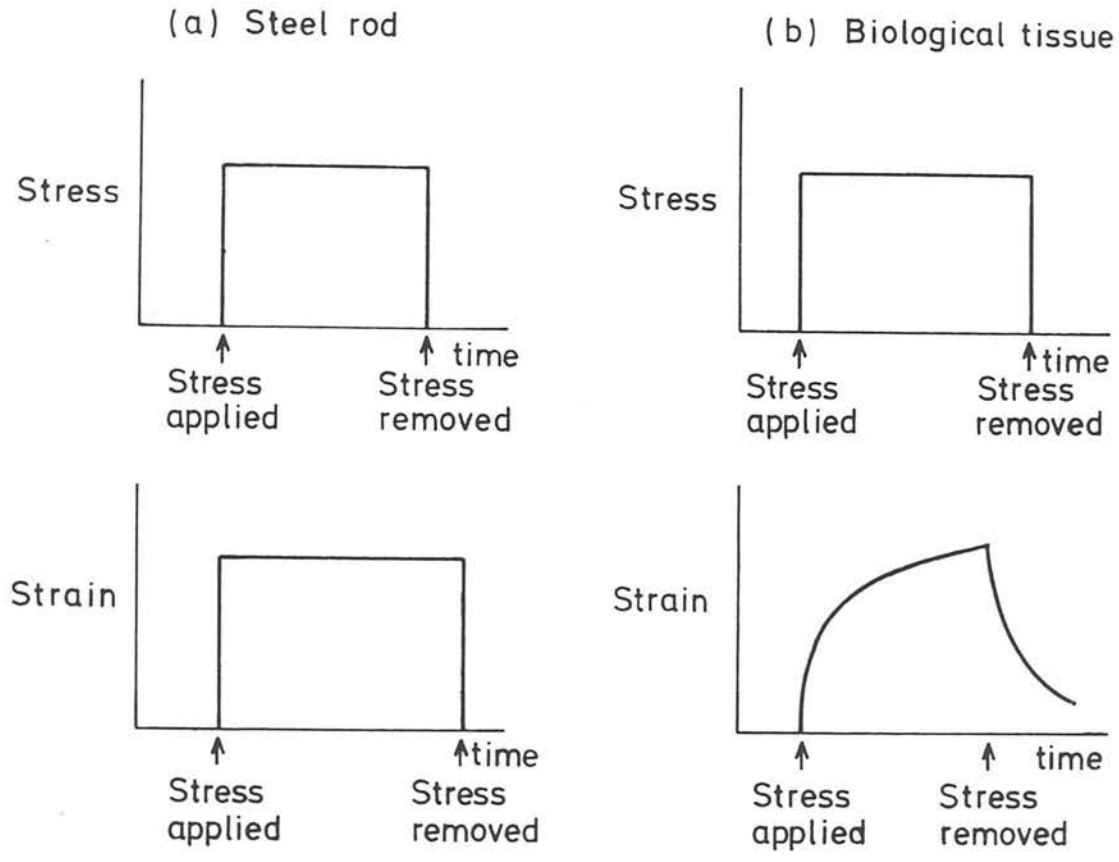


Figure 4 : Graph of stress (upper) and strain (lower) against time for a rod (a) and typical biological tissue (b).

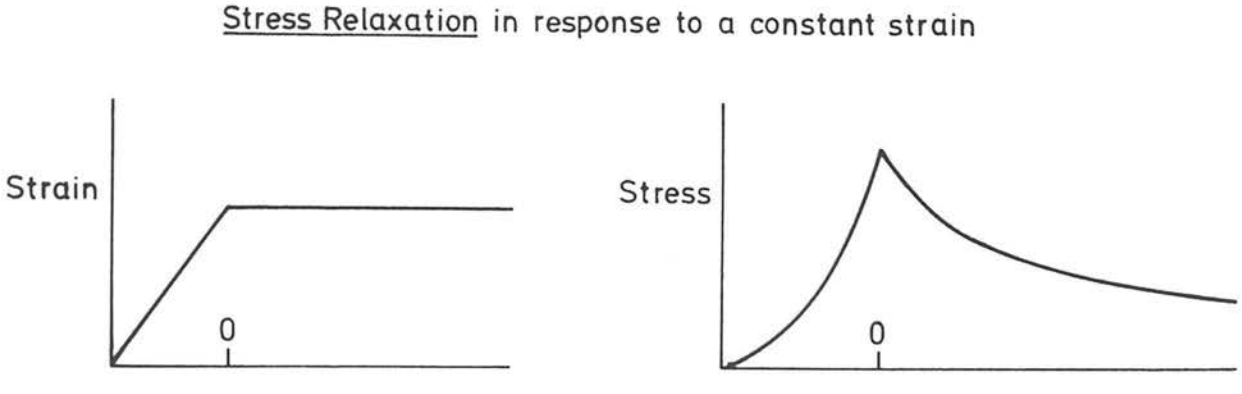


Figure 5 : Stress relaxation in a biological tissue where the strain (extension) is held at time 0.

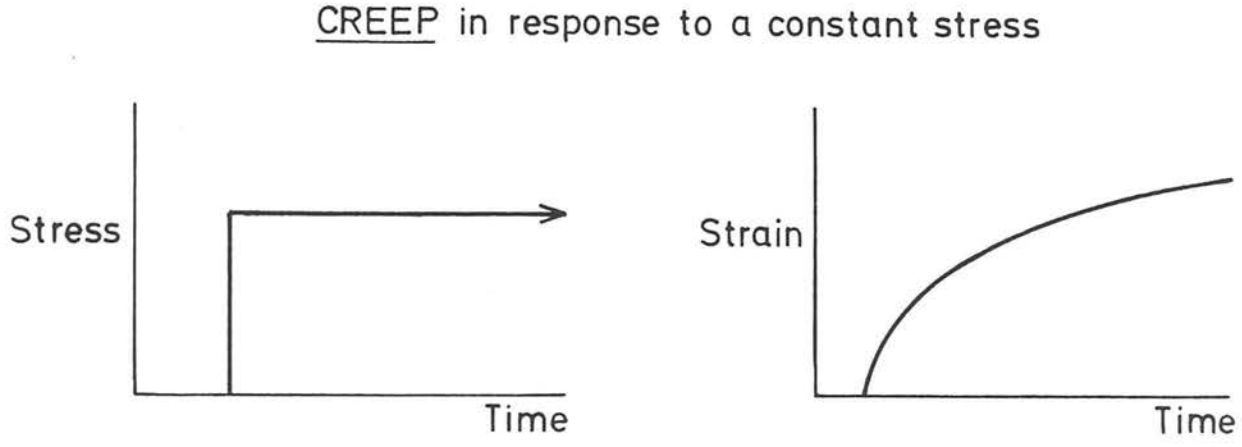


Figure 6 : Viscoelastic property of creep. Continued deformation of the tissue with a fixed stress.

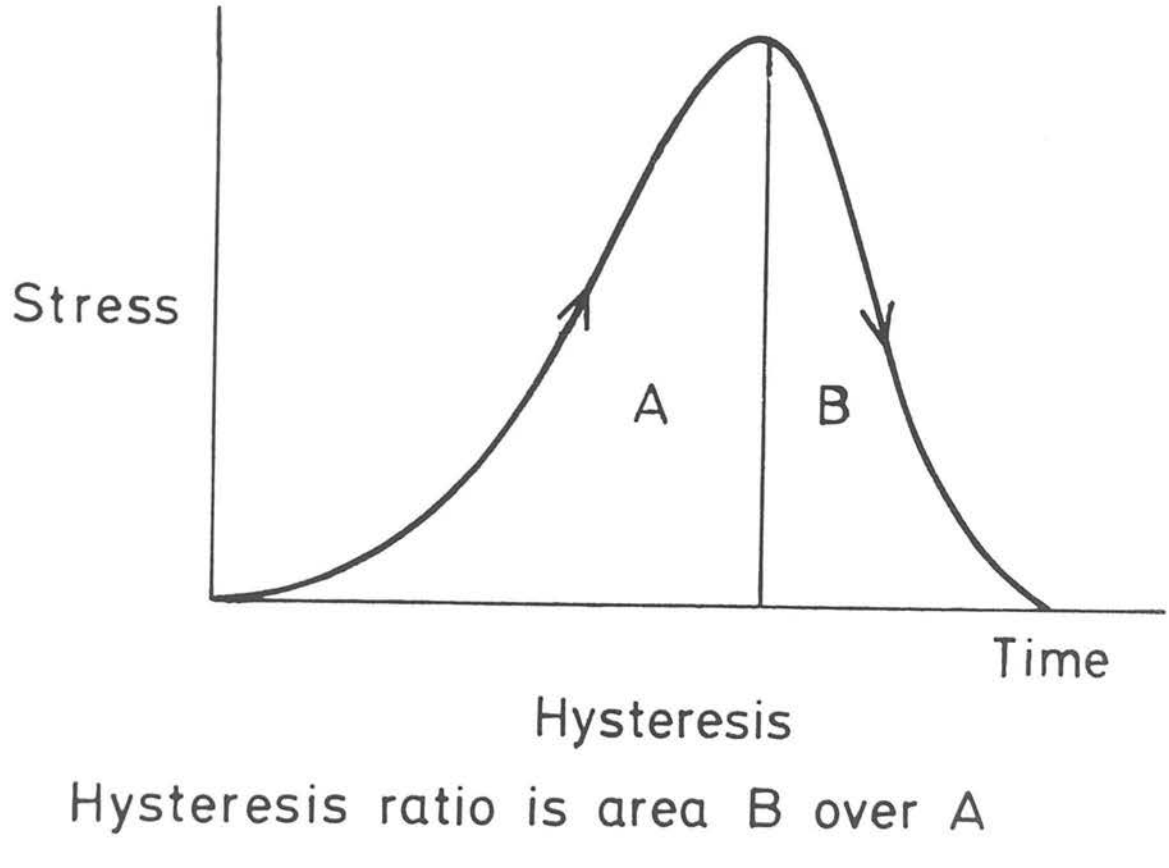


Figure 7 : Viscoelastic property of hysteresis.

Properties result from all the materials comprising the structure and their interactions with each other. The colon is a muscular tube arranged in four layers as previously described.

Collagen : Collagen is the basic structural element for soft and hard tissues in animals and man. It is a protein based on tropocollagen molecules. A collection of tropocollagen molecules forms a collagen fibril and bundles of fibrils form fibres. The arrangement of collagen fibres within a tissue varies from tissue to tissue. Collagen is a strong, stiff material being the main load-carrying and stress-bearing element in biological tissues. Its tensile strength is in the order of $1x10^8$ Nm^{-2} and Young's modulus is approximately $1x10^9$ Nm^{-2} (Fung, 1981).

Elastin : Elastin is the biological material which is closest to an ideal elastic material in that its stress/strain relationship is almost proportional or linear. Thus on removal of a load it almost returns to its original dimensions with little energy lost to the system. It is a protein found in vertebrates, present as thin strands in connective tissue. Its Young's modulus is $3x10^5$ Nm^{-2} (Wainwright *et al*, 1976). Elastin is remarkable also in that it retains its elastic properties even after tissue fixation with formalin or gluteraldehyde (Fung, 1981).

Elastin may be thought of as a network of globular protein molecules which are compressed or restrained by the tendency of hydrophobic amino acids to exclude water. When elastin is stretched water exposed to non-polar side groups becomes ordered and the opening of the hydrophobic region removes some of the restraints on the polymer chain. Thus on stretching the water becomes more ordered and the polymer chain becomes

less ordered (Wainwright *et al*, 1976). This is in fact different from the underlying mechanism of elasticity in rubber polymers whose chains become more ordered when stretched.

Ground substance : This is a hydrophilic gel containing glycosaminoglycans and tissue fluid. Dense connective tissue contains very little ground substance whilst greater amounts are to be found in loose connective tissue. The hydrophilic forces within the gel result in ground substance not merely being a viscous substance but also one which has a low modulus of elasticity, in the order of 1-10 Nm^{-2} (Wainwright *et al*, 1976).

Smooth muscle : Smooth, or non-striated muscle has in common with other muscle tissue a contractile system based on actin and myosin molecules, the system being dependent on ATP for energy. Change in the cell membrane induces flux of Na^+ and K^+ ions and creates an action potential. A Ca^{++} flux furnishes the excitation-contraction coupling. The arrangement of smooth muscle packing varies from tissue to tissue. For instance the pattern in guinea pig taenia coli is such that each muscle cell is surrounded by about 12 others. The cells are not straight, but are interwoven with one another. The extracellular space varies according to the site of the smooth muscle. In intestinal smooth muscle it is in the order of 9-12%, whereas it varies from 25-39% according to species for vascular smooth muscle (Fung, 1981). The extracellular space contains a variety of materials, including collagen, blood vessels, nerves, macrophage fibroblasts, mucopolysaccharides and elastin.

Intestinal smooth muscle exhibits spontaneous contractions (Price, Patucci and Fung, 1977) and intracellular recordings of colonic smooth muscle in

man demonstrated regular action potential discharge at a rate of 22 cycles per minute (Duthie, 1979). Colonic contractions are found at two frequencies in man, ie. at three cycles per minute and six to nine cycles per minute (Duthie, 1979), possibly originating from a pacemaker region to the right of the transverse colon. Intestinal smooth muscle is under nervous and hormonal control.

SOME MECHANICAL CONSIDERATIONS.

Stress/strain curve of skin : In composite biological tissues such as skin, viscoelastic, gel-forming glycosaminoglycans, elastin, cellular and reticular elements are combined with stiff, high modulus collagen fibres. Skin is capable of stretching to 150% or more of its original dimensions and is therefore highly expansile. The colon, like skin, is an expansile structure composed of the above elements but also has smooth muscle. However, it has not been studied in the same detail as skin.

A study of the stress/strain curve of an expansile tissue gives information about the arrangement of collagen fibres within the whole structure. The stress/strain curve of intact skin is shown in Figure 8. Collagen is a stiff material and must therefore be arranged in a criss-cross network in order that the whole structure may be expandable. This arrangement allows the combination of strong stiff fibres within a readily expandable matrix of ground substance and elastin. Examining the stress/strain curve for intact skin (Daly and Odland, 1979) three phases may be identified (Figure 8). Initially all the collagen fibres are slack (area A), then some fibres begin to take up the stress (area B) and then they all become taut (area C). Brown (1973) carried out an electron microscopic study of the effect of stress on abdominal skin *in vitro* and showed that whilst in area A of

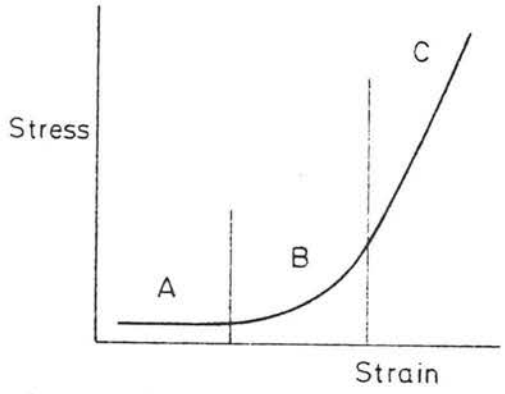
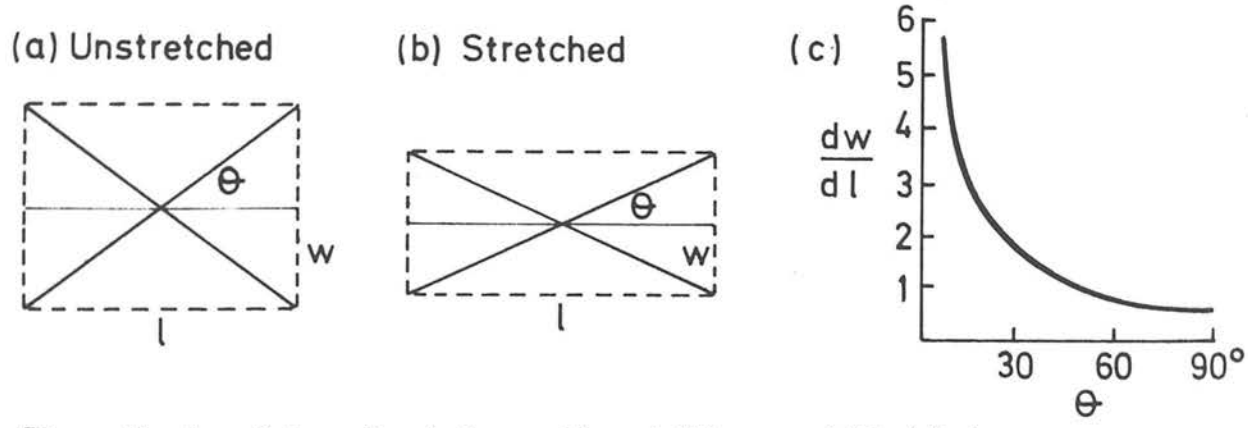


Figure 8: A typical stress/strain curve for biological tissue. Initially (A) all the tissue is slack, then (B) some fibres take up strain and finally (C) they all become taut.



The effects of tensile deformation (dl) on width (dw) on the orientation of fibre angle (θ)

Figure 9

the stress/strain curve the fibres are wavy, they straighten out in area B and are all straight in area C. A criss-cross arrangement would not be readily expandable if it consisted of a matrix of continuous fibres but the collagen in a biological tissue such as skin (and presumably bowel) is believed to be arranged in the form of a discontinuous network (Wainwright *et al*, 1976).

Fibre angle : A further factor limiting the distensibility of the bowel is the angle (θ) between the individual collagen fibres (Figure 9). When the angle becomes acute, stretching results in the fibres becoming rapidly taught (areas B and C) and so registering a higher stress at a lower strain than if the angle were more obtuse. Thus, if the fibre angle (θ, Figure 9) is small the tissue as a whole is stiffer (Figure 9c). The effect of stretching on the fibre angle can be seen in Figures 9a and 9b.

When the fibre angle is small (eg. parallel fibres in tendon), the material is a tensile structure, capable of bearing high stress with little change in length. If there is a large fibre angle embedded in an amorphous ground substance, then the load is born by the viscoelastic ground substance (area A, Figure 8) until the fibre angle reduces with stretch. Once the angle is small the collagen fibres bear the load. This is the arrangement for an expansile structure such as skin and presumably also for the bowel.

A light microscopic study of individual layers of bowel wall provides support for such an arrangement of collagen fibres in the colon (Cavarlho, 1973). The angle between the collagen fibres becomes more acute from the serosal to the mucosal side (ie. more acute in relation to the transverse axis of the organ). Thus on distending the bowel one would expect the layers to

rupture from the mucosa to serosa since those layers with the most acute angle bear stress first. This was not the finding of Burt (1931) who demonstrated that the mucosal layer was the last to perforate when he distended the colon with air. One explanation for this is that the mucosal layer is possibly more elastic than the other layers. This would explain why, if diverticular disease were related to a defect in the bowel wall, the stiffer external layers break and allow the elastic mucosa to herniate through, forming a diverticulum.

Law of Laplace : The properties of the bowel wall are further complicated by the fact that the bowel is a cylindrical tube. The Law of Laplace, which may be generally applied to vessels and tubes, states that the pressure required to distend a tube against a given tension in its wall is inversely proportional to the radius of the tube. A balloon, for example, is more difficult to blow up when the radius is small than when it is large. In the gastrointestinal tract the law indicates that relative to atmospheric pressure, the tension required to balance a certain distending pressure increases as the radius increases.

$$Sh = pr_i \quad \text{or} \quad p = Sh/r_i$$

Where . . . . S is the circumferential hoop stress relative to atmospheric pressure

h is the wall thickness

p is the amount the internal pressure exceeds atmospheric pressure

r_i is the internal radius of the tube.

The circumferential hoop stress (rp/h) is twice the longitudinal stress

(rp/2h) in a tubular structure. This is why, when tubes are distended, the split formed when they rupture is longitudinal. Rupture occurs because of the circumferential stress and then extends along the line of least resistance. This happens when one fries a sausage and the stuffing swells. It also happens when the bowel is distended with air (Burt, 1931).

Pre-strain : Skin, blood vessels and bowel are in a permanent state of tension in the body and on removal from a living or freshly dead animal they shorten by 25-30%. This tension or pre-strain as it is sometimes called, is probably a device to counteract any changes in length as the intraluminal pressure increases. If blood vessels obeyed Hooke's law (ie. had a linear stress/strain curve), then the circumferential strain would also be twice the longitudinal and a change in diameter of half a millimetre would be associated with a change in length of the femoral artery of 25 mm. It is obvious that a change of length of this magnitude cannot and does not take place (Gordon, 1978).

Poisson's ratio : Another reason why such changes in length do not take place when there is a change in diameter is the existence of Poisson's ratio. When a rubber band is stretched it becomes noticeably thinner. The change in length over the change in width when a material is stretched is termed Poisson's ratio. Poisson's ratio is related to Young's modulus and so if we know both Young's modulus and Poisson's ratio for a material we can calculate the changes in length and width when a strain is applied. Poisson's ratio is around 1/4 for metals and concrete, but for biological tissues it is at least 1/2, if not higher (Gordon, 1978). The effect of Poisson's ratio is that if we pull on an artery or membrane it will contract

in the direction at right angles to the pull. However if there is already a pre-tension in both directions at right angles to each other, as is the case in the living animal, then the effects of these (tensions) stresses will be additive and the resultant strains will be less than one would have expected had either of the stresses been applied separately.

Viscoelastic design : The advantages of a viscoelastic design in living tissues include the combination of expansibility, strength and maintenance of shape. If the bowel were made of steel it would be strong, but unable to distend like a pipe. If it were made of rubber like a balloon, it would change its shape in response to an increase in pressure. As soon as a cylindrical balloon is subject to a circumferential strain of 50% or more, the inflation process becomes unstable and the tube will bulge out like a snake eating a football and form an aneurysm. This theory can easily be tested by blowing up a balloon. Viscoelastic design is essential for expansile structures such as the bowel.

THE EFFECT OF AGEING ON THE COLONIC WALL.

If there is any truth in the theory that diverticular disease is in part a mechanical disease then one should expect there to be a change in the mechanical properties of the bowel with increasing age since the incidence of diverticular disease increases with age (Parks, 1975).

Strength : Yamada (1970), quoting the work of Iwasaki, reported that the tensile strength of the Japanese colon does fall with age in all regions and when tested both longitudinally and transversely (Figure 10). As far as I am aware no one else has published results on this issue.

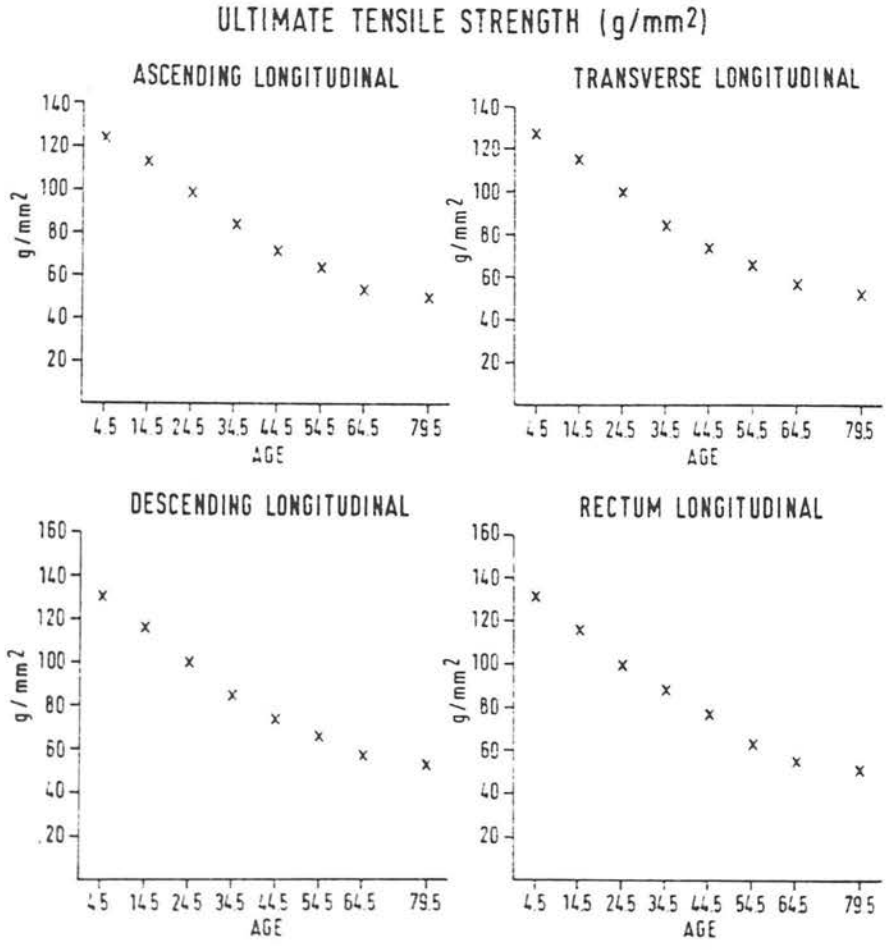


Figure 10 Drawn from Yamada (1970) showing the decline in tensile strength of the colon and rectum with age.

Smooth muscle : Pace (1966) examined the effects of ageing on colonic musculature and connective tissue. Table III shows the thickness of circular and longitudinal colonic muscle with increasing age.

TABLE III. Thickness of the muscle wall of the ascending colon with age (Pace, 1966).

Age	Anterior taenia	Circular muscle
4 months gestation	0,2 mm	0,3 mm
7 months gestation	1,3 mm	1,3 mm
5 years	3,3 mm	2,6 mm
43 years	5,3 mm	3,6 mm
85 years	9,0 mm	5,3 mm

Connective tissue : Connective tissue changes with age are :

1. Collagen . . progressive increases with age but the connective tissue layer between the muscle coats is much reduced from the age of 10 years onwards. Individual collagen fibres increase in thickness up to the age of 60 years or so, after which their thickness decreases slightly. With increasing age the collagen bundles in the submucosa, but nowhere else, begin to show fraying of their ends and their staining reactions with Mallory and Van Gieson deteriorate.

2. Elastin . . this shows a progressive increase throughout life in all layers of the colon. Individual fibres become shorter and thicker and are less wavy and less regularly arranged. In the highest age groups there are coarse, uneven fibres with such changes as granulation, splitting, swelling and even hyaline degeneration.

3. Reticular tissue . . the number of fibres increases with age and there is an increase in their waviness. In extreme old age there are marked

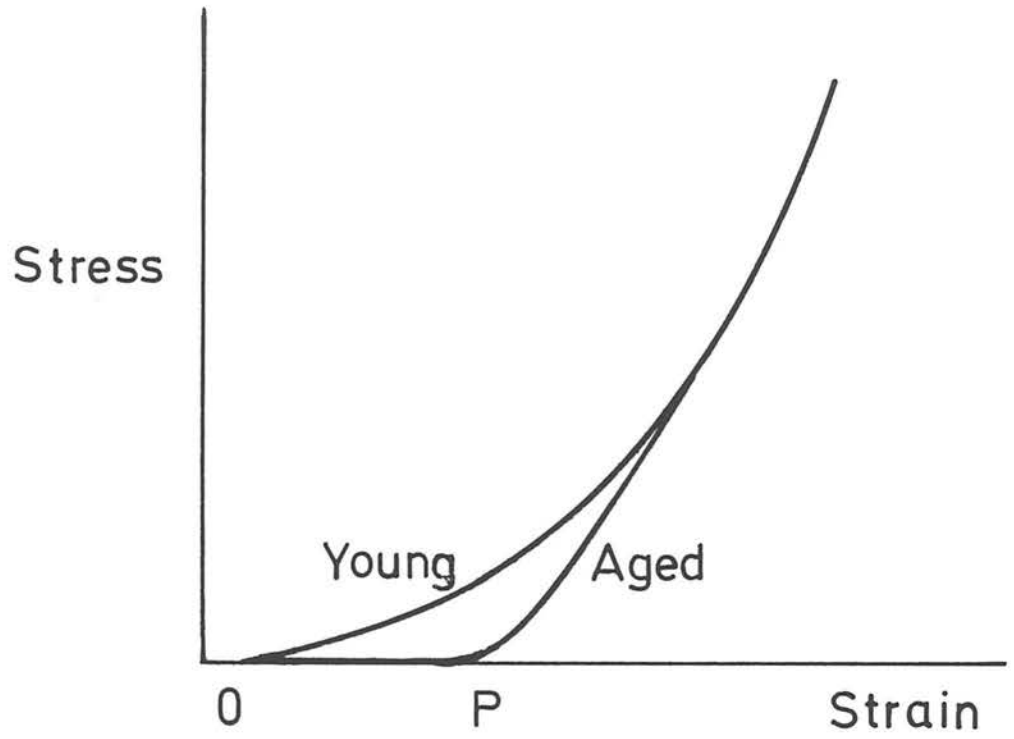
changes in calibre and they stain brownish black rather than jet black with silver.

Pace's work demonstrates that there is an increase in thickness in both muscle and connective tissue with increasing age. Yamada's book reports on the decline in tensile strength with age. Relating these is not easy except that there is obviously some qualitative decline in the mechanical integrity of these elements which more than offsets any improvement expected by an increase in their number.

Elasticity : The effects of ageing have been studied in skin and blood vessels in more detail. The initial elastic deformation region (Figure 8, area A) of the stress/strain curve (Figure 8) decreases with age and yet the final slope (Figure 8, area C) is similar to all ages. This suggests that the stiffness of collagen fibres does not vary significantly with age in the skin. If the stress/strain curve is examined at low stress levels, the difference between young and old skin can be seen in Figure 11. This behaviour is in fact similar to that seen when elastin is enzymatically removed and one can thus suggest that the effect is due to gradual destruction of the elastin network with age. It is not necessary to destroy the elastin, but simply fragment it to achieve this effect (Daly and Odland, 1979).

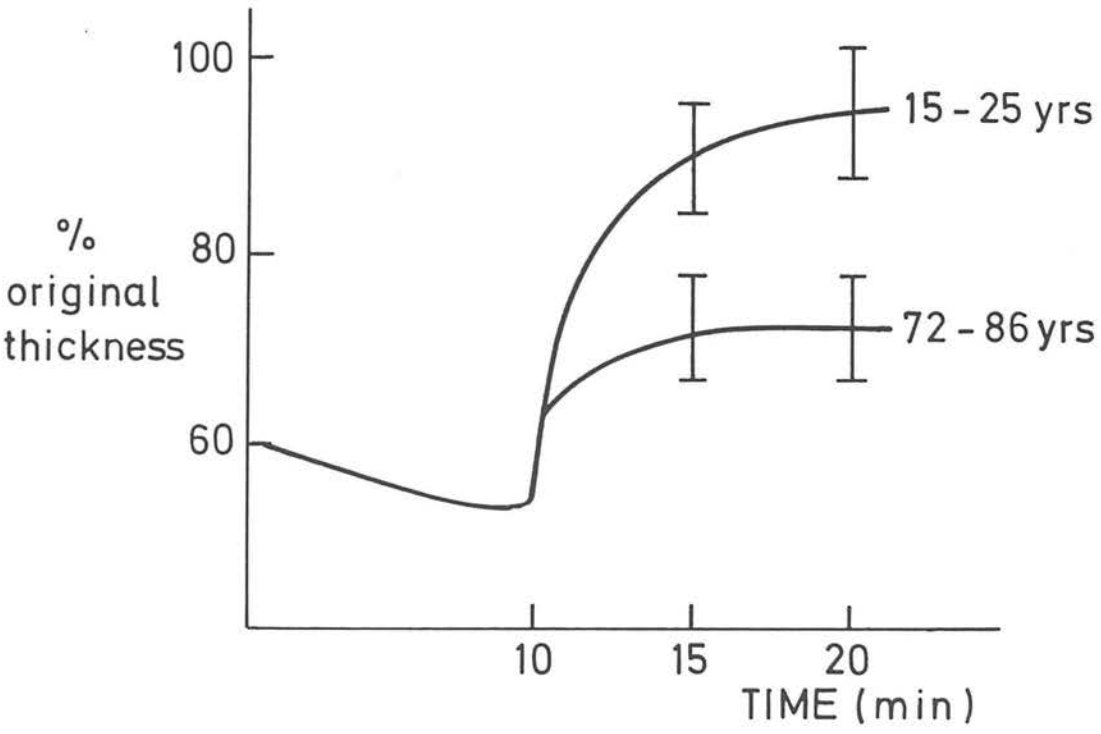
When the distance O-P is long the skin is inelastic and wrinkles appear. Skin is only elastic at low stress levels, ie. during the initial deformation (Figure 8, area A). Once collagen fibres start to carry the stress (Figure 8, area B) the tissue behaves in a viscoelastic manner.

In the aorta the diameter increases with age as does the wall thickness. The wall thickness increases more than the diameter relatively so that the



Stress/Strain curve for young and old skin

Figure 11 : Redrawn from Daly and Odland (1979).



Recovery after compression for young and old skin (anterior tibia)

Figure 12 : Redrawn from Daly and Odland (1979),

ratio h/d increases with age. Accompanying these changes in dimensions are interesting changes in elastic properties. In the thoracic aorta at physiological pressure (100 mmHg) the incremental Young's Modulus increases with age implying increasing stiffness. More peripherally, there is no change or a fall. One explanation for this is that the diameter of the aorta increases with age and thus is further along the strain axis of its stress/strain curve (Caro *et al*, 1978). The same process might occur in the colon.

Although measurable changes in the elasticity of skin and blood vessels with age have been reported there is practically no study of elasticity in the bowel. Yamada (1970) quoting Iwasaki's work stated that the ultimate percentage elongation (strain at burst) was greatest in the 20-29 year age group and declined to 84% of its maximum value between 60 and 89 years of age.

Viscoelastic properties : Compression tests on live human skin also show age-dependent properties (Daly and Odland, 1979). Figure 12 is a graph of original skin thickness plotted against time for a compression test of skin over the anterior aspect of the tibia. Skin thickness was measured ultrasonically and the graph shows that aged skin showed poorer elastic recovery after compression over a 20 minute period.

Animal studies : It is possible that the increased incidence of diverticular disease in the aged is related to a decline in mechanical integrity of the colonic wall with age. This possibility is further underlined by studies of the tensile strength of the colon in animals (Yamada, 1970). The colons of dogs, cats, cows and even domestic fowl have a greater tensile strength than the rabbit, an animal in which it has been possible to induce diverticula

(Hodgson and Johnson, 1975). The only other animal in which diverticula have been reported is the rat (Wierda, 1943; Carlson and Holzel, 1949), but the tensile strength of its colon has not been studied previously. The rats only developed diverticula after two years of low residue, high fat diet. Two years is the average lifespan of the rat so that these diverticula only developed when the rats were aged.

Diverticular disease is a disease associated with increasing age and a Western diet. Although the mechanical properties of the colon have been little studied to date there is evidence to suggest that there may be a wall abnormality in diverticular disease. If the mechanical integrity of the colonic wall declines with age this may explain why diverticulae are most common in the aged. The effect of a western diet on the mechanical properties of the bowel wall has not been studied at all.

Biological tissues can not be assumed to behave like engineering materials. Biological materials show viscoelastic behaviour and have non-linear stress/strain curves. There are many problems both in selecting which tests should be performed in order to give meaningful results and also in trying to study what is a complex composite structure.

This study was designed to :

1. Establish a method for testing the mechanical properties of the colon.

2. Measure the mechanical properties of the rat and human colon and the influence of age, sex, race and diverticular disease.

Materials and Methods.

Rat.

SOURCES AND DIET.

Male, Sprague-Dowley rats fed on a vegetarian diet since weaning (Table IV) were used to establish and test the method developed for examining the mechanical properties of the colon. Their diet since weaning is listed in Table IV.

TABLE IV. A : Diet fed to rats since weaning until 6 weeks of age.
B : Diet fed to rats from 6 weeks of age. *

A		B	
Ground wheat	46,0%	Crude protein	17.0%
Ground oats	24,45%	Crude oil	4,8%
Dried skim milk	2,5%	Salt	1,15%
Dried yeast	2,5%	Vitamin + mineral supplements	2,2%
Fish meal	15,0%	(ingredients : barley, wheat,	
Tallar fat	5,0%	maize, middlings, soya bean	
Salt	0,5%	meal, white fish meal, soya oil,	
Cod liver oil	0,5%	molasses, limestone, salt,	
Vitamin + mineral supplements	2,5%	methionine, vitamins and trace elements)	
Inert binding agent	1,05%		
Crude fibre	3,21%	Crude fibre	3,7%

* Grain Harvesters Ltd, Algot 5 Rodent Diet No 482.

These rats were obtained from Nottingham School of Agriculture. From weaning until transportation to Edinburgh both male and female rats were fed on diet A, which is the female breeding diet used at Nottingham School of Agriculture. This diet was given unrestricted to the rats. Diet B was given on arrival at Ethicon Research Laboratories animal house, but restricted by 10% of the amount an average rat would eat so as to avoid

over-eating. The female rats obtained for the old versus young female rat comparison were aged 6-9 months on arrival and were therefore fed on diet A until this age and diet B subsequently. Their ages and weights are specified for each experiment. Before removal of the colon the rat was killed by carbon dioxide intoxication - a method which is painless and panic-free since the rat merely falls asleep.

ANATOMY OF THE RAT COLON.

The large bowel of the rat consists of a caecum, colon and rectum. The carcum does not occupy a constant position in the abdomen but the junction between caecum and colon is obvious. The colon passes retroperitoneally to become the rectum, a long structure in the rat. The rectum extends from the upper abdomen to across almost the entire posterior abdominal wall. Water absorption takes place throughout the length of the rat colon, liquid faeces are present proximally but by the time the bowel becomes retroperitoneal the faeces are concentrated into pellets.

METHOD OF REMOVAL.

Colons were removed immediately after death, except where otherwise stated. Once removed, the faeces were gently squeezed out of the colon irrigated with physiological saline to remove as much faecal residue from the lumen of the bowel as was possible. When pre-strain was to be measured the colon was marked with a Magic Marker before removal, the distance between two marks being measured before and after with a ruler. The colon was handled gently at all times, only the ends or mesentery were held with forceps, and these ends were not used for the testing of mechanical properties.

One centimetre rings of colon were cut by hand with a fresh, sharp scalpel blade with the colon laid alongside a ruler. If the colon was pinned down no tension was put on it. This method of cutting was estimated by eye to be accurate within a millimetre once the segment was cut. The cut was always made at right angles to the long axis of the colon once any kinking due to the attachment of the mesentery had been straightened out by division of adherent bands of mesentery. A 10 mm ring of colon was thus obtained for testing and placed in physiological saline at room temperature.

MEASUREMENT OF DIMENSIONS.

Where measurements of the dimensions of the rat colon were made, an adjacent ring of colon was opened by cutting along the long axis of the bowel. The thickness was measured by placing the opened ring between two microscope slides of known dimensions and placing the slides in a Mercer No 54 gaugemeter. Care was taken to excise fat and mesentery before measurement of the thickness. The slides served to spread the compressive force of the tissue, minimising 'squash' effects. There is nonetheless some 'squash' effect and the thickness was taken to be the initial thickness once the pistons of the gaugemeter came into contact with the slides.

Measurement of the internal diameter of the colon was necessary to calculate the percentage elongation and to calculate the amount of strain for viscoelastic tests. The method used measured the distance between the top of the upper hook and the bottom of the lower hook as soon as stress is registered on the recording chart (50g scale). Values obtained are shown in Table V.

TABLE V. Dimensions of the rat colon.

	Thickness of rat colon		Internal diameter of rat colon	
Male	Proximal	0,55 mm	Proximal	5,6 mm
(8 weeks)	Distal	0,57 mm	Distal	5,0 mm
240-270g	Mean	0,53 mm	Mean	5,3 mm
Male	Proximal	0,65 mm	Proximal	5,4 mm
(12 months)	Distal	0,57 mm	Distal	5,2 mm
370-435g	Mean	0,61 mm	Mean	5,3 mm
Female	Proximal	0,54 mm	Proximal	5,2 mm
(7 weeks)	Distal	0,54 mm	Distal	5,2 mm
185-195g	Mean	0,54 mm	Mean	5,2 mm
Female	Proximal	0,65 mm	Proximal	6,4 mm
(14-17 months)	Distal	0,64 mm	Distal	6,0 mm
260-300g	Mean	0,65 mm	Mean	6,2 mm

Initial plans to test the mechanical properties of strips of colon were abandoned because strips were difficult to cut accurately. Although testing methods for small strips have been reported (Yin and Fung, 1971) these would have been time-consuming and would have jeopardised, if not made impossible, the completion of this thesis.

TESTING METHOD AND MACHINERY.

An Instron 1026 (Figure 13) was used to test the tensile mechanical properties of the rat colon. The machine used had a fixed lower clamp and movable cross-head. It was capable of maintaining a constant strain and cycling to constant strain but a pre-determined stress could not be automatically applied. The load range was from 0-50 kg and the minimum full-scale chart deflection was from 0-50g.

The rate of extension (equivalent to the cross-head speed of the Instron) of the colonic rings was 50 mm/min for all experiments. Since the internal diameter of the rat colon varies from 5-6 mm this gives a strain

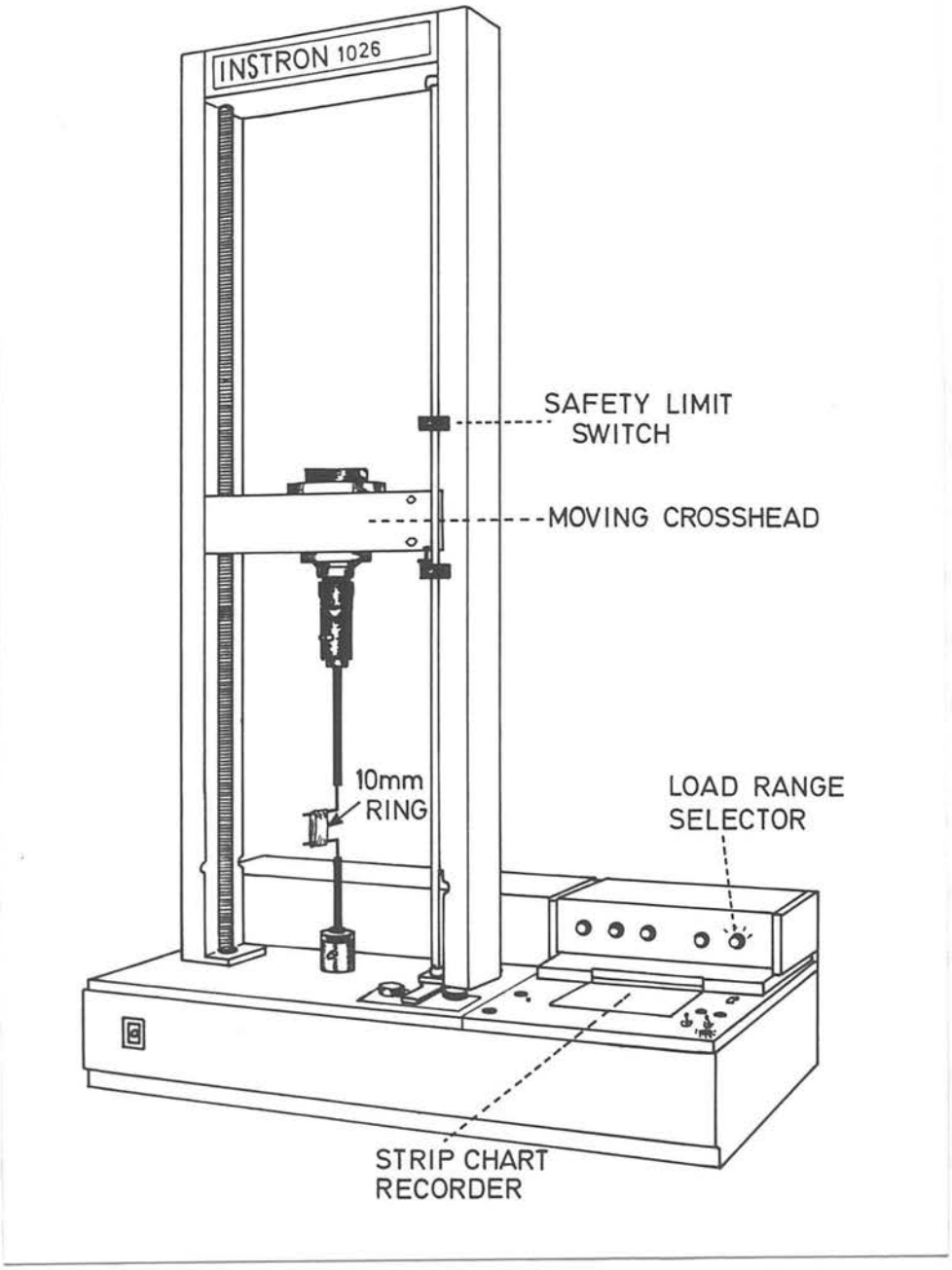


Figure 13 : Instron 1026 tensile tester with colonic ring loaded for testing.

rate of 833-1000%/min (50/internal diameter times 100). 50 mm/min is a conventionally used rate of extension. The stress/strain relationship does not change very much as the strain rate is changed over a range of 10,000 (Fung, 1981).

The stress registered whilst testing was recorded at a chart speed of 200 mm/min.

Stainless steel hooks, 2,25 mm in diameter, were used to test the mechanical properties of the rat colon. These were adapted to fit the clamp holding sockets of the Instron 1026. The rat colon ring was slipped onto the hooks when they were almost touching so that they passed through the lumen of the bowel. The application of the colon was an intricate procedure requiring care not to damage the tissue. Non-toothed, blunt but fine forceps were used. Testing was carried out by upward movement of the hook attached to the cross-head from the fixed lower hook (Figure 13). These hooks were of sufficient diameter not to cut through the tissue and therefore rupture of the rat colon usually occurred between the hooks, most frequently at the mesenteric border.

The burst properties were tested in air at room temperature but the viscoelastic properties were tested in physiological saline at 35-37°C. The testing of burst properties took only a few seconds so that dehydration was not felt to be a significant factor affecting the stress/strain characteristics. The Instron 1026 had to be adapted for testing in physiological saline at 35-37°C (Figure 14). A large plastic basin in which a window was inserted was adapted to fit over the lower clamp socket. Once this fitting was

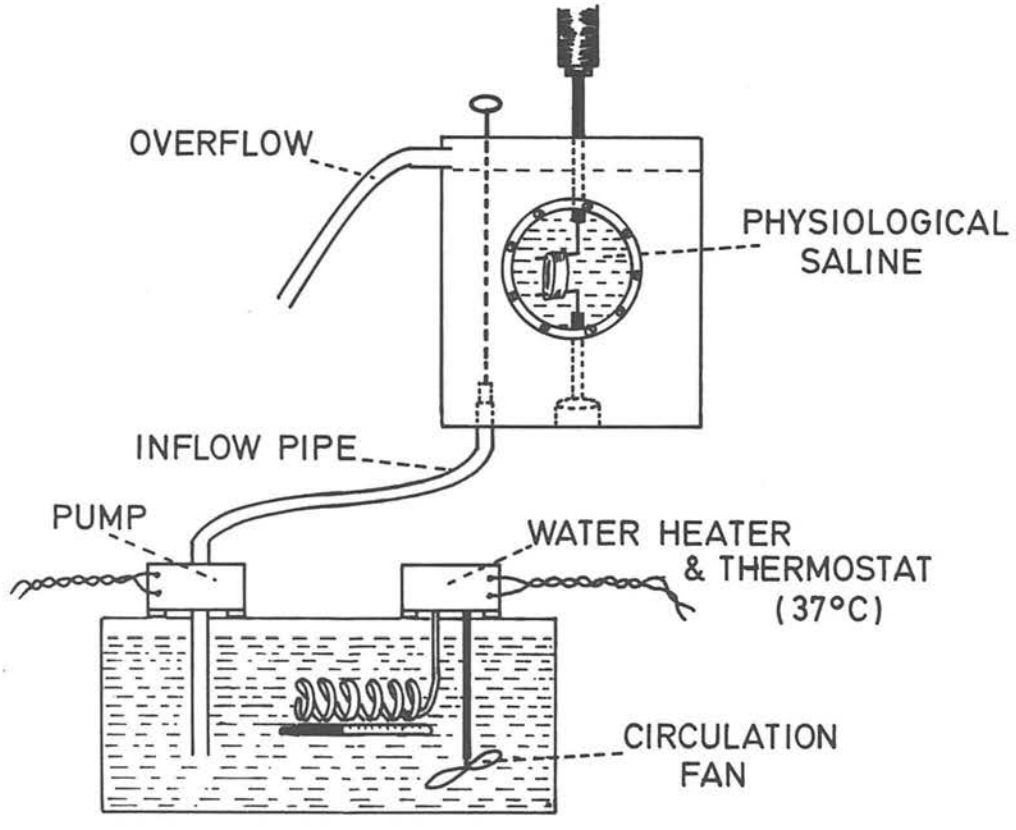


Figure 14 : Equipment for viscoelastic testing.

water-tight the basin could be filled with physiological saline from a water bath which maintained the temperature at 37°C. The testing temperature was never noted to fall below 35°C. The plastic basin was fitted with in-flow and overflow pipes so that the saline could be pumped in. The inflow pipe was plugged once the basin was full and the testing of viscoelastic properties carried out. There was no circulation of saline during testing since it was felt this would cause flickers on the chart recording stress/strain characteristics.

Viscoelastic properties were studied after pre-conditioning the tissue at 100% strain for nine cycles. Preconditioning is necessary to obtain reproducible results for viscoelastic testing (Fung, 1981). The reason that preconditioning occurs in a specimen is that the internal arrangement of the tissue changes with the cycling. By repeated cycling, eventually a steady state is reached at which no further change will occur unless the cycling routine is changed.

Nine cycles were necessary to reach this steady state and a tenth cycle was used to study hysteresis. Stress relaxation was studied by stopping the cycling process at 100% strain on the eleventh cycle. The reason why 100% strain was chosen was that the stress registered at lower degrees of strain was too low to allow accurate study of the stress relaxation curve. The normal stress registered for the rat colon at 100% strain was in the order of 10-30g.

MEASUREMENTS.

All measurements were made on tensile tests, ie. measuring mechanical properties by extension (increasing tension) of the tissue.

Burst strength (BS) : The maximum stress registered as the tissue is extended until it bursts. It has the units of stress. Measurements were made in grams. Since collagen is the strongest material in the colonic wall the burst strength is a measure of the strength of collagen.

Tensile strength (TS) : This is the burst strength divided by the cross-sectional area of tissue under test. Units are therefore in this study in g/mm^2. These can be converted to Newtons/m^2 by multiplying by $0,98 \times 10^6$.

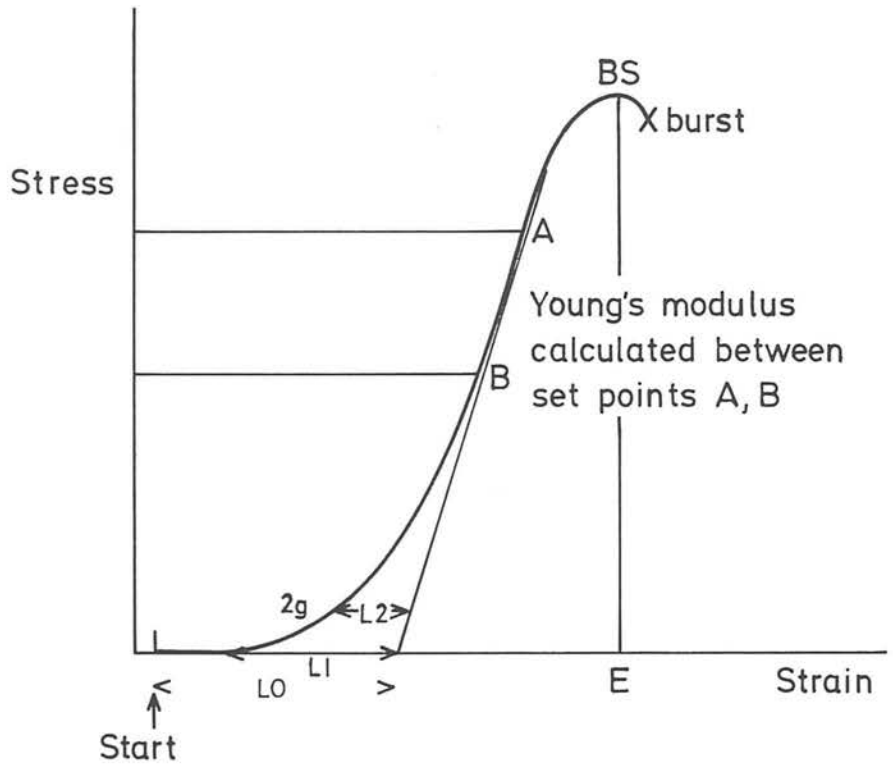
Young's modulus (M) : The stress/strain ratio measured between specified points of stress on the stress/strain curve (Figure 15). These specified points are given with each methodological experiment. The units are g/mm^2.

L values (L0, L1, L2) : These may be understood by studing Figure 15. They are measured on the stress/strain curve after drawing the best possible tangent to the steep part of the slope and extending this to the baseline. They are lengths in millimetres equivalent to the amount of extension (strain) of the test ring. They are an attempt to derive a measure of elasticity from the stress/strain curve (Daly and Odland, 1979).

L0 is the distance from the origin of the stress/strain curve to the point of intersection of the tangent and baseline. It is an *in vitro* measurement since tissues are normally under prestrain *in vivo*.

L1 is the distance from the take-off point on the stress/strain curve, ie. where stress begins to be registered to the point of intersection between the tangent and baseline. L1 is also an *in vitro* test.

L2 is the distance from the point on the stress/strain curve where 2g stress is registered to the tangent. The reason for this measurement is



The stress / strain curve of a rat colon

Figure 15

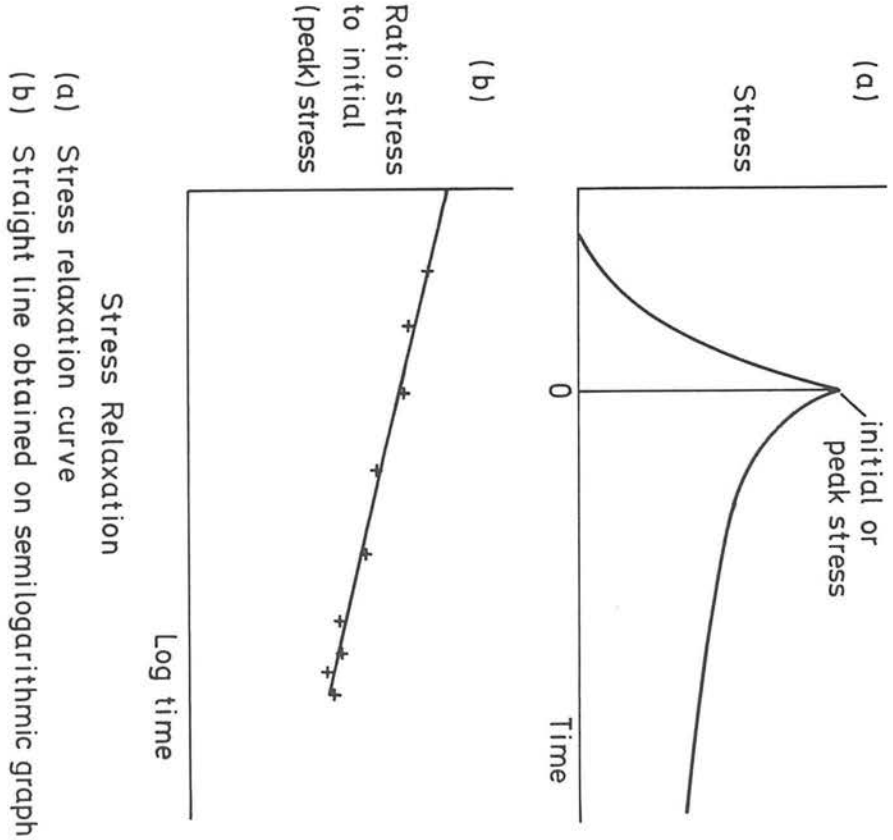


Figure 16

that the take-off point (L1 above) may be difficult to determine.

Percentage elongation (%E) : This is calculated by expressing the amount of extension of the tissue until it ruptures as a percentage of its internal diameter at stress 0. Thus from Figure 15 it is $\frac{OE}{ID}$ x100%.

Width at burst (WB) : This is the internal diameter of the ring as it ruptures. It is therefore equal to the internal diameter at stress 0 (gauge length) plus the distance OE (Figure 15).

Energy under the curve (J) : This is the area under the stress/strain curve to burst. It is a measure of the energy required to burst the tissue.

Stress relaxation (SR) (Figure 16) : The stress registered in a tissue exponentially declines with time when the tissue is held at a fixed strain. The resultant curve can be plotted on a semilogarithmic graph of the ratio of initial stress at any given time against log time. 100% strain was used as the fixed strain level and stress decline followed for 3 minutes. A Hewlett Packard 85 desktop computer with a magnetic plate was used to convert the stress relaxation curve to a straight line. The computer programme is listed in Appendix B (language - basic). The slope of the semilogarithmic line was taken as a numerical value for stress-relaxation and the r value was always greater than 0,9 and nearly always greater than 0,98.

Hysteresis (H) (Figure 7) : The 10th pre-conditioning cycle was used to calculate the hysteresis ratio. The area under the descending part of the curve was expressed as a ratio of that under the ascending part.

METHODOLOGICAL STUDIES.

The ultimate aim in studying the rat colon was to establish a method for testing the human colon. Post-mortem colon is the only non-diseased human bowel available, so that therefore it was necessary to investigate the influence of the time after death at which the colon was removed from the corpse on the mechanical integrity of the tissues.

An additional aim was to compare the African and European colon. This necessitated storage and transportation of specimens back from Africa since there are no facilities available in the continent for testing bio-materials and the Instron 1026 is too large to transport. Thus the preservation of mechanical properties using different methods of storage had to be studied.

All human tissue must be irradiated before testing at Ethicon Research Laboratories, therefore the effect of irradiation had to be determined. The irradiation process takes 9 hours so that material cannot be tested on the same day as being collected. Therefore it was important to define how long mechanical properties could be preserved in physiological saline.

The following factors were investigated :

1. Test environment.
2. Maintenance of mechanical properties in physiological saline.
3. Storage mediums.
4. Reproducibility of the method.
5. Length of storage.
6. Difference between proximal and distal colon and rectum.

7. Irradiation.

8. Time after death that colon is excised from corpse.

Some of these factors were studied simultaneously with others in balanced design experiments and therefore the individual methodological experiments carried out will be described rather than examining each factor individually. The results are discussed on pages

Experiment 1 :

Aim - to determine the variation between adjacent rings of rat colon and the variation between individual rats. The influence of test environment was assessed.

Design - a Latin square based on three variables :

1. ring site (a, b or c) (contiguous segments), where (a) is the most proximal ring and (c) the most distal.
2. the individual rat (1-6).
3. the test environment: saline, Earl's solution or air.

	a	b	c	Weight
RAT 1	A	S	E	390g
RAT 2	A	S	E	400g
RAT 3	S	E	A	410g
RAT 4	S	E	A	382g
RAT 5	E	A	S	410g
RAT 6	E	A	S	380g

Where :
A . . Air
S . . Saline
E . . Earl's solution

Method - rats were 3 month old males, weighing 380-410g. These were killed by the standard method of CO_2 intoxication. Testing was carried out within 2 hours of death. Statistical analysis was by analysis of variance.

Results - as can be seen from the means in Table VI, the test environment made no significant difference to the values obtained. There was only one

significant difference for segment site. The Young's modulus between 25 and 100g of stress was greater the more proximal the segment. This means that the proximal colon is stiffer than the distal. The numbers tested are small however, and the conclusions drawn must therefore be guarded. Sixteen analyses of variance were conducted so that by chance one would expect one result to be significant at the 5% level.

TABLE VI. Results of Experiment 1, comparing three preparation methods and three segment sites.

	Preparation Method			Segment (contiguous)		
	A	S	E	A	B	C
Burst strength (g)	326 ± 43	342 ± 75	327 ± 50	346 ± 37	327 ± 53	323 ± 75
Percentage elongation	200 ± 25	213 ± 32	207 ± 19	201 ± 27	201 ± 25	219 ± 23
Young's modulus (25-100g/mm²)	10 ± 3	15 ± 10	14 ± 8	17 ± 10*	12 ± 5	9 ± 4
Young's modulus (125-200g/mm²)	47 ± 16	58 ± 22	58 ± 18	61 ± 25	57 ± 7	44 ± 17
L1 (mm)	33 ± 3	33 ± 7	33 ± 4	31 ± 6	34 ± 5	33 ± 2
L2 (mm)	29 ± 5	23 ± 4	23 ± 3	25 ± 6	23 ± 2	27 ± 6
Width at burst (mm)	19 ± 1	21 ± 1	20 ± 2	20 ± 2	20 ± 2	20 ± 2
Energy under curve (KJ)	10 ± 3	10 ± 3	9 ± 2	10 ± 1	9 ± 2	11 ± 4

Statistical analysis = analysis of variance.

* M1 falls from A to C - t=2,41 11df P <0,05.
Same trend in M2 but this was not significant.

Experiment 2 :

The mechanically stabilised state - mechanical properties are constant for duration.

Aim - to confirm the development of a mechanically stabilised state when

the colon is kept in physiological saline at 4°C and to determine its duration. A mechanically stabilised state is one in which the mechanical properties remain constant under the conditions of storage.

Design - a Latin square design was adopted. Three variables were tested :

1. segment site, five contiguous segments A to E, where A was the most proximal segment and E the most distal.
2. individual rat variation (rats 1-5).
3. mechanical tests were performed on 5 days (0,1,2,4,7 days of storage).

	0	**1**	**2**	**4**	**7 (days storage)**
RAT 1	A	B	C	D	E
RAT 2	B	A	D	E	C
RAT 3	C	D	E	A	B
RAT 4	D	E	B	C	A
RAT 5	E	C	A	B	D

Method - six week old, male rats weighing 170-195g were killed in the standard way by CO_2 intoxication and their colons were removed immediately after death. The colons were emptied of faeces, irrigated with physiological saline and then stored for the designated period of time (see above) in physiological saline at 4°C. Testing was carried out at room temperature. The following measurements were made:

. . Burst strength (BS)
. . Extension at burst (%E)
. . L values - L0, L1, L2
. . Stress relaxation (SR)
. . Hysteresis (H)
. . Energy under curve (J)
. . Young's modulus - 25-100g (M1)
- 125-200g (M2)

Statistical analysis was by analysis of variance.

Results - the rat colon may be stored for at least seven days in physiological saline at 4°C without significant change in burst strength, percentage elongation at burst, L values (L1 and L2), energy under the curve and Young's modulus between 25 and 100g, and hysteresis ratio. For these tests there is a mechanically stabilised state.

Stress relaxation rose after 24 hours of saline storage and the Young's modulus between 125 and 200g progressively fell with each day of storage. These changes suggest that the rat colon becomes less stiff and more flexible with storage in physiological saline at 4°C.

Because there appeared to be little change in the mechanical properties of the rat colon at Day 7, specimens being viscoelastically tested were stored under the same conditions until Day 17. By this time the stress-relaxation rose to 0,2350 and the hysteresis ratio to 0,98. However, of the five specimens only three could be tested because the other two were unable to be extended to 100% strain before rupture. It therefore appears that an increased steepness of the stress relaxation slope and a rising hysteresis ratio are synonymous with degradation.

Viscoelastic properties depend in part upon tissue hydration. The colonic tissue may absorb water during 24 hours storage in physiological saline, which may explain why its stress-relaxation slope is altered by Day 1.

Distally placed segments (D and E) were stronger and more elastic. Percentage elongation, L2, stress relaxation, were all raised significantly in these segments. The rat colon is therefore more elastic as it approaches the rectum. There is also a macroscopic difference in the wall in this

TABLE VII.a. Mean values of results obtained in Experiment 2, comparing days of storage in physiological saline.

	Day 0	Day 1	Day 2	Day 4	Day 7	Day 17
Burst strength	264,0 ± 41,0	256,0 ± 49,0	243,0 ± 43,0	241,0 ± 52,0	252,0 ± 58,0	
Percentage elongation	95,0 ± 11,0	87,0 ± 18,0	112,0 ± 27,0	100,0 ± 43,0	123,0 ± 31,0	
L0	32,6 ± 4,2	34,2 ± 2,7	35,8 ± 6,9	42,5 ± 12,4	36,0 ± 8,3	
L1	22,0 ± 3,3	25,4 ± 6,5	27,4 ± 4,8	21,0 ± 11,2	19,0 ± 8,6	
L2	14,4 ± 2,3	15,10 ± 5,5	17,4 ± 5,8	13,0 ± 8,5	12,0 ± 7,1	
Stress relaxation	0,1769 ± 0,0221	0,2157 ± 0,0711	0,2041 ± 0,0244	0,1967 ± 0,0192	0,2114 ± 0,047	0,2350*
Hysteresis	0,79 ± 0,05	0,69 ± 0,06	0,07 ± 0,08	0,78 ± 0.05	0,86 ± 0,06	0,98
Energy under curve	68,0 ± 28,0	59,0 ± 15,0	59,0 ± 22,0	61,0 ± 13,0	55,0 ± 36,0	
Young's modulus (25-100g)	282,0 ± 76,0	429,0 ± 87.0	302,0 ± 109.0	238,0 ± 90,0	267,0 ± 249,0	
Young's modulus (125-200g)	1013,0 ± 437,0	972,0 ± 274,0	894,0 ± 202,0	461,0 ± 163,0	350,0 ± 118,0***	

* P <0,05
*** P <0,001

TABLE VIIb. Values of results obtained in Experiment 2, comparing segment site.

	A	B	C	D	E
Burst strength	251,0 ± 55,0	251,0 ± 43,0	250,0 ± 39,0	268,0 ± 37,0	270,0 ± 50,0*
Percentage elongation	81,0 ± 23,0	89,0 ± 18,0	97,0 ± 16,0	120,0 ± 30,0	118,0 ± 31,0
L0	40,2 ± 12,2	37,2 ± 6,6	33,0 ± 2,9	37,2 ± 7,9	32,2 ± 1,6
L1	21,2 ± 9,1	21,6 ± 8,0	19,4 ± 8,0	25,0 ± 7,1	27,6 ± 5,0
L2	11,6 ± 5,3	10,8 ± 3,7	16,6 ± 6,5	18,0 ± 7,8	16,9 ± 4,3*
Stress relaxation	0,2029 ± 0,0221	0,1717 ± 0,0176	0,1905 ± 0,0205	0,2215 ± 0,0278	0,2177 ± 0,321*
Hysteresis	0,77 ± 0,04	0,83 ± 0,06	0,74 ± 0,10	0,78 ± 0,08	0,76 ± 0,05
Energy under curve	55,0 ± 21,0	45,0 ± 15,0	55,0 ± 84,0	73,0 ± 14,0	82,0 ± 38,0*
Young's modulus (25-100g)	327,0 ± 109,0	374,0 ± 239,0	303,0 ± 116,0	206,0 ± 63,0	325,0 ± 135,0
Young's modulus (125-200g)	754,0 ± 320,0	802,0 ± 359,0	832,0 ± 403,0	638,0 ± 388,0	729,0 ± 623,0

* P <0,05

region. Proximally the colonic wall has a spiral, striated appearance. Distally it looks more like the rectum, somewhat homogenous without the diagnonal striations.

The significant differences in the distal segments emphasize the importance of balancing segment effects in subsequent experiments.

Reference to the L values in Table VII shows that the standard deviation tended to rise with days storage in physiological saline at 4°C. This may be indicative of tissue decomposition.

For most measurements made a mechanically stabilised state exists for up to a week. Subtle changes probably do occur due to tissue hydration, even within this period. Variation and errors in testing, particularly of elastic and viscoelastic properties would be minimised by testing in the first 24 hours. There were no significant differences between individual rats for any of the measurements made.

Experiment 3 :

Storage - Aim -

1. To establish a reliable method of storage for the rat colon which hopefully would be applicable to the human colon.

2. To determine over what period of time the colon could be stored.

3. To determine the influence of irradiation on the rat colon.

4. The effect of time after death before removal of the colon from the corpse.

Design - a Latin square design was adopted. Three variables were tested with and without irradiation :

a. storage medium (salt at 20°C and 4°C; storage at -20°C and immersion in liquid nitrogen).

b. time after death before removal of the colon from the corpse (0, 6, 24 and 48 hours after death).

c. length of storage (7, 11, 21 and 28 days).

Days storage	0	6	24	48 hours after death
7	Salt 20°C	Salt 4°C	-20°C	N_2
11	Salt 4°C	Salt 20°C	N_2	-20°C
21	-20°C	N_2	Salt 20°C	Salt 4°C
28	N_2	-20°C	Salt 4°C	Salt 20°C

One square was completed as above with the large bowel irradiated and one with the large bowel not irradiated. Both colon and rectum were tested for each rat. One square = one rat, therefore 32 rats in all.

Method - seven week old, male, vegetarian rats were killed in the standard way by CO_2 intoxication. The colon and rectum were removed from the corpse after the designated interval. Those rats which had their large bowels removed at 6 hours after death were left at 20°C after death, but those which had their bowels removed at 24 and 48 hours after death were placed in a sealed polythene bag at 4°C until their colons and rectums were removed. This it was hoped would simulate the treatment and storage of the human corpse after death. Irradiation was carried out on Day 0 in physiological saline and the large bowel was placed into the appropriate storage medium on Day 1. Storage in salt meant that the bowel was

completely immersed in salt in a polythene bag. Those colons to be stored at -20°C or in liquid nitrogen (-185°C) were put into a sealed polythene bag and the bag placed in a deep freezer or liquid nitrogen flask accordingly. Thirty-two rats were tested in all. Two rings were cut from each colon and each rectum, one from the proximal end and one from the distal end of each. Those rings stored at -20°C in liquid nitrogen were allowed to thaw and return to +20°C before testing. Those rings stored in salt were also tested at +20°C after rehydration for one hour in physiological saline.

The following measurements were made :

1. Burst strength (BS).
2. Extension at burst (%E).
3. Width at burst (WB).
4. L values, L1 and L2.
5. Young's modulus measured between the following set points of stress: 10 to 25g (M1) and 30 to 60g (M2). Lower set points were chosen in this experiment because it was appreciated that these ranges of stress were more likely to be in the physiological range. Also the tissue was significantly weakened by liquid nitrogen storage and deep freezing so that the previous set points were not applicable. The set points in the first two experiments were considered to be too far apart, since a curve more closely resembles a straight line over a short distance than a long one.
6. Energy under curve (J).

Methodological results and conclusions

Storage medium – burst strength was significantly preserved in the colons which were stored in salt, although there was no significant result for the rectum. The percentage elongation was significantly greater in the case of salt storage for the rectum. Neither burst strength nor percentage elongation appeared to be influenced by the temperature of salt storage. Other measurements were unaffected by the choice of storage medium. Since salt is cheap, readily obtainable and requires no special equipment other than a polythene bag for storage it was the best of the tested methods.

TABLE VIIIa. **Results – storage medium (Mean ±SD).**

		Storage medium			
Measurement		**Salt 20°C**	**Salt 4°C**	**–20°C**	**Liquid N_2**
Burst strength (g)	Colon	208,0 ± 37,0	220,0 ± 45,0	164,0 ± 41,0	176,0 ± 29,0
	Rectum	176,0 ± 49,0	149,0 ± 25,0	161,0 ± 32,0	157,0 ± 32,0
Percentage elongation	Colon	144,0 ± 20,0	129,0 ± 26,0	117,0 ± 30,0	125,0 ± 20,0
	Rectum	148,0 ± 29,0	135,0 ± 15,0	118,0 ± 24,0	111,0 ± 21,0
Young's modulus (M1) (g/mm^2) (10–25g)	Colon	13,8 ± 3,3	14,3 ± 5,4	15,2 ± 4,9	15,3 ± 4,4
	Rectum	14,6 ± 2,7	17,8 ± 3,7	16,3 ± 4,1	16,8 ± 4,6
Young's modulus (M2) (g/mm^2) (30–60g)	Colon	35,5 ± 8,6	29,5 ± 4,2	32,8 ± 9,2	31,4 ± 10,1
	Rectum	29,8 ± 7,8	34,4 ± 7,0	33,3 ± 5,1	36,0 ± 8,4
L1 (mm)	Colon	20,5 ± 4,3	19,4 ± 3,4	17,3 ± 4,4	17,6 ± 3,4
	Rectum	16,4 ± 7,6	13,7 ± 5,1	14,2 ± 4,1	13,8 ± 4,1
L2 (mm)	Colon	12,7 ± 4,7	12,4 ± 3,1	10,4 ± 3,9	9,9 ± 2,4
	Rectum	9,2 ± 4,7	6,2 ± 3,6	7,4 ± 3,3	6,6 ± 3,0
Energy under curve (KJ)	Colon	63,0 ± 15,0	58,0 ± 14,0	42,0 ± 15,0	44,0 ± 8,0
	Rectum	66,0 ± 16,0	55,0 ± 16,0	45,0 ± 10,0	46,0 ± 9,0

For significance of analyses of variance see Table IX (P 51).

Time after death - time after death affected elastic properties. L values fell and modulus values rose with increasing time after death. Both changes imply greater stiffness in the colonic tissue, probably due to the process of rigor mortis. Other measurements were unchanged with time after death between 0-48 hours.

TABLE VIIIb. Results - time after death (hours) (Mean ± SD).

Measurement		0 hrs	6 hrs	24 hrs	48 hrs
Burst strength (g)	Colon	202,2 ± 34,0	215,0 ± 52,0	175,0 ± 30,0	177,0 ± 49,0
	Rectum	180,0 ± 20,9	160,0 ± 26,0	175,0 ± 42,0	129,0 ± 29,0
Percentage elongation	Colon	128,0 ± 10,0	130,0 ± 25,0	124,0 ± 30,0	132,0 ± 34,0
	Rectum	134,0 ± 11,0	124,0 ± 11,0	120,0 ± 32,0	134,0 ± 39,0
Young's modulus (M1) (g/mm^2) (10-25g)	Colon	12,5 ± 4,8	16,8 ± 2,6	15,5 ± 5,1	13,8 ± 4,0
	Rectum	13,8 ± 2,6	15,7 ± 1,7	12,8 ± 5,0	18,3 ± 4,0
Young's modulus (M2) (g/mm^2) (30-60g)	Colon	25,0 ± 4,1	37,4 ± 11,4	33,8 ± 5,1	32,3 ± 5,3
	Rectum	31,1 ± 4,2	33,0 ± 4,0	39,8 ± 7,9	28,7 ± 7,8
L1 (mm)	Colon	21,8 ± 5,2	18,8 ± 3,7	17,0 ± 3,0	17,3 ± 4,9
	Rectum	18,5 ± 4,1	15,1 ± 3,2	15,3 ± 5,8	9,4 ± 3,1
L2 (mm)	Colon	15,6 ± 2,8	10,7 ± 2,8	9,4 ± 1,9	9,8 ± 3,5
	Rectum	10,7 ± 3,5	8,4 ± 1,7	7,2 ± 3,4	3,3 ± 1,0
Energy under curve (KJ)	Colon	57,0 ± 18,0	58,0 ± 14,0	45,0 ± 14,0	48,0 ± 15,0
	Rectum	59,0 ± 10,0	47,0 ± 5,0	53,0 ± 20,0	51,0 ± 19,0

For significance of analyses of variance see Table IX (p 51).

Length of storage – the percentage elongation rose with increasing length or storage. Increased percentage elongation might represent deterioration in the tissue. On the other hand very poor tissue is capable of very little expansion before rupture so that this finding is difficult to interpret. A constant length of storage was therefore chosen for the human study. The other measurements were unaffected by length of storage between 7–28 days.

TABLE VIIIc. Results – length of storage (days) (Mean ± SD).

Measurement		7 days	11 days	21 days	28 days
Burst strength (g)	Colon	196,0 ± 63,0	188,0 ± 47,0	216,0 ± 21,0	169,0 ± 19,0
	Rectum	145,0 ± 35,0	152,0 ± 22,0	183,0 ± 45,0	162,0 ± 28,0
Percentage elongation	Colon	100,0 ± 23,0	130,0 ± 22,0	135,0 ± 11,0	150,0 ± 12,0
	Rectum	102,0 ± 23,0	129,0 ± 15,0	131,0 ± 17,0	147,0 ± 30,0
Young's modulus (M1) (g/mm^2)	Colon	NOT DONE	15,4 ± 3,9	12,4 ± 2,1	16,1 ± 5,6
	Rectum	NOT DONE	18,9 ± 3,8	14,7 ± 3,3	15,1 ± 2,9
Young's modulus (M2) (g/mm^2)	Colon	NOT DONE	37,3 ± 8,0	30,7 ± 5,5	28,9 ± 8,7
	Rectum	NOT DONE	36,0 ± 7,3	32,7 ± 4,1	31,2 ± 8,7
L1 (mm)	Colon	20,7 ± 4,7	17,3 ± 4,7	17,0 ± 2,3	19,9 ± 3,1
	Rectum	16,6 ± 6,3	12,8 ± 3,2	14,7 ± 6,9	14,2 ± 4,2
L2 (mm)	Colon	13,1 ± 4,7	9,9 ± 4,4	11,3 ± 2,5	11,0 ± 2,4
	Rectum	8,6 ± 4,9	5,6 ± 3,1	8,4 ± 3,6	7,0 ± 3,1
Energy under curve (KJ)	Colon	52,0 ± 24,0	50,0 ± 17,0	58,0 ± 8,0	48,0 ± 7,0
	Rectum	45,0 ± 13,0	47,0 ± 13,0	61,0 ± 14,0	58,0 ± 16,0

For significance of analyses of variance see Table IX (p 51).

Irradiation – since only one out of sixteen measurements was affected by irradiation, irradiation did not appear to be detrimental to the mechanical properties of the colonic tissue. The one measurement affected was the modulus between 10 and 25g (M1) in the colon only, the tissue becoming less stiff with irradiation ($P < 0,05$).

TABLE VIIId. Results – irradiation (Mean ± SD).

Measurement		Irradiation	No irradiation
Burst strength (g)	Colon	196,0 ± 36,0	188,0 ± 51,0
	Rectum	155,0 ± 31,0	167,0 ± 39,0
Percentage elongation	Colon	130,0 ± 26,0	127,0 ± 25,0
	Rectum	124,0 ± 21,0	131,0 ± 31,0
Young's modulus (M1) (g/mm^2) (10–25g)	Colon	12,9 ± 2,7	16,4 ± 4,9
	Rectum	15,5 ± 3,5	17,0 ± 4,0
Young's modulus (M2) (g/mm^2) (30–60g)	Colon	29,5 ± 6,2	35,0 ± 8,9
	Rectum	30,1 ± 7,6	35,9 ± 5,7
L1 (mm)	Colon	19,0 ± 2,8	18,4 ± 4,9
	Rectum	13,0 ± 4,1	16,0 ± 5,9
L2 (mm)	Colon	12,0 ± 3,1	10,7 ± 4,1
	Rectum	7,5 ± 3,6	7,3 ± 3,9
Energy under curve (KJ)	Colon	56,0 ± 14,0	48,0 ± 16,0
	Rectum	51,0 ± 13,0	54,0 ± 17,0

For significance of analyses of variance see Table IX (p 51).

TABLE IX. Summary of results of experiment 3 (for means ± SD see Table VIIIa–d)

		Storage Medium	Hours after Death	Length of Storage	Irradiation
Burst strength (g)	Colon	*	NS	NS	NS
	Rectum	NS	*	NS	NS
Percentage elongation	Colon	NS	NS	**	NS
	Rectum	**	NS	**	NS
Young's modulus (M1) (g/mm^2) (10–25g)	Colon	NS	NS	NS	*
	Rectum	NS	NS	NS	NS
Young's modulus (M2) (g/mm^2) (30–60g)	Colon	NS	*	NS	NS
	Rectum	NS	*	NS	NS
L1 (mm)	Colon	NS	NS	NS	NS
	Rectum	NS	**	NS	NS
L2 (mm)	Colon	NS	*	NS	NS
	Rectum	NS	**	NS	NS
Energy under curve (KJ)	Colon	**	NS	NS	NS
	Rectum	**	NS	*	NS

NS = not significant
* = P <0,05
** = P <0,01

Experiment 4 :

Aim – To check the effect of irradiation and salt storage on the mechanical properties of the rat colon. Salt appeared to be the storage medium of choice from Experiment 3 and human colons were to be irradiated before testing. The effect of salt storage on viscoelastic properties had not been previously tested.

Method - Five 200-230g male, Sprague-Dowley rate (age 7 weeks) were killed by CO_2 intoxication. Their colons were excised and four 10 mm rings were cut from each. These segments were treated according to a balanced design similar to those used in the previous experiments. Rings stored in saline were kept at 4°C overnight. Those stored in salt and irradiated were kept at 4°C. It was intended not to irradiate half of the salt irradiated group but due to an administrative error all the salt stored specimens were irradiated. Irradiation took place the day before testing, using a dosage of 2,5 megarads over 9 hours. Specimens stored in salt were irradiated in salt (ie. dehydrated). Dehydration reduces irradiation damage.

Results - These are shown in Table X. Irradiation appeared to have no great effect on burst strength, percentage elongation or L values. Although the values for the saline irradiated group approached or reached statistical significance the difference was not large (9% for percentage elongation, 17,2% for burst strength). Irradiation appeared to have no effect at all on the salt stored group, possibly because salt storage dehydrates the tissue which minimised the destructive effect of irradiation. Human colons were to be irradiated in salt, thus irradiation would be unlikely to affect the mechanical properties of the human colon as tested in this study.

Salt storage for 24 days preserved the mechanical properties of the rat colon as well as saline storage overnight at 4°C.

TABLE X. Results of Experiment 4.

	Saline 24 hrs Non-irradiated (5)	Saline 24 hrs Irradiated (5)	Salt 24 days Irradiated (10)
Burst strength (g)	244,0 ± 43,0	202,0 ± 30,0*	246,0 ± 69,0
Percentage elongation	235,0 ± 21,0	216,0 ± 9,0**	225,0 ± 15,0
L1 (mm)	27,8 ± 6,3	22,3 ± 4,8	27,0 ± 7,6
L2 (mm)	18,75 ± 5,2	17,75 ± 3,1	19,0 ± 2,7

* $P < 0,1$
** $P < 0,05$

Human.

Colons obtained at autopsy were used for testing of the mechanical properties. There was no practical alternative to the use of post mortem material since those patients who have colectomies have colonic disease and it is not safe to biopsy the human colon at laparotomy when there is no colonic disease.

REMOVAL OF COLONIC SEGMENT.

In the Edinburgh group the whole colon was recieved intact shortly after autopsy.

The colonic segments were excised directly from the body in the Ugandan colons. The reason for this difference was to accommodate the departments supplying the colons and cause as little inconvenience as possible in order to ensure continued enthusiasm. Approximately 10 cm of bowel were excised from the following sites (Figure 17):

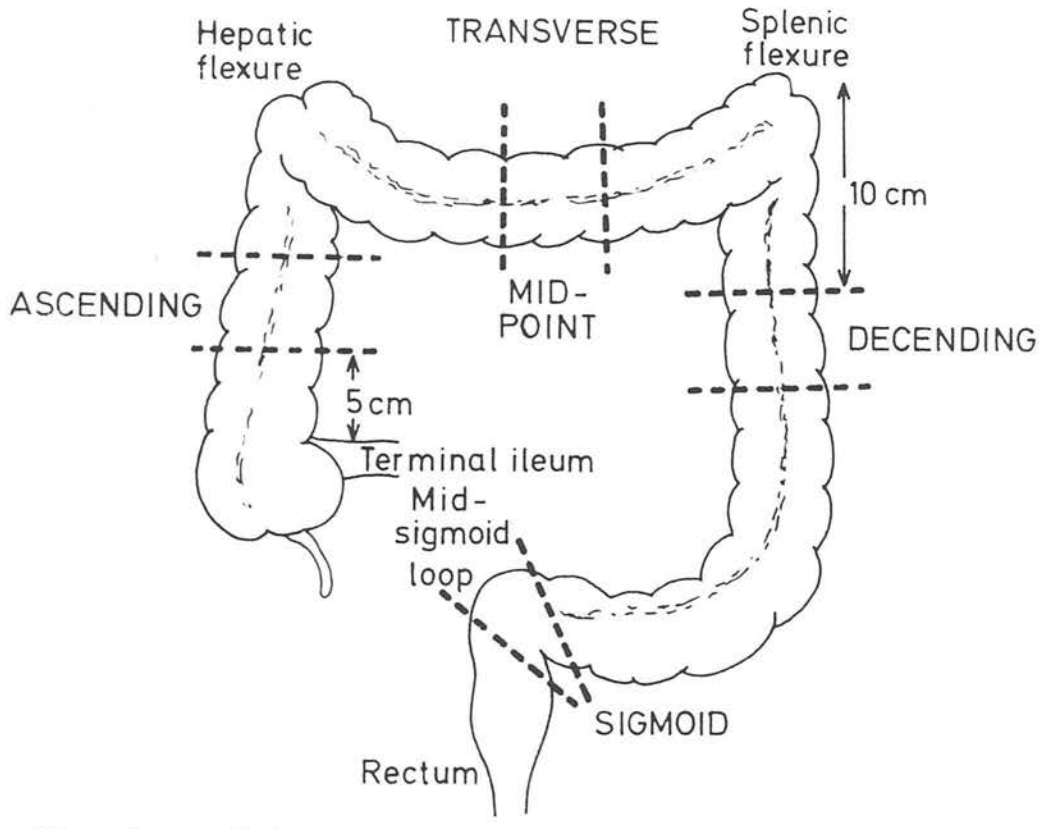
Ascending colon . . 5 cm from the ileocaecal junction, where the diameter of the colon appears more uniform.

Transverse colon . . the mid transverse colon as judged by the attachment of the greater omentum and the middle colic artery.

Descending colon . . 10 cm below the splenic flexure.

Sigmoid colon . . the middle of the sigmoid loop. In Scottish colons this site is usually 20-30 cm below the site of removal of the descending colon but the sigmoid loop is much longer in the African.

The segments were irrigated with tap water to empty them of as much faecal material as possible. It was noted that the Ugandan colons were



Sites for excision of segments for the human colon

Figure 17

generally much cleaner than the Edinburgh ones before irrigation. The ascending colon was the most difficult segment to adequately clean, especially those from Edinburgh.

Once clean, the segments were placed in individually labelled polythene bags containing coarse salt. The segments were completely covered with salt and the bag sealed. Coarse sea salt (Edinburgh Real Foods) and Analar salt were used for the Edinburgh colons and even coarser salt (Gift of the EEC to Uganda) bought in the local market for the Ugandan colons. Those Edinburgh colons which were tested within 24 hours were placed immediately into physiological saline rather than salt.

EXAMINATION FOR DIVERTICULAR DISEASE.

The remaining colon was examined for diverticula. This included close inspection of the colon and opening it along its entire elngth and examining the mucosal surface for openings to diverticula after washing the faeces off under a tap. The diagnosis of diverticular disease by muscle thickness alone was not attempted. Only the Edinburgh colons were opened to search for diverticular disease. The Ugandan colons were not opened because the city mortuary in Kampala was short of water and to have prolonged my presence there by searching for diverticula might have stretched their co-operation beyond its limits. It would have been possible to have carefully examined the colons in Makerere University post mortem suite at Mulago Hospital, but initially it seemed unlikely that I would be obtaining material there. Diverticular disease is known to be extremely rare in Africans and there was certainly no evidence of diverticular disease on inspection of the bowel from the outside.

SOURCES.

Edinburgh colons were obtained from fiscal post mortems and from the Pathology Department, Western General Hospital. Before the post mortem examination the body was kept at 4°C once delivered to the mortuary.

Kampala colons were obtained from fiscal cases and the Pathology Department, Makerere University. The body refrigerator/cold room broke down the week before I arrived in Kampala and there was little chance of it being restored to function in the short term. The bodies were therefore kept at room temperature (approximately 20°C).

The date and time of death were recorded, together with the patient's age, sex and cause of death. Concomitant diseases such as malnutrition, renal disease, etc. were listed. Colons from patients with jaundice were excluded as were those with bowel disease other than diverticular disease and those who were receiving steroid therapy. Some of the Ugandans' ages were not known since Africans often do not know their age and in these cases an estimation of age was made by local people. The colons received in Edinburgh and Kampala are shown in Tables XI to XIV.

It was noted that the Ugandan colons had hardly any fat in the mesentery or the omentum. All the Edinburgh colons contained a great deal of fat except for the babies. Having been to Uganda and observed life there, I am confident that the Ugandans eat their indigenous diet; they certainly do not eat a Western diet.

Three sigmoid and two transverse colons were obtained from the Edinburgh patients (all over 50). Two were undergoin resection for diverticular disease, one for mucosal prolapse and one for carcinoma of the colon.

STORAGE.

The colonic segments were stored in salt for 28-35 days in a sealed polythene bag. Edinburgh colons were kept in a cold room (4°C), except when being transferred for testing. Ugandan colons were kept at 4°C in a refrigerator for 7-10 days and thereafter were kept at room temperature. When travelling by air the colons were taken as hand luggage so that they were not subjected to extremes of temperature and pressure such as might occur in the baggage hold.

IRRADIATION.

Irradiation of all colons was carried out according to the health and safety protocol at Ethicon Laboratories, Sighthill Industrial Estate, Edinburgh. 2,5 megarads over 9 hours was delivered by their Cobalt 60 plant and the temperature rose to 43°C during irradiation. Irradiation was carried out a few days before testing. It was not possible to irradiate the colons at a fixed interval before testing but the interval was always less than a week.

Those colons which were tested within 24 hours of removal were placed inside a thermos flask containing ice. The colon itself was in physiological saline in a polythene bag, the ice was not in direct contact with the tissue. The temperature within the flask following irradiation was 16°C.

PREPARATION OF TISSUE FOR TESTING.

Those colons which were stored in salt were placed in physiological saline at room temperature for 2 to 6 hours to allow rehydration before being prepared further. The colonic segment was cleaned of mesentery and fat and laid out on a cork base. Care was taken to lay the tissue on the base without tension (pins were not used), and two rings were cut from

TABLE XI. Edinburgh colons (32).

Time after death	AGE (years) Birth to 1yr	1–15	15–30	30–40	40–50	50–70	70+	Total
0–12h	2	–	2	–	–	–	3	7
12–24h	2	–	1	1	–	3^{d}	–	**7**
24–36h	3	–	–	–	1	2^{dd}	1^{d}	**7**
36–48h	1	–	1	–	1	1	1	**5**
48+h	1	1	1	–	1	1^{d}	1	6
Total	9	1	5	1	3	7	6	32

d = denotes 1 patient with diverticular disease.

Age range 24 weeks to 81 years.

Cause of death – 22 adults (12 male, 10 female)

1. Violence (RTA, fall) = 6
2. Suicide = 5
3. Myocardial infarction = 3
4. Infection = 3
5. Malignancy = 1
6. Subarachnoid haemorrhage = 1
7. Haemorrhage = 1
8. Not known = 2

TABLE XII. Edinburgh group.

Sex	Age	Cause of death	Time after death of removal of colon (hrs)	Diverticular Disease present
F	57 yrs	Overdose	58 hrs	Yes
M	20 yrs	RTA	35 hrs	No
F	70 yrs	RTA	35 hrs	No
M	70 yrs	RTA	35 hrs	No
F	41 yrs	Overdose	24-36 hrs	No
M	19 yrs	RTA	12-24 hrs	No
M	53 yrs	?overdose	12-24 hrs	No
F	28 yrs	Overdose	0-12 hrs	No
M	63 yrs	Myocardial infarction	24-36 hrs	Yes
M	70 yrs	Bronchopneumonia	53 hrs	No
F	68 yrs	Pulmonary embolus and malignancy	27 hrs	Yes
M	67 yrs	Acute bronchitis or chronic bronchitis	21 hrs	No
M	9 mths	Cot death	9 hrs	No
F	52 yrs	Subarachnoid haemorrhage	21 hrs	Yes
M	5 mths	Cot death	0-12 hrs	No
F	74 yrs	Not known	24-36 hrs	Yes
M	63 yrs	Head injury bronchopneumonia	42 hrs	No
M	2 mths	Pneumonia, genetic disorder	60 hrs	No
F	4 yrs	Cardiac disorder, renal failure	48 hrs	No
F	27 weeks	Premature birth	12-24 hrs	No
M	24 weeks	Spontaneous abortion	12-24 hrs	No
M	40 weeks	Microcephalic	12-24 hrs	No
F	49 yrs	Hanging	36-48 hrs	No
F	43 yrs	Bleeding gastric ulcer	72-84 hrs	No
F	78 yrs	Suffocation suicide	36-48 hrs	No
F	30 weeks	Premature birth	36-48 hrs	No
M	37 weeks	Intraventricular haemorrhage	12 hrs	No

TABLE XII (continued).

Sex	Age	Cause of death	Time after death of removal of colon (hrs)	Diverticular disease present
M	74 yrs	Myocardial infarction	24-36 hrs	No
M	36 yrs	Unknown, ?overdose	23 hrs	No
M	21 yrs	Head injury, pneumonia	72-84 hrs	No
M	22 yrs	Multiple injuries	36-48 hrs	No
M	9 mths	Cot death	12-24 hrs	No

TABLE XIII. Kampala colons (20).

Time after death	A G E (years) Birth to 1 yr	1–15	15–30	30–40	40–50	50+	Total
0–12h	–	–	–	3[m]	1	–	4
12–24h	–	1	3	2	2[m]	2[m]	10
24–36h	–	–	1	–	–	–	1
36–48h	1	–	–	–	–	1[m]	2
48–72h	2	–	–	1[m]	–	–	3
Total	3	1	4	6	3	3	20

m = denotes 1 malnourished patient.

Age range 36 weeks to 62 years.

Cause of death – 17 adults (13 male, 4 female)

1. Violence (assault, gunshot, electrocution) = 11
2. Infection (pneumonia, septicaemia) = 6

Associated malnutrition present in five cases, all dying of infection

TABLE XIV. Kampala group.

Sex	Age	Cause of death	Time after death of removal of colon (hrs)
M	19 yrs	Skull fracture - assault	34 hrs
M	22 yrs	Gunshot to chest and head	12-24 hrs
M	30 yrs	Gunshot to face	12-24 hrs
F	55 yrs	Assault, acute subdural	14 hrs
M	30 yrs	Electrocution	12 hrs
F	30 yrs	Pneumonia, malnourished	50 hrs
M	62 yrs	Tuberculosis	18 hrs
F	42 yrs	Pneumonia	12-24 hrs
M	30 yrs	Road traffic accident	23 hrs
M	35 yrs	Gunshot	14 hrs
F	20 yrs	Ruptured spleen	14 hrs
M	36 weeks	Premature birth - pneumonia	50 hrs
M	40 weeks	Fresh stillbirth	56 hrs
M	30 yrs	Assault - skull fracture	10 hrs
F	53 yrs	Assault, anaemia	40 hrs
M	14 yrs	Pneumonia	24-36 hrs
M	41 yrs	Meningitis, malnutrition	17 hrs
M	44 yrs	Malnourished, diabetes	6 hrs
M	35 yrs	Multiple trauma	6 hrs
F	40 weeks	Fresh stillbirth	48 hrs

the segment with a template utilising a $3\frac{1}{2}$" Gillette raxor blade. The cutting template was hammered rapidly through the tissue into the cork. This gave a clean cut, with consistent width of ring providing folds of tissue were unfolded prior to the cut. A 10 mm width ring was cut. TIssue between the two cut rings was used to measure reference dimensions. The rings were placed in physiological saline at room temperature until tested. Spare tissue was discarded. The human tissue could not have been accurately cut by hand and eye as was done for the rat tissue because the bowel is wider than the scalpel blade. The tissue is also too thick to allow a clean cut without hammering the cutting blade through rapidly. Before assuming constant width after cutting with the template a number of cut segments were checked for measurement using a ruler.

MEASUREMENT OF REFERENCE DIMENSIONS.

The floppiness and softness of colonic tissue makes measurement of tissue dimensions difficult. Three measurements were required :

1. The width since this must be multiplied by the thickness to give the cross-sectional area of the ring. As mentioned above a constant 10 mm ring was cut using a template.

2. The thickness, to allow calculation of the cross-sectional area. The method used was to place a piece of bowel wall taken from between the two excised rings between two glass microscope slides of known dimensions and measure the thickness with a Mercer No 54 gaugemeter. The slides serve to distribute the compressive forces on the soft tissue and reduce inaccuracies due to compressive stress relaxation.

   Attempts to measure the thickness using tissue gauge forceps were inaccurate because it was difficult to judge when one was

compressing the tissue.

3. The internal diameter of the bowel. This was necessary to calculate the strain to be applied for viscoelastic tests and the ultimate extension of the tissue at breakage. The method used measured the distance between the bottom of the bottom hook and the top of the upper hook as soon as stress is registered on the 50g scale of the Instron. The internal diameter thus measured at stress 0 was used to calculate 30% strain and percentage elongation.

A method of checking this internal diameter was to cut another ring of tissue from the test colon, preferably between the two test rings, and open the ring and measure its length when laid out on relatively friction-free surface. I used a stainless steel worktop covered with physiological saline for this. The internal diameter was then calculated as half this length minus twice the thickness. Attempts to measure the length by hanging the strip of bowel in a measuring cylinder were unsatisfactory because the tissue is so floppy and light that it did not hang without kinking.

TEST APPARATUS.

The same Instron 1026 was used for testing human tissue as was used for the rat. The only difference was that 4,76 diameter hooks were made since these were stronger and also wider, exerting less cutting pressure on the tissue in contact with the hooks. The 2,25 mm diameter rat hooks were used for the neonatal colons which were too small for the larger human hooks.

TESTING METHODS.

The viscoelastic properties were studied in physiological saline at 37°C. The ring of colon was first preconditioned for nine cycles at 30% strain. A tenth cycle was recorded in order to measure hysteresis and then stress relaxation was measured at 30% strain for 3 minutes. There was no recovery period allowed between preconditioning and testing hysteresis and stress relaxation. In every case the strain rate was 50 mm per minute.

Once the viscoelastic tests had been performed the ring of colon was returned to physiological saline at room temperature for 30 to 120 minutes to allow the tissue to recover before recording the stress/strain curve to rupture. The recording of the stress/strain curve to rupture was also at the end of a test session since it involved changing the load cell on the Instron. The preconditioned ring and one which had not been pre-conditioned were thus tested.

The hysteresis ratio and slope of the stress relaxation curve were calculated as described for the rat colon. From the stress/strain curve to rupture the burst strength, tensile strength and percentage elongation at burst were calculated.

HUMAN METHODOLOGICAL STUDIES.

The following methodological studies were carried out on human colons :

1. The effect of salt storage for 28-35 days.
2. Reproducibility between adjacent segments.
3. The influence of preconditioning on the burst properties.

The effect of salt storage : Six colons were tested twice, once at

24 hours after overnight irradiation whilst in physiological saline and once at 28-35 days after salt storage. The colons thus tested were :

No 5 . . . . 41 year old female overdose.

No 6 . . . . 19 year old male student killed in RTA.

No 8 . . . . 28 year old female overdose.

No 9 . . . . 63 year old male myocardial infarction.

No 15 . . . . 52 year old female subarachnoid haemorrhage.

No 26 . . . . 78 year old female plastic bag suicide.

The following were measured :

Burst strength (BS)

Tensile strength (TS)

Thickness (T)

Internal diameter (ID)

Width at burst (WB)

Percentage elongation (%E)

Stress relaxation (SR).

Each colon was tested at the standard four sites, ascending, transverse, descending and sigmoid, giving 40 measurements in all, since preconditioned and non-preconditioned rings were treated separately (Table 15). Statistical analysis was by means of paired T tests. Only two groups were statistically significant at the 5% level. This is in fact what would be expected by chance since the five percent level implies a one in 20 chance of significance. These figures suggest that salt storage for 28-35 days has little effect on the mechanical properties tested. It is interesting to note that the mean for percentage elongation is always higher for the salt group than for the saline, except for the non-preconditioned specimen for the

TABLE XV.

	Cross-sectional area (mm^2) (thickness x10 mm)		
	Salt	Saline	Statistical Significance
Ascending	17,5 ± 4,5	15,1 ± 0,7	NS
Transverse	16,2 ± 3,1	16,3 ± 0,9	NS
Descending	16,8 ± 3,1	17,5 ± 4,1	NS
Sigmoid	24,5 ± 6,6	23,5 ± 5,6	NS
BURST STRENGTH (g)			
Preconditioned			
Ascending	1172 ± 262	1331 ± 398	NS
Transverse	1575 ± 775	1406 ± 550	NS
Descending	1361 ± 518	1768 ±1009	NS
Sigmoid	1273 ± 667	1010 ± 474	NS
Non-preconditioned			
Ascending	1160	1000	-
Transverse	1068 ± 178	978 ± 321	NS
Descending	1201 ± 255	1287 ± 287	NS
Sigmoid	1173 ± 404	1135 ± 341	NS
TENSILE STRENGTH (g/mm^2)			
Preconditioned			
Ascending	70 ± 22	89 ± 29	NS
Transverse	104 ± 64	87 ± 36	NS
Descending	81 ± 26	105 ± 58	NS
Sigmoid	54 ± 27	45 ± 21	NS
Non-preconditioned			
Ascending	77	62,5	-
Transverse	67 ± 20	60 ± 23	NS
Descending	77 ± 28	84 ± 42	NS
Sigmoid	47 ± 17	51 ± 20	NS

TABLE XV (continued)

	Internal diameter		
	Salt	Saline	Statistical Significance
Ascending	42 ± 11	52 ± 13	NS
Transverse	35 ± 10	42 ± 12	NS (P <0,1)
Descending	28 ± 7	31 ± 10	NS
Sigmoid	26 ± 10	30 ± 10	NS
WIDTH AT BURST			
Preconditioned			
Ascending	118 ± 18	123 ± 17	NS
Transverse	122 ± 12	113 ± 14	NS
Descending	93 ± 13	93 ± 8	NS
Sigmoid	86 ± 16	83 ± 18	NS
Non-preconditioned			
Ascending	85	102	M
Transverse	117 ± 9	113 ± 20	NS
Descending	101 ± 9	92 ± 10	P <0,05*
Sigmoid	87 ± 18	89 ± 17	NS
PERCENTAGE ELONGATION			
Preconditioned			
Ascending	190 ± 76	144 ± 39	NS
Transverse	279 ± 154	187 ± 88	P <0,05*
Descending	253 ± 102	228 ± 108	NS
Sigmoid	262 ± 99	195 ± 82	NS (P <0,1)
Non-preconditioned			
Ascending	88	200	M
Transverse	198 ± 196	211 ± 63	NS
Descending	281 ± 82	230 ± 110	NS (P <0,1)
Sigmoid	262 ± 102	218 ± 101	NS
STRESS RELAXATION			
Ascending	0,182 ± 0,017	0,173 ± 0,020	NS
Transverse	0,193 ± 0,016	0,185 ± 0,014	NS
Descending	0,184 ± 0,022	0,168 ± 0,022	NS
Sigmoid	0,194 ± 0,021	0,170 ± 0,026	NS

ascending colon but there was only one sample in this group. When considered with the results of the rat storage experiments there is the suggestion that the percentage elongation at burst is increased by salt storage. This maybe a function of time of storage or the medium itself. The width at burst is a more consistent measure of strength for the human colon and it is worth noting that only one out of seven paired T tests reached statistical significance for width at burst.

Reproducibility of results : The other point which can be made from Table XV is that there is no statistically significant differences between adjacent rings when one ring was preconditioned at 30% strain and the other was not. Wilcoxin signed ranks were used to assess statistical significance for all adjacent segments tested after salt storage. Each site of the colon was assessed separately but no statistical difference was found in any part of the colon between preconditioned (PC) and non-preconditioned (NPC) segments. As these segments are adjacent to each other these results suggest that the method used to test the human colon is reproducible and reliable.

Using the preconditioned and non-preconditioned segments as replicates coefficients of variation were calculated. These are shown in Table XVI for burst strength, percentage elongation and width at burst. The same internal diameter and thickness measurements were applied to both pre-conditioned and non-preconditioned segments so their coefficients of variation are not given in Table XVI.

Stress relaxation was measured in two adjacent segments in two adult Edinburgh post-mortem colons, and one neonatal Kampala colon. In addition

the four operative specimens had adjacent segments tested viscoelastically. The coefficient of variation for stress five relaxation was 7% which is small.

TABLE XVI. Coefficients of variation for testing two adjacent segments, one preconditioned, one not preconditioned.

	Ascending	Transverse	Descending	Sigmoid
Burst strength	24%	16%	20%	18%
Percentage elongation	10%	9%	9%	13%
Width at burst	6%	5%	5%	7%

STATISTICAL METHODS.

Since many of the measurements varied over an order of magnitude and were highly skewed, non-parametric tests were used where possible. Paired data were compared by Wilcoxon signed ranks tests. (Preconditioned rings against adjacent non-preconditioned rings, salt against saline, different colon sites), while groups of subjects were compared by Wilcoxon rank sum tests (infants aged more than or less than one week, Edinburgh infants against Kampala infants, diverticular disease present or absent). Multiple regression analyses of measurement values against age, race, sex and time after death were carried out on the logarithms of the values, which appeared to be approximately symmetrical in their distributions (Figures 18-26). Coefficients of variation were calculated using the preconditioned and non-preconditioned values for adjacent segments as replicates.

Results.

Rat.

PRE-STRAIN.

The pre-strain measured on 9 seven-week old male rats ranged from 8-13%, median 10%.

EFFECT OF SEGMENT SITE.

Reference to Table VII (Experiment 2) shows that distally placed colonic segments were stronger and more extensible than proximally ones. The rectum however was weaker than the colon though the percentage elongation was similar for both regions. L-values were significantly lower for the rectum (Table XIX).

AGE.

Table XVII shows the difference between young, seven-week old female rats and 14-17 month females which were losing weight, in poor condition, and within a few weeks of death. The burst strength was significantly reduced in old age as was percentage elongation, and the stress relaxation slope was flatter. The older colon was thicker, with a greater internal diameter.

Table XVIII shows values obtained for male rats aged seven weeks and one year. The burst strength was greater in the one year age group but there was no corresponding increase in tensile strength since the thickness of the colon increased with age also, although this increase did not quite reach statistical significance.

TABLE XVII.

	7 week females	14–17 month females
Burst strength (g)	276 ± 39	229 ± 42*
Thickness (mm)	0,54	0,65 *
Tensile strength (g/mm²)	51,1 ± 7,2	35,2 ± 6,5***
Percentage elongation	212 ± 23	183 ± 22 *
Width at burst (mm)	10,6 ± 1,0	11,75 ± 1,3
Internal diameter (mm)	5,0	6,4 *
Stress relaxation	0,198 ± 0,005	0,185 ± 0,015*

* P <0,05
***P <0,001

TABLE XVIII.

	7 week males	1 year males
Burst strength (g)	280 ± 19	368 ± 81***
Thickness (mm)	0,53 ± 0,07	0,61 ± 0,09[1]
Tensile strength (g/mm²)	52,8 ± 3,6	60,3 ± 13,2
Percentage elongation	223 ± 7	251 ± 15***
Width at burst (mm)	11,8 ± 0,4	13,3 ± 0,8***
Internal diameter (mm)	5,3	5,3
Stress relaxation	0,181 ± 0,010	0,179 ± 0,017

[1] P <0,1
***P <0,001

TABLE XIX. Colon and rectum results (Experiment 3).

	Colon	Rectum	Significance
Burst strength (g)	191,0 ± 44,0	161,0 ± 35,0	**
Percentage elongation	130,0 ± 24,0	128,0 ± 26,0	NS
Young's Modulus (M1) (10-25g)	14,8 ± 4,3	16,3 ± 3,7	NS
Young's Modulus (M2) (30-60g)	32,6 ± 8,1	33,3 ± 7,1	NS
L1	18,6 ± 4,0	14,5 ± 5,3	***
L2	11,3 ± 3,7	7,4 ± 3,7	***
Energy under curve	51,5 ± 15,8	52,7 ± 15,0	NS

P >0,01
P >0,001

The values in this table are not comparable with those in Tables XVII and XVIII for reasons discussed fully under materials and methods. The main difference is that Experiment 3 was carried out to test four variables and the means take into account all the variables. Also the value for percentage elongation was obtained by automatic read-out rather than from the stress/strain curve. Differences between this method and that used for the rest of this study were constant within this experiment.

SEX.

There was no significant difference between seven-week old male and female rats in any of the mechanical measurements made. The older rats were not in similar age groups, nor were they in similar condition, since the one year old males appeared frisky compared with the 14-17 month old females which were losing weight and poorly.

TENSILE STRENGTH.

The tensile strength of the young rat colon is in the order of 50 g/mm^2 (50×10^6 Nm^{-2}).

THICKNESS OF COLON.

The young rat colon is 0,54 mm thick at seven weeks of age. It appears to thicken with age.

INTERNAL DIAMETER.

The internal diameter of the rat colon is fairly constant at 5,0 to 5,3 mm in the young rat. When the tissues age this diameter rises.

PERCENTAGE ELONGATION.

The young rat colon is capable of extending to a width of approximately 12 mm or 200-225% of its initial diameter.

Human.

Twenty-two adult colons from Edinburgh and 17 adult colons from Kampala were studied. In addition 10 Edinburgh and 3 Kampala children's colons were tested.

The following measurements were made :

1. Burst strength (BS) (g).
2. Cross-sectional area (thickness times a constant width of 10 mm) (mm^2).
3. Tensile strength (TS) which is calculated by dividing the burst strength by the cross-sectional area (g/mm^2).
4. Internal diameter at stress 0 (ID) (mm).
5. Width at burst (WB) (mm).
6. Percentage elongation at burst (%E).
7. Stress relaxation which is a regression slope based on a ratio and therefore has no units.

For colons from individuals over the age of 10 years regression analysis was performed with regard to four variables for each of the above seven measurements :

1. Age in years.
2. Race, whether Edinburgh or Kampala. Separate regressions were plotted for each group.
3. Time after death.
4. Sex.

COLONIC SITE.

Reference to Tables XX and XXI show that the mean differences in colonic sites were for internal diameter of the colon and the width at

burst. The internal diameter of the colon fell from ascending to descending colon. The width at burst also fell correspondingly. There was little difference between the descending and sigmoid colon.

The sigmoid colon was the thickest region of the colon in both Edinburgh and Kampala but differences between the ascending, transverse and descending colons were not significant. The sigmoid colon had the lowest tensile strength of the colon in both races but since this was only so for tensile strength and not burst strength this decrease in tensile strength was related to an increased thickness of the sigmoid colon wall rather than an actual weakness of its structure.

TABLE XX. Wilcoxon signed ranks tests for site differences between measurements

	Burst Strength		Cross-Sectional area		Tensile Strength		Width at Burst		Internal Diameter		Percentage Elongation		Stress Relaxation	
	E	K	E	K	E	K	E	K	E	K	E	K	E	K
AvT							***	**	*	*				
AvD							***	***	***	**				*
AvS			***	***	*		***	***	***	***	*	*	**	*
TvD							***	***	***	**				
TvS			***	**	**	*	**	***	***	**	*			
DvS			***	***	*	*	*							

A ... Ascending
T ... Transverse
D ... Descending
S ... Sigmoid

E ... Edinburgh
K ... Kampala

* = P <0,05
** = P <0,01
*** = P <0,001

NB : where no * inserted the test was not significant.

TABLE XXI. Overall means and standard deviations for colonic sites by race (Edinburgh and Kampala).

		Ascending colon	Transverse colon	Descending colon	Sigmoid colon
Burst Strength (g)	E	1378,0 ± 822,0	1223,0 ± 701,0	1242,0 ± 657,0	1266,0 ± 646,0
	K	1799,0 ± 648,0	1687,0 ± 585,0	1638,0 ± 499,0	1618,0 ± 663,0
Cross-Sectional Area (mm^2)	E	14,7 ± 6,5	14,1 ± 6,2	14,7 ± 7,4	19,0 ± 9,3
	K	14,3 ± 4,2	13,1 ± 4,2	14,8 ± 5,7	16,6 ± 5,9
Tensile Strength (g/mm^2)	E	104,0 ± 65,0	98,0 ± 57,0	104,0 ± 61,0	81,0 ± 49,0
	K	134,0 ± 56,0	139,0 ± 57,0	127,0 ± 65,0	110,0 ± 51,0
Internal Diameter (mm)	E	36,0 ± 20,0	30,0 ± 15,0	23,0 ± 12,0	23,0 ± 13,0
	K	49,0 ± 22,0	43,0 ± 22,0	35,0 ± 15,0	36,0 ± 16,0
Width at Burst (mm)	E	99,0 ± 48,0	90,0 ± 39,0	70,0 ± 31,0	71,0 ± 30,0
	K	129,0 ± 46,0	108,0 ± 41,0	94,0 ± 33,0	111,0 ± 36,0
Percentage Elongation (%E)	E	206,0 ± 179,0	221,0 ± 187,0	222,0 ± 125,0	253,0 ± 185,0
	K	182,0 ± 99,0	171,0 ± 122,0	192,0 ± 143,0	235,0 ± 148,0
Stress Relaxation	E	0,179 ± 0,028	0,189 ± 0,029	0,185 ± 0,020	0,188 ± 0,024
	K	0,162 ± 0,025	0,171 ± 0,020	0,181 ± 0,017	0,178 ± 0,019

PRESENTATION OF DATA BY MEASUREMENT.

The main findings are described for each individual measurement with accompanying summary, tables XXII-XXX.

Tables A1-A4 (Appendix) show means and standard deviations for each measurement made according to age and race. Reference to Figures 18-26 allows one to appreciate the scatter of data and broad differences in the age distribution of colons from Edinburgh and Kampala. Regression lines have been plotted for age and race and the slope of the regression line and point of intercept on the y (log) axis are given in Table XXXI. The slope of the line is related to the effect of age on the mechanical property being measured. A statistically significant regression is shown by a star with P value in the table. A statistical difference between intercept points for regression lines for Edinburgh and Kampala is also starred on the table.

Regressions against age for Edinburgh and Kampala were plotted individually also. The significance of these is listed for each value in Tables XXXII and XXXIII. Figures 27 to 32 show regression for Edinburgh sigmoid colons with reference to diverticular disease.

Burst strength : The burst strength for the human colon was about 1500 g. There was a decline in burst strength with age, significant in all regions except the ascending. The burst strength was greater in the Kampala group (1600-1800 g) than the Edinburgh group (1200-1400 g), but the differences did not reach statistical significance. The descending colon was stronger in males than females, but none of the other regions showed any difference with sex. The time after death of removal of the colon did not affect the burst strength.

TABLE XXII. **Significance of multiple regression analyses of log burst strength against age, race, time after death and sex.**

	Age	Race	Time after Death	Sex
Ascending	NS	NS	NS	NS
Transverse	*	NS	NS	NS
Descending	**	NS	NS	*
Sigmoid	*	NS	NS	NS

* P <0,05
** P <0,01

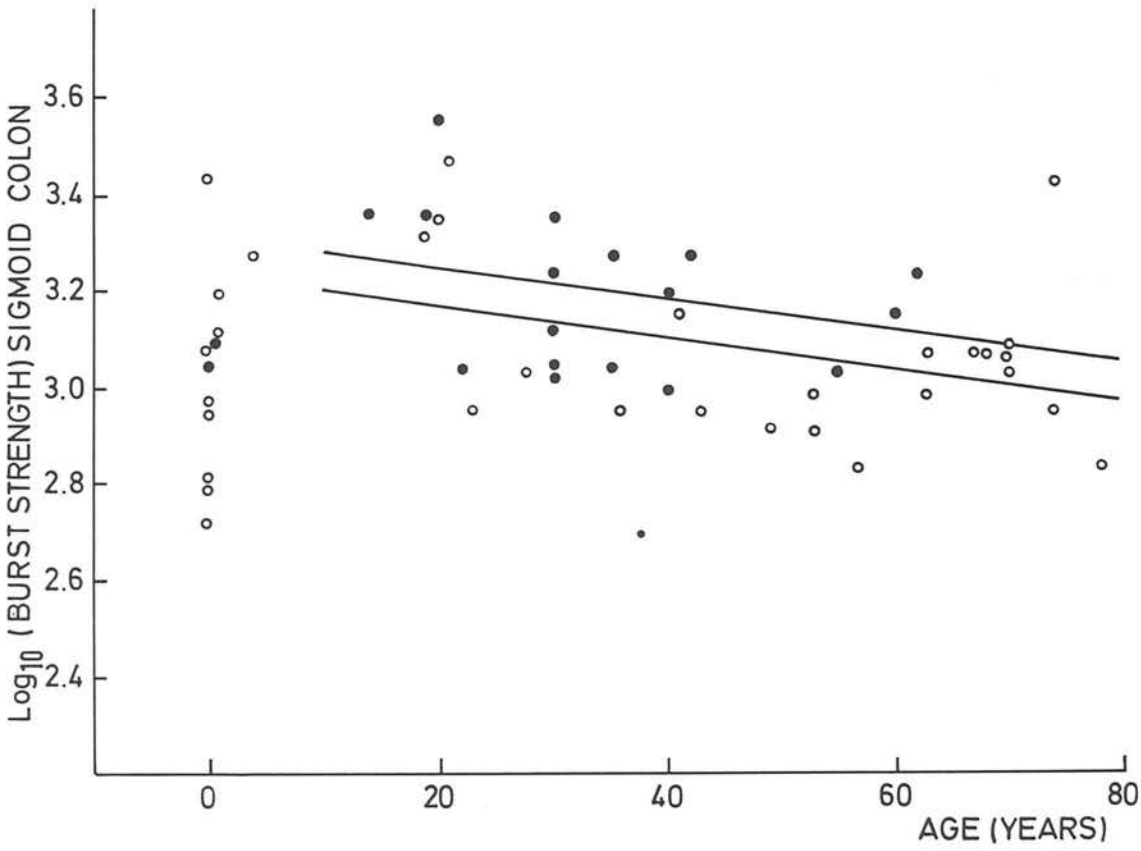


Figure 18 : Log_{10} burst strength against age for Edinburgh (lower line – open circles) and Kampala (upper line – closed circles) sigmoid colons. The regression slopes have been drawn parallel since there was no significant difference between them (Tables XXXI–XXXIII). There is a significant regression with age when both race groups are considered together. Neither group is significant alone. There is no significant difference between the races though the Kampala group seemed generally to have a higher burst strength than the Edinburgh group.

Tensile strength : The tensile strength of the Edinburgh colon was in the order of 100g/mm² and 130g/mm² for Kampala. This difference between the two races was statistically significant in all four regions of the colon. Tensile strength also fell with age, although the trend only reached statistical significance for the transverse and sigmoid regions.

TIme after death of removal of the colon did not affect the tensile strength.

As for burst strength, there was a significantly greater tensile strength in the descending colon for males compared with females, but this sex difference was not confirmed in any other region of the colon.

TABLE XXIII. **Significance of multiple regression analyses of log tensile strength against age, race, time after death and sex.**

	Age	Race	Time after Death	Sex
Ascending	NS	*	NS	NS
Transverse	**	**	NS	NS
Descending	NS	*	NS	*
Sigmoid	*	*	NS	NS

* P <0,05
** P <0,01

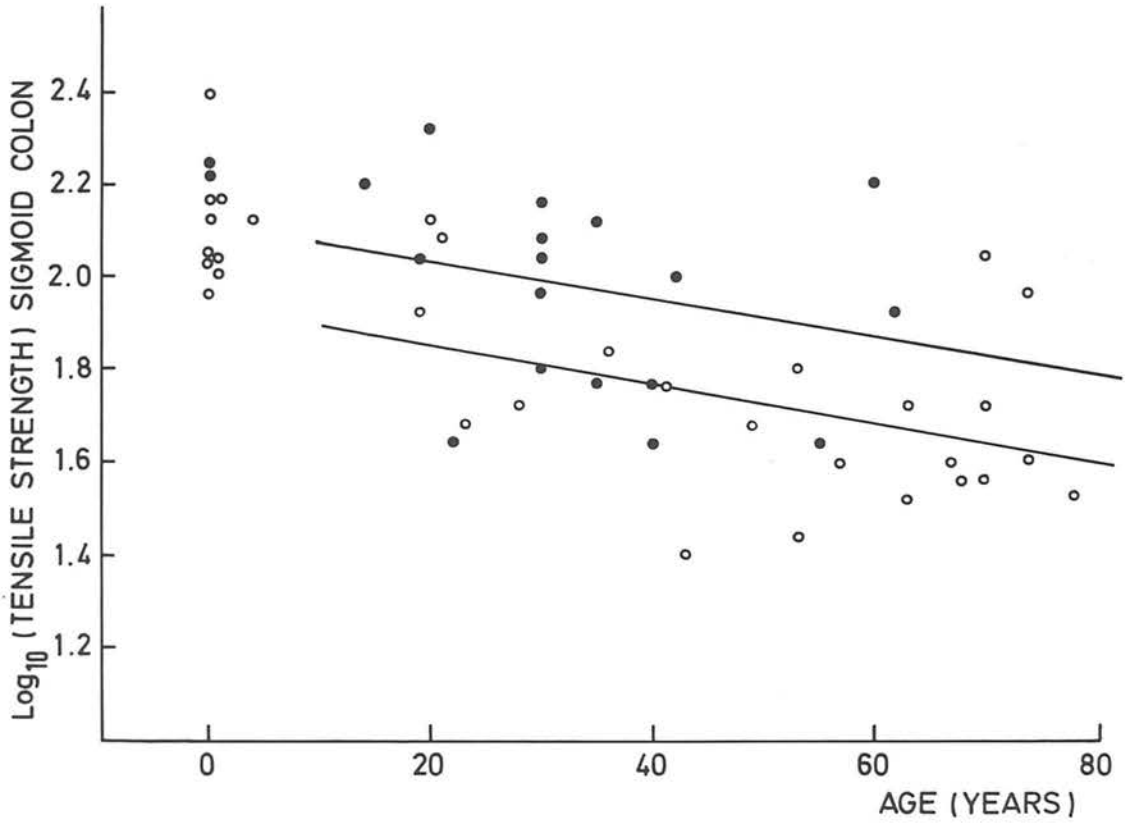


Figure 19 : Log_{10} tensile strength (g/mm^2) against age for Edinburgh (lower line – open circles) and Kampala (upper line – closed circles) sigmoid colons. The slope of the regression is identical for both race groups (Tables XXXII–XXXIII) and the regressions with age have been drawn parrallel. The Kampala group has a significantly higher intercept with the vertical axis, representing greater tensile strength ($P < 0,05$).

Cross-sectional area (width x thickness) : Since the width was constant (10 mm) this was a measure of the thickness of the colon.

The colon as measured by this method was 1,5 mm thick. There was a tendency for the African colon to be thinner, though this never reached statistical significance, except in the sigmoid colon. There were no age related differences in the thickness of the colon. Sex did not affect the thickness. Time after death showed no trend in the regression analyses, but Kendall's rank correlations showed a tendency for the Kampala colon to become thinner with increasing time after death. This difference was due to two Edinburgh outliers obtained more than 72 hours after death (Figure 21). In the first 48 hours after death, when the Kampala colons were obtained, there was no significant correlation.

TABLE XXIV. **Significance of multiple regression analysis of log cross-sectional area against age, race, time after death and sex.**

	Age	Race	Time after Death	Sex
Ascending	NS	NS	NS	NS
Transverse	NS	NS	NS	NS
Descending	NS	NS	NS	NS
Sigmoid	NS	*	NS	NS

* $P < 0,05$

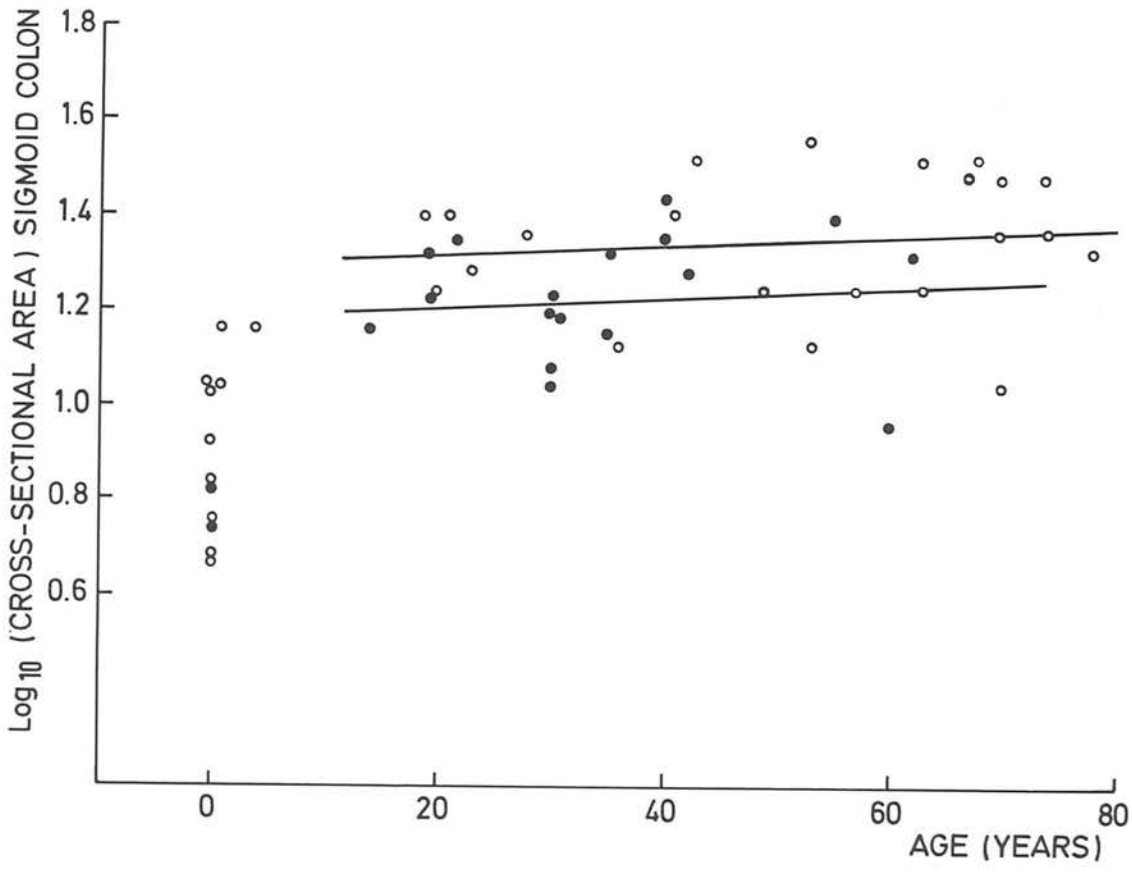


Figure 20 : Log_{10} cross-sectional area (mm^2) against age for the sigmoid colon. The open circles represent the Edinburgh group (upper regression line) whilst closed circles represent Kampala (lower regression line). In this study the width was constant (10 mm) so that cross-sectional area represents thickness. The trend with each group to thicken with age was not significant either when the race groups were analysed together or separately. The Edinburgh sigmoid colon was significantly thicker than the Kampala ($P < 0,05$).

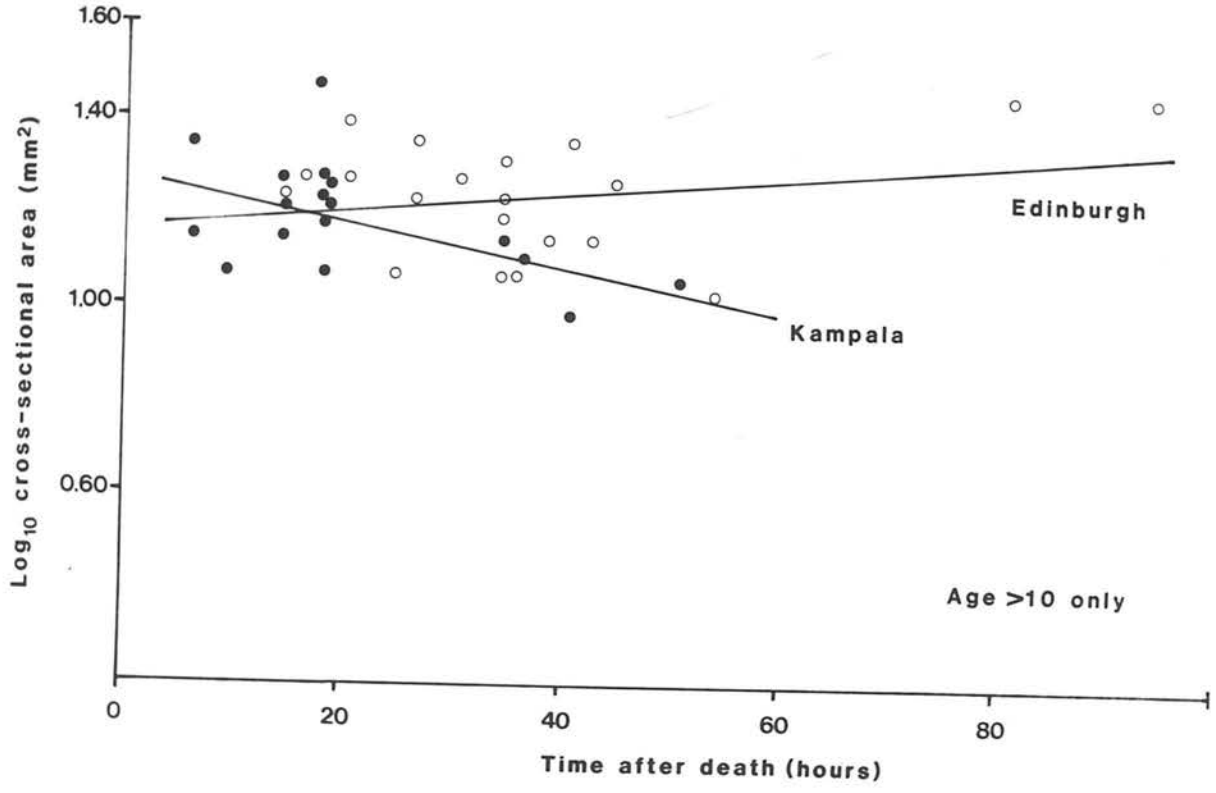


Figure 21 : Log_{10} cross-sectional area (mm^2) against time after death for sigmoid colon from Edinburgh (open circles - upper line) and Kampala (closed circles, lower line). Note that the two regressions were similar up to 48 hours after death. The slope of the Edinburgh regression is stressed by two outliers, obtained more than 72 hours after death.

Internal Diameter : The internal diameter of all regions of the colon fell with age. The internal diameter depended upon site (Tables XX, XXI) but reference to Tables A1-4 (Appendix) shows that reduction with age was about 30%, from early adult life to old age.

The internal diameter of the distal colon was greater in the Kampala group, although the effect was not quite significant in the sigmoid.

The internal diameter at the male sigmoid colon was greater than that in females (32,4 ± 16,6 mm for males, 23,1 ± 11,4 mm for females). Other regions showed no trend towards a sex difference in internal diameter. Time after death did not affect the internal diameter of the colon.

TABLE XXV. Significance of multiple regression analyses of log internal diameter against age, race, time after death and sex.

	Age	Race	Time after Death	Sex
Ascending	*	NS	NS	NS
Transverse	*	NS	NS	NS
Descending	*	*	NS	NS
Sigmoid	*	NS	NS	*

* P >0,05

Plotting separate regressions against age for both Edinburgh and Kampala (Tables XXXII, XXXIII) suggested that the age decline in internal diameter was more marked in the Edinburgh group. The Kampala colon, particularly distally showed less tendency to decline with age.

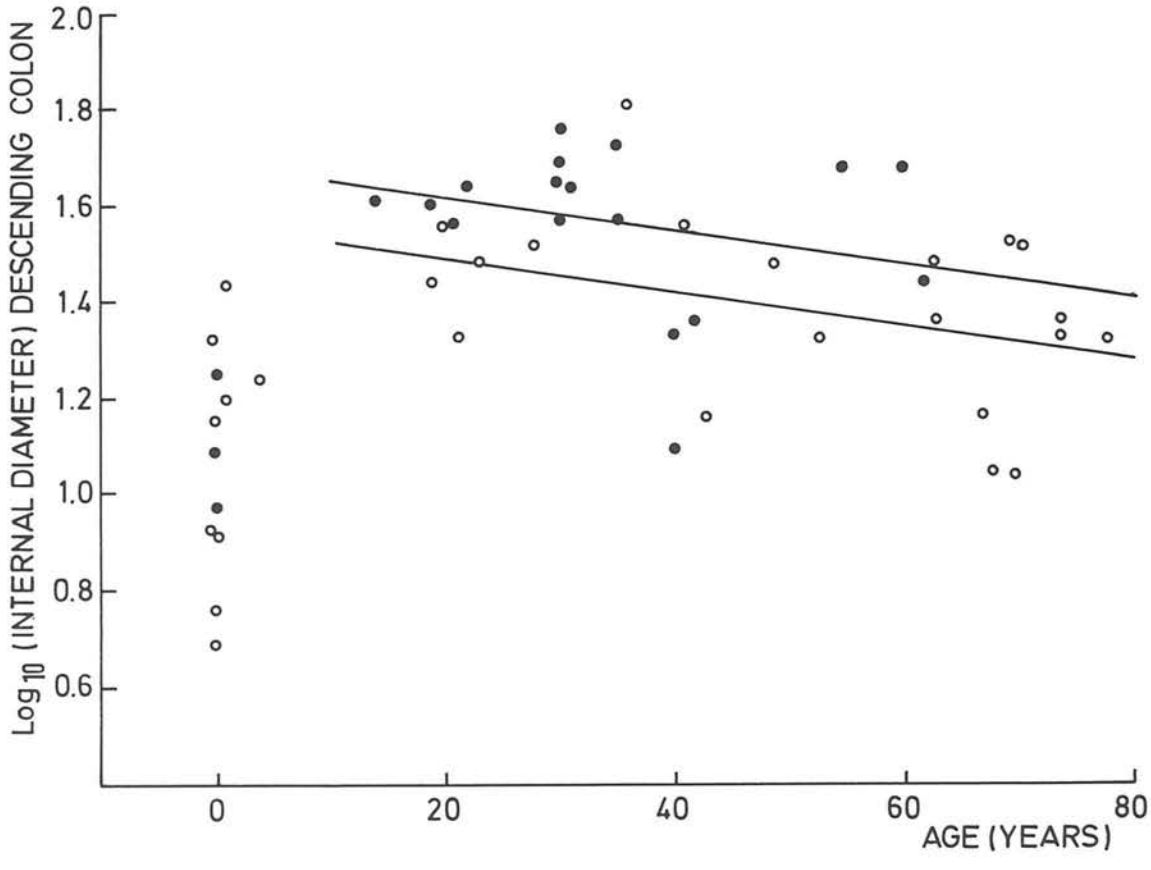


Figure 22 : Descending colon : fitted parallel lines for regression of Log_{10} internal diameter (mm) of Edinburgh (open circles - lower regression) and Kampala (closed circles - upper regression). There was a statistically significant regression with age when both race groups were analysed together. The Kampala colons had a significantly greater internal diameter than the Edinburgh ($P < 0,05$). When each race group was examined separately for an age regression there was a statistically significant result for the Edinburgh colons only.

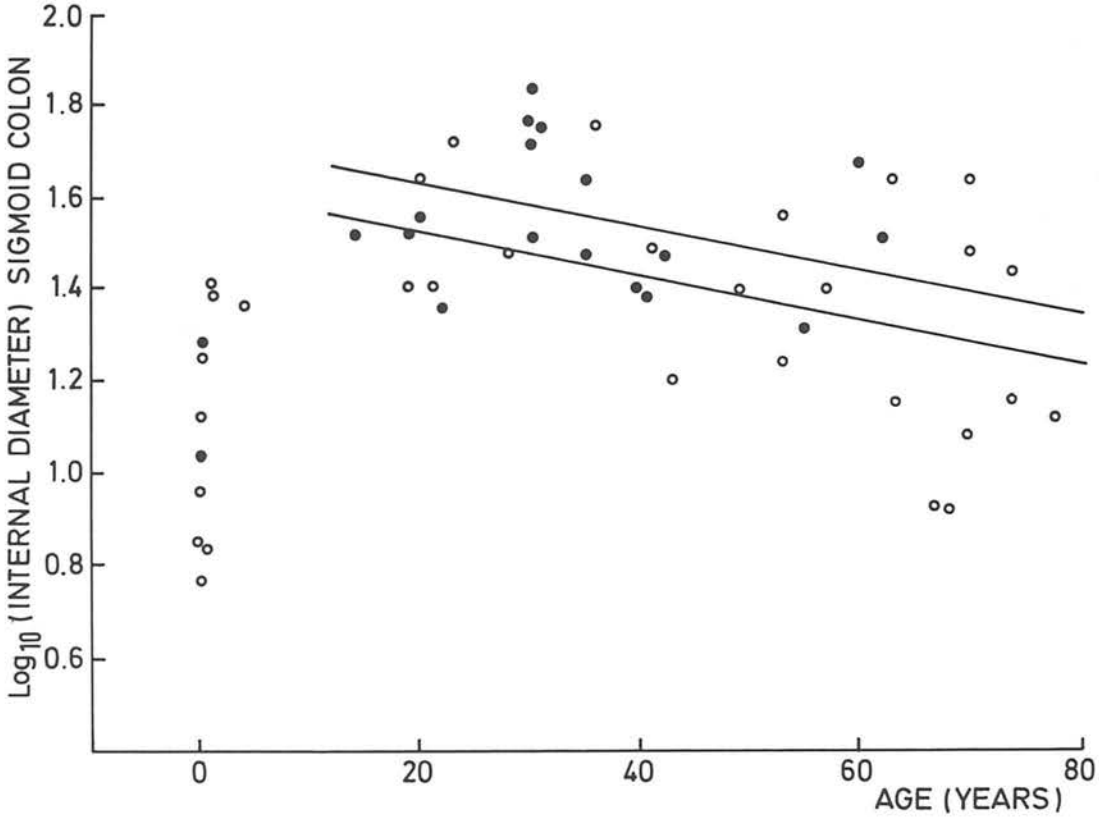


Figure 23 : Log_{10} internal diameter (mm) against age for sigmoid colon from Edinburgh (open circles – lower line) and Kampala (closed circles – upper line). There was a significant regression with age in the Edinburgh group ($P < 0,01$) but not the Kampala group. Multiple regression analysis including both groups of colons (fitted parallel lines as in figure) showed a significant regression with age ($P < 0,05$). The Kampala colons just failed to be statistically wider than the Edinburgh.

Width at burst (internal diameter of colon at burst) : The colon was capable of stretching to a greater extent before breaking in the Kampala group in descending and sigmoid colons, when compared with the Edinburgh group. There was also a highly significant age effect, with width at burst reducing with age in the sigmoid region. In the sigmoid region the diameter of the Kampala colon was 24% wider at burst. The colon was capable of stretching to 70–130 mm depending on site, age and race.

TABLE XXVI. **Significance of multiple regression analyses of log width at burst against age, race, time after death and sex.**

	Age	Race	Time after Death	Sex
Ascending	NS	NS	NS	NS
Transverse	NS	NS	NS	NS
Descending	NS	**	NS	NS
Sigmoid	***	***	NS	NS

** P <0,01
*** P <0,001

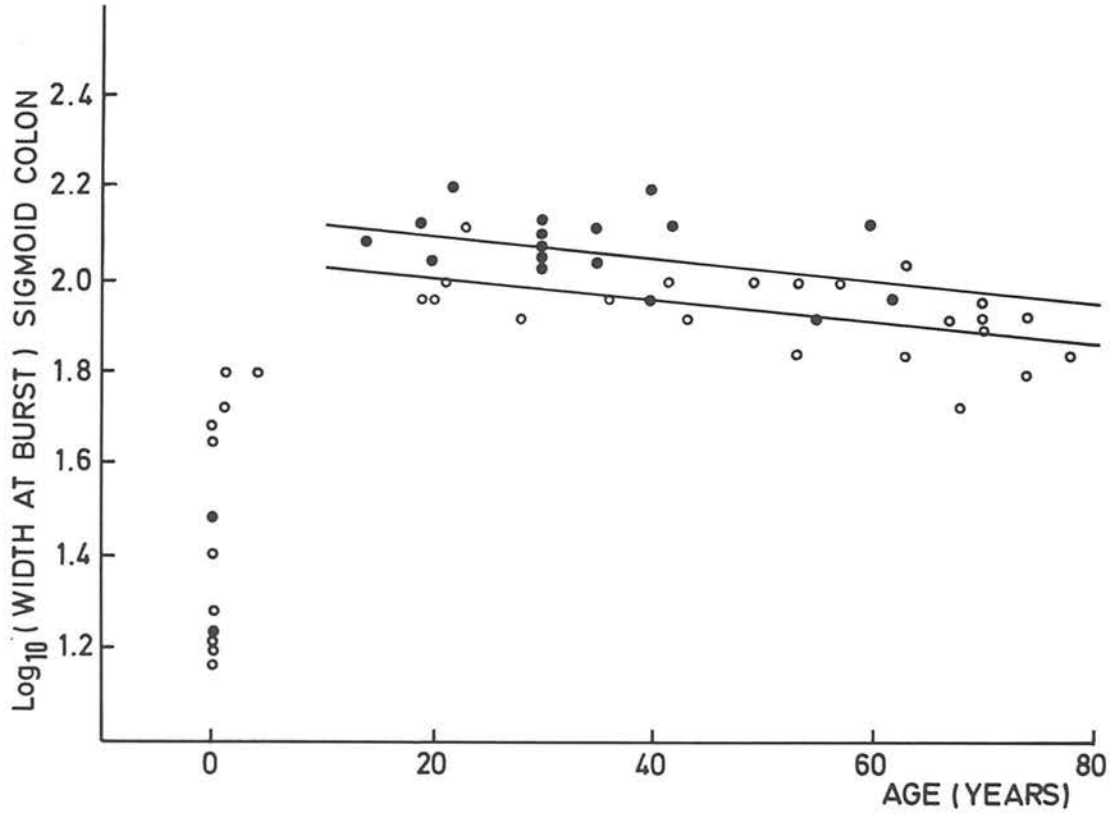


Figure 24 : Log_{10} width at burst (mm) for sigmoid colon from Edinburgh (open circles - lower line) and Kampala (closed circles, upper line). The difference between race groups was highly significant ($P < 0{,}001$) as was the regression with age ($P < 0{,}001$). The two race groups had similar slopes (Tables XXXII and XXXIII), although when analysed separately, only the Edinburgh regression was statistically significant.

Percentage Elongation : Although there was a rise in percentage elongation with age, there was a wide variation. The human colon was capable of approximately 200% expansion before rupture, and time after death did not influence the percentage elongation. If the colons were analysed separately by race the Edinburgh colons showed a significant rise in percentage elongation in all regions of the colon ($P < 0,05$). Kampala colons shared the same trend of increase in percentage elongation with age but this was not significant. There were no statistical differences between Edinburgh and Kampala colons and the increase in percentage elongation with age was not quite significant when both groups were analysed together by multiple regression analysis (Table XXVII).

TABLE XXVII. Significance of multiple regression analyses of log percentage elongation against age, race, time after death and sex.

	Age	Race	Time after Death	Sex
Ascending	NS	NS	NS	NS
Transverse	NS	NS	NS	NS
Descending	NS	NS	NS	NS
Sigmoid	NS	NS	NS	NS

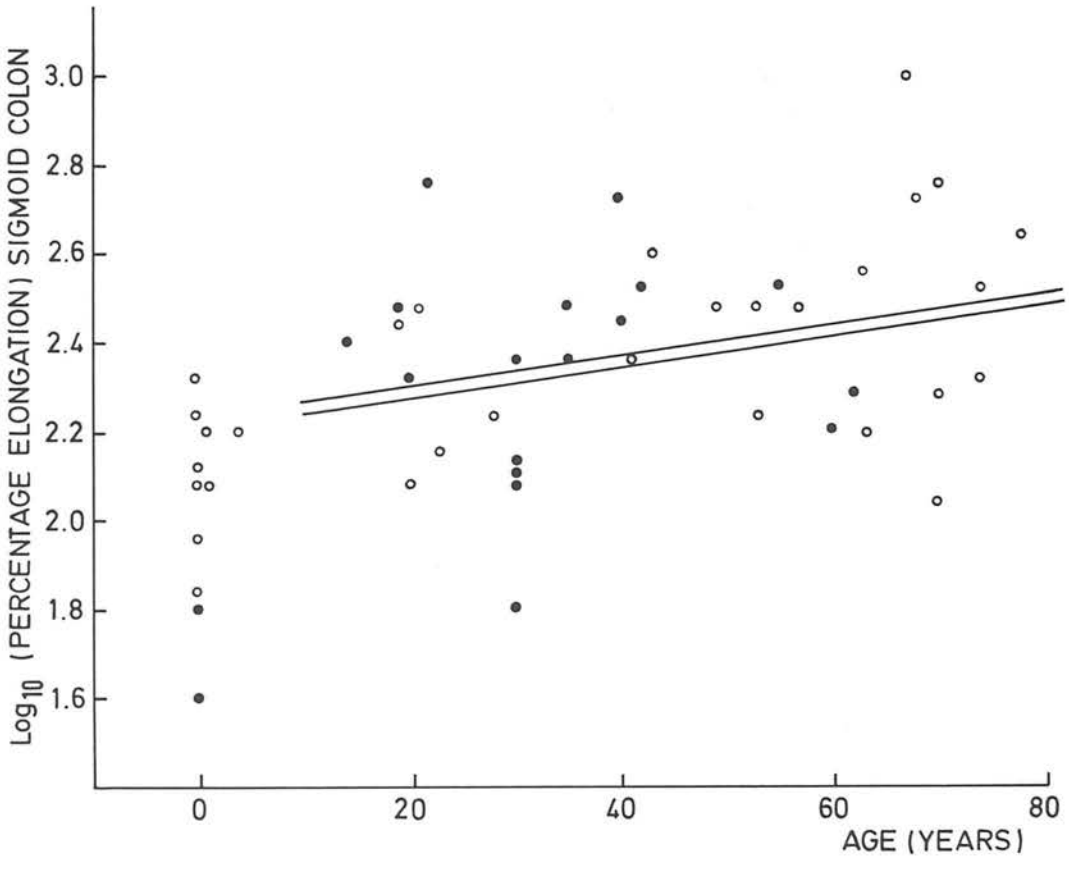


Figure 25 : Log_{10} percentage elongation against age for the sigmoid colon from Edinburgh (open circles – upper line) and Kampala (closed circles – lower line). There is a wide scatter of values. The increase in percentage elongation with age just fails to reach statistical significance when the colons are analysed together (Table XXXI). When analysed separately there is a statistically significant increase for the Edinburgh colons ($P < 0,05$) but not for the Kampala ones (Tables XXXII and XXXIII). There was no significant difference between the races on multiple regression analysis (Tables XXVII and XXXI).

Stress Relaxation : Stress relaxation was fairly constant throughout all the age groups.

Sex and time after death alter groups. Sex and time after death did not influence the stress relaxation slope.

TABLE XXVIII. **Significance of multiple regression analyses of log stress relaxation against age, race, time after death and sex.**

	Age	Race	Time after Death	Sex
Ascending	NS	NS	NS	NS
Transverse	NS	NS	NS	NS
Descending	NS	NS	NS	NS
Sigmoid	NS	NS	NS	NS

Treating the Edinburgh and Kampala regressions separately (Tables XXXII and XXXIII) there were significant regressions but there were no consistent effects. There was an increase in stress relaxation in the Edinburgh ascending colon with age ($P < 0,05$) and a decrease in the Edinburgh descending colon ($P < 0,05$). The descending colon in Kampala in contrast increased in stress relaxation with age ($P < 0,01$). There was no significant difference in intercept between the two race groups suggesting that each has a similar stress relaxation. Stress relaxation therefore appears to be fairly constant irrespective of age, sex or race.

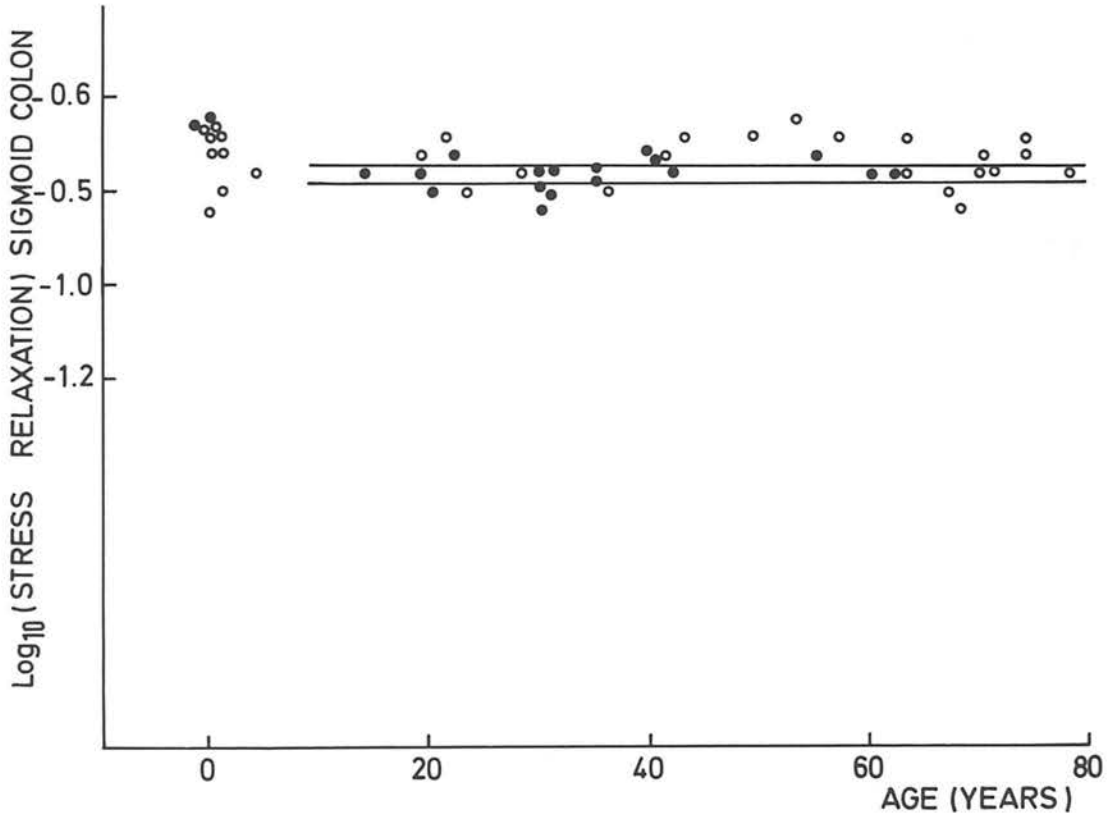


Figure 26 : Log_{10} stress relaxation of the sigmoid colon for Edinburgh (open circles - lower regression line) and Kampala (closed circles - upper regression line). There was no significant regression with age when analysing both race groups together (Tables XXVIII and XXXI), nor when treating them separately (Tables XXXII and XXXIII).

SUMMARY OF RESULTS FOR AGE AND RACE .

TABLE XXIX. **Summary of results of linear regression analyses for age >10 years.**

	Ascending	Transverse	Descending	Sigmoid
Burst strength	NS	*	**	*
Tensile strength	NS	**	NS	*
Cross-sectional area	NS	NS	NS	NS
Internal diameter	*	*	*	*
Width at burst	NS	NS	NS	***
Percentage elongation	NS	NS	NS	NS
Stress relaxation	NS	NS	NS	NS

* P <0,05
** P <0,01
*** P <0,001

TABLE XXX. **Summary of differences between Edinburgh and Kampala colons (>10 years) – significance of linear regression analysis.**

	Ascending	Transverse	Descending	Sigmoid
Burst strength	NS	NS	NS	NS
Tensile strength	*	*	*	*
Cross sectional area	NS	NS	NS	*
Internal diameter	NS	NS	*	NS
Width at burst	NS	NS	**	***
Percentage elongation	NS	NS	NS	NS
Stress relaxation	NS	NS	NS	NS

TABLE XXXI. Fitted parallel regression lines of Log_{10} (measurement) on age (age >10).

	Intercept for Edinburgh	Kampala	Common Slope	Significance of Difference Slope	in intercept
BURST STRENGTH					
Ascending	3,10	3,25	-0,0004	NS	NS
Transverse	3,24	3,34	-0,0038	P <0,05	NS
Descending	3,26	3,34	-0,0037	P <0,01	NS
Sigmoid	3,24	3,32	-0,0033	P <0,05	NS
CROSS SECTIONAL AREA					
Ascending	1,18	1,13	0,0008	NS	NS
Transverse	1,16	1,09	0,0010	NS	NS
Descending	1,28	1,21	-0,0006	NS	NS
Sigmoid	1,30	1,20	0,0009	NS	P <0,05
TENSILE STRENGTH					
Ascending	1,94	2,12	-0,0013	NS	P <0,05
Transverse	2,08	2,25	-0,0049	P <0,01	P <0,01
Descending	1,98	2,14	-0,0030	NS	P <0,05
Sigmoid	1,94	2,12	-0,0042	P <0,05	P <0,05
WIDTH AT BURST					
Ascending	2,16	2,18	-0,0011	NS	NS
Transverse	2,10	2,11	-0,0010	NS	NS
Descending	1,96	2,03	-0,0004	NS	P <0,01
Sigmoid	2,06	2,15	-0,0024	P <0,001	P <0,001
INTERNAL DIAMETER					
Ascending	1,84	1,86	-0,0043	P <0,05	NS
Transverse	1,72	1,82	-0,0039	P <0,05	NS
Descending	1,56	1,70	-0,0035	P <0,05	P <0,05
Sigmoid	1,62	1,73	-0,0048	P <0,05	NS
PERCENTAGE ELONGATION					
Ascending	2,05	2,04	0,0046	NS	NS
Transverse	2,14	2,03	0,0041	NS	NS
Descending	2,17	2,08	0,0040	NS	NS
Sigmoid	2,23	2,21	0,0034	NS	NS
STRESS RELAXATION					
Ascending	-0,83	-0,85	0,0013	NS	NS
Transverse	-0,79	-0,81	0,0009	NS	NS
Descending	-0,73	-0,75	0,0001	NS	NS
Sigmoid	-0,74	-0,77	0,0001	NS	NS

TABLE XXXII. Log_{10} (measurement) versus age for Edinburgh only + age $\geqslant$10.

	Regression Intercept	Slope	Correlation (r)	Significance
BURST STRENGTH				
Ascending	3,10	-0,0005	-0,04	NS
Transverse	3,24	-0,0035	-0,38	P < 0,05
Descending	3,26	-0,0038	-0,55	P < 0,01
Sigmoid	3,24	-0,0032	-0,36	NS
CROSS SECTIONAL AREA				
Ascending	1,18	0,0016	0,19	NS
Transverse	1,16	0,0013	0,21	NS
Descending	1,28	-0,0011	-0,18	NS
Sigmoid	1,30	0,0011	0,15	NS
TENSILE STRENGTH				
Ascending	1,94	-0,0022	-0,21	NS
Transverse	2,08	-0,0048	-0,46	P < 0,05
Descending	1,98	-0,0027	-0,32	NS
Sigmoid	1,94	-0,0043	-0,42	P < 0,05
WIDTH AT BURST				
Ascending	2,16	-0,0007	-0,22	NS
Transverse	2,10	-0,0008	-0,32	NS
Descending	1,96	-0,0004	-0,12	NS
Sigmoid	2,06	-0,0024	-0,56	P < 0,01
INTERNAL DIAMETER				
Ascending	1,84	-0,0043	-0,45	P < 0,05
Transverse	1,72	-0,0039	-0,44	P < 0,05
Descending	1,56	-0,0040	-0,44	P < 0,05
Sigmoid	1,62	-0,0060	-0,50	P < 0,01
PERCENTAGE ELONGATION				
Ascending	2,05	0,0054	0,39	P < 0,05
Transverse	2,14	0,0047	0,38	P < 0,05
Descending	2,17	0,0046	0,42	P < 0,05
Sigmoid	2,23	0,0050	0,37	P < 0,05
STRESS RELAXATION				
Ascending	-0,83	0,0016	0,38	P < 0,05
Transverse	-0,79	0,0012	0,27	NS
Descending	-0,73	-0,0008	-0,41	P < 0,05
Sigmoid	-0,74	-0,0001	-0,02	NS

TABLE XXXIII. Log_{10} (measurement) versus age for Kampala only, age ≥ 10.

	Intercept	Slope	Correlation (r)	Significance
BURST STRENGTH				
Ascending	3,25	-0,0004	-0,03	NS
Transverse	3,34	-0,0049	-0,41	NS
Descending	3,34	-0,0034	-0,34	NS
Sigmoid	3,32	-0,0039	-0,34	NS
CROSS SECTIONAL AREA				
Ascending	1,13	-0,0011	-0,14	NS
Transverse	1,09	0,0008	0,11	NS
Descending	1,21	0,0009	0,11	NS
Sigmoid	1,20	0,0004	0,04	NS
TENSILE STRENGTH				
Ascending	2,12	0,0007	0,06	NS
Transverse	2,25	-0,0057	-0,45	P < 0,05
Descending	2,14	-0,0043	-0,37	NS
Sigmoid	2,12	-0,0043	-0,28	NS
WIDTH AT BURST				
Ascending	2,18	-0,0020	-0,33	NS
Transverse	2,11	-0,0015	-0,26	NS
Descending	2,03	-0,0001	-0,02	NS
Sigmoid	2,15	-0,0021	-0,39	NS
INTERNAL DIAMEER				
Ascending	1,86	-0,0046	-0,39	NS
Transverse	1,82	-0,0044	-0,32	NS
Descending	1,70	-0,0024	-0,19	NS
Sigmoid	1,73	-0,0016	-0,14	NS
PERCENTAGE ELONGATION				
Ascending	2,04	0,0031	0,18	NS
Transverse	2,03	0,0035	0,18	NS
Descending	2,08	0,0033	0,19	NS
Sigmoid	2,21	-0,0003	-0,02	NS
STRESS RELAXATION				
Ascending	-0,85	0,0002	0,04	NS
Transverse	-0,81	0,0002	0,06	NS
Descending	-0,75	0,0023	0,72	P < 0,01
Sigmoid	-0,77	0,0007	0,24	NS

TABLE XXXIV. Individual results for neonatal and infant ascending colons.

Age		Burst Strength (g)	Cross Sectional Area (mm)	Tensile Strength (g/mm^2)	Width at Burst (mm)	Internal Diameter (mm)	Percentage Elongation	Stress Relaxation
24 weeks gestation	E	554	6	92	15	9	67	0,1850
27 weeks gestation	E	625	6	104	12	5	140	0,2020
30 weeks gestation	E	615	6	102	18	9	94	0,1960
36 weeks gestation	K	0	0	0	0	0	0	0,0
37 weeks gestation	E	720	7	103	12	6	118	0,2080
40 weeks gestation	K	1900	8	238	20	9	117	0,1570
40 weeks gestation	K	1600	6	267	21	9	133	0,1830
1 week	E	400	5	80	22	10	120	0,1970
9 weeks	E	1150	8	144	43	19	126	0,1870
21 weeks	E	3430	11	312	42	20	108	0,1770
38 weeks	E	1350	9	150	60	39	53	0,1320
38 weeks	E	3675	14	262	69	19	261	0,1940

TABLE XXXV. Individual results for neonatal and infant transverse colons.

Age		Burst Strength (g)	Cross Sectional Area (mm)	Tensile Strength (g/mm^2)	Width at Burst (mm)	Internal Diameter (mm)	Percentage Elongation	Stress Relaxation
24 weeks gestation	E	400	6	73	15	9	61	0,2070
27 weeks gestation	E	700	6	117	12	5	130	0,2160
30 weeks gestation	E	805	6	134	16	9	78	0,1960
36 weeks gestation	K	1950	8	244	15	9	67	0,1980
37 weeks gestation	E	915	5	183	11	6	91	0,2140
40 weeks gestation	K	1425	7	197	29	12	142	0,1750
40 weeks gestation	K	1270	6	231	28	18	56	0,1880
1 week	E	700	5	140	24	14	71	0,2270
9 weeks	E	735	8	92	43	27	59	0,1970
21 weeks	E	0	10	0	0	27	0	0,1770
38 weeks	E	1600	8	200	55	36	53	0,2240
38 weeks	E	3525	16	220	58	18	219	0,1890

TABLE XXXVI. Individual results for neonatal and infant descending colons.

Age		Burst Strength (g)	Cross Sectional Area (mm)	Tensile Strength (g/mm²)	Width at Burst (mm)	Internal Diameter (mm)	Percentage Elongation	Stress Relaxation
24 weeks gestation	E	622	4	156	13	9	53	0,1660
27 weeks gestation	E	860	4	215	15	5	200	0,1960
30 weeks gestation	E	430	5	86	13	9	53	0,1960
36 weeks gestation	K	1405	6	234	11	9	22	0,1990
37 weeks gestation	E	1050	5	210	15	6	164	0,1970
40 weeks gestation	K	950	8	119	35	12	192	0,1820
40 weeks gestation	K	1570	5	314	31	18	69	0,1890
1 week	E	460	5	92	25	15	67	0,1870
9 weeks	E	900	7	129	44	21	110	0,1780
21 weeks	E	1125	6	187	0	0	0	0,0
38 weeks	E	1760	8	220	52	27	91	0,1300
38 weeks	E	3650	14	261	52	17	212	0,1760

TABLE XXXVII. Individual results for neonatal and infant sigmoid colons.

Age		Burst Strength (g)	Cross Sectional Area (mm)	Tensile Strength (g/mm²)	Width at Burst (mm)	Internal Diameter (mm)	Percentage Elongation	Stress Relaxation
24 weeks gestation	E	892	8	112	16	7	129	0,0
27 weeks gestation	E	615	7	88	16	7	121	0,2060
30 weeks gestation	E	885	6	148	15	9	67	0,2140
36 weeks gestation	K	1200	7	171	16	11	41	0,2240
37 weeks gestation	E	650	5	130	19	6	208	0,1960
40 weeks gestation	K	MISSING						
40 weeks gestation	K	1070	6	178	31	19	61	0,2020
1 week	E	525	5	105	25	13	88	0,2020
9 weeks	E	1175	11	107	48	18	167	0,2120
21 weeks	E	2750	11	250	44	0	0	0,1470
38 weeks	E	1373	14	98	55	25	118	0,1620
38 weeks	E	1550	11	141	63	24	160	0,1930

NEONATAL AND INFANT COLONS .

Ten Edinburgh and 3 Kampala children's colons were tested. Those aged under one year are ranked according to site in Tables XXXIV to XXXVII. Table XXXVIII shows the results of Wilcoxon Rank Sum tests on these colons.

Edinburgh and Kampala colons were compared aged less than one week, since two of the three Kampala colons were obtained from fresh stillbirths and the other from a baby born at 32 weeks gestation which lived only 4 weeks.

There were no significant racial differences other than tensile and burst strength for the transverse colon which were greater in the Kampala group. The other 26 Wilcoxon Rank Sum tests were non-significant.

Colons from babies aged less than one week were compared with those greater than one week to see what effects birth and commencement of diet might have on the colon. Cross-sectional area (ie. thickness), width at burst and internal diameter all increased significantly after birth. This was related undoubtedly to growth. There was no difference in percentage elongation before and after birth suggesting that the increased width at burst was related to growth and not increased capacity for stretch. The stress relaxation was lower after birth in the descending colon, but not other regions. The figures for strength (both tensile and burst) show no clearcut trend. There was increased burst strength after birth in the sigmoid colon and there is a suggestion of a similar trend in the other regions. This increased burst strength is probably related to the growth of the colon after birth and thus thickness, since the tensile strength was not significantly increased after birth. In fact the neonatal and infant colons appeared to be one and a half to two times as strong as the adult colons in terms of tensile strength (150-200 g/mm^2).

TABLE XXVIIII. Wilcoxon rank sum tests for group comparisons. Neonatal and infant colons.

		Age <1 wk EvsK	Age <1 yr <1wk vs >1 wk E+K
Burst strength (g)	Ascending	NS	NS
	Transverse	*	NS
	Descending	NS	NS
	Sigmoid	NS	*
Cross-sectional area (mm^2)	Ascending	NS	**
	Transverse	NS	**
	Descending	NS	*
	Sigmoid	NS	**
Tensile strength (g/mm^2)	Ascending	NS	NS
	Transverse	*	NS
	Descending	NS	NS
	Sigmoid	NS	NS
Width at burst (mm)	Ascending	NS	**
	Transverse	NS	*
	Descending	NS	*
	Sigmoid	NS	**
Internal diameter (mm)	Ascending	NS	**
	Transverse	NS	**
	Descending	NS	*
	Sigmoid	NS	*
Percentage elongation	Ascending	NS	NS
	Transverse	NS	NS
	Descending	NS	NS
	Sigmoid	NS	NS
Stress relaxation	Ascending	NS	NS
	Transverse	NS	NS
	Descending	NS	*
	Sigmoid	NS	NS

* P <0,05
** P <0,01

E = Edinburgh
K = Kampala

DIVERTICULAR DISEASE (TABLE XXXIX).

Five Edinburgh colons with mild to moderate diverticular disease were compared with 8 Edinburgh colons without diverticular disease. Both groups were over 50 years of age.

There were no significant differences for any of the measurements made at any site of the colon between those over 50 years with diverticular disease, and those without. The dimensions of both groups of colons were similar. Figures 27-32 show that diverticular disease colons (open circles) lie on the same regression slope as non-diverticular disease colons (closed circles).

OPERATIVE SPECIMENS.

Three sigmoid colons and two transverse colons were obtained from four Edinburgh patients. Two patients had severe diverticular disease, one had carcinoma and one had rectal prolapse. All four were over the age of 50. These were compared with the 13 Edinburgh colons over the age of 50. Statistical analysis was by Wilcoxon Rank Sum tests (Table XXXX). The operative specimens were similar to their post mortem counterparts with regard to all mechanical tests. The only measurement which was significantly different was the thickness. The operative specimens being much thicker than the 13 Edinburgh post mortem colons. The numbers of operative specimens were small. These results are discussed under 'Effect of death' (p 126).

TABLE XXXIX **Measurement on Edinburgh colons over the age of 50 years with (5) (d) and without (ND) diverticular disease (8).**

		Ascending	Transverse	Descending	Sigmoid
Burst Strength (g)	D	1326,0 ± 520,0	1342,0 ± 888,0	1055,0 ± 267,0	1302,0 ± 784,0
	ND	1353,0 ± 741,0	978,0 ± 328,0	1139,0 ± 164,0	1041,0 ± 202,0
Cross-Sectional Area (mm^2)	D	15,0 ± 2,5	16,0 ± 4,1	17,8 ± 4,6	27,2 ± 8,8
	ND	18,1 ± 5,1	17,6 ± 2,6	17,5 ± 5,5	23,0 ± 8,2
Tensile Strength (g/mm^2)	D	84,8 ± 26,2	92,0 ± 75,1	65,1 ± 31,0	48,9 ± 24,5
	ND	76,2 ± 42,8	57,1 ± 23,1	70,2 ± 24,8	51,5 ± 25,7
Width at Burst (mm)	D	120,0 ± 23,0	104,0 ± 13,0	84,0 ± 21,0	77,0 ± 23,0
	ND	126,0 ± 27,0	109,0 ± 11,0	88,0 ± 8,0	83,0 ± 10,0
Internal Diameter (mm)	D	43,0 ± 6,0	33,0 ± 5,0	20,0 ± 7,0	21,0 ± 13,0
	ND	40,0 ± 19,0	29,0 ± 9,0	22,0 ± 8,0	23,0 ± 13,0
Percentage Elongation	D	182,0 ± 68,0	218,0 ± 25,0	345,0 ± 115,0	323,0 ± 135,0
	ND	276,0 ± 161,0	318,0 ± 153,0	290,0 ± 125,0	375,0 ± 288,0
Stress Relaxation	D	0,179 ± 0,020	0,181 ± 0,033	0,178 ± 0,014	0,193 ± 0,034
	ND	0,185 ± 0,022	0,193 ± 0,020	0,183 ± 0,011	0,182 ± 0,019

Statistical comparison of diverticular disease and no diverticular disease was by Wilcoxon signed ranks. There were no significant differences.

TABLE XXXX Values for Edinburgh transverse and sigmoid colon over age 50 and values for operative specimens.

Burst Strength (g)		Cross-Sectional Area (mm^2)		Tensile Strength (g/mm^2)		Percentage Elongation		Internal Diameter (mm)		Width at burst (mm)		Stress Relaxation	
T	S	T	S	T	S	T	S	T	S	T	S	T	S
List of post mortem Edinburgh colons < 50 years													
1000	700	20	18	50	39	204	125	28	24	85	54	,236	,209
900	1130	15	23	60	49	156	0	35	13	88	0	,205	,174
650	1120	15	31	43	36	127	17	45	45	102	53	,0	,198
740	640	12	13	62	49	301	158	22	35	88	90	,206	,0
2900	950	13	18	223	53	227	171	33	42	109	114	,163	,175
1460	1200	16	11	91	109	307	186	27	29	110	83	,186	,177
620	1180	13	33	48	36	206	512	28	9	86	52	,153	,143
1575	1200	16	29	98	41	226	527	34	8	111	50	,160	,152
1200	850	13	37	92	23	223	305	41	17	132	69	,164	,224
1000	2350	21	30	48	78	243	264	35	14	120	51	,188	,217
985	1100	20	34	49	32	452	320	19	15	105	63	,222	,210
780	820	21	21	37	39	569	408	17	13	114	66	,187	,178
1000	850	21	22	48	39	266	198	33	28	119	82	,184	,186
List of operative specimens													
660	1950	33	108	20	19,5	308	743	25	8,3	102	70	,171	,180
2600	650	37	40	70	13	248	195	36	30	129	83	,188	,202
	1760		33		53		620		10		72		,184
Significance of Wilcoxon Rank Sum													
NS	NS	*	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

* P <0,05

T = transverse
S = sigmoid

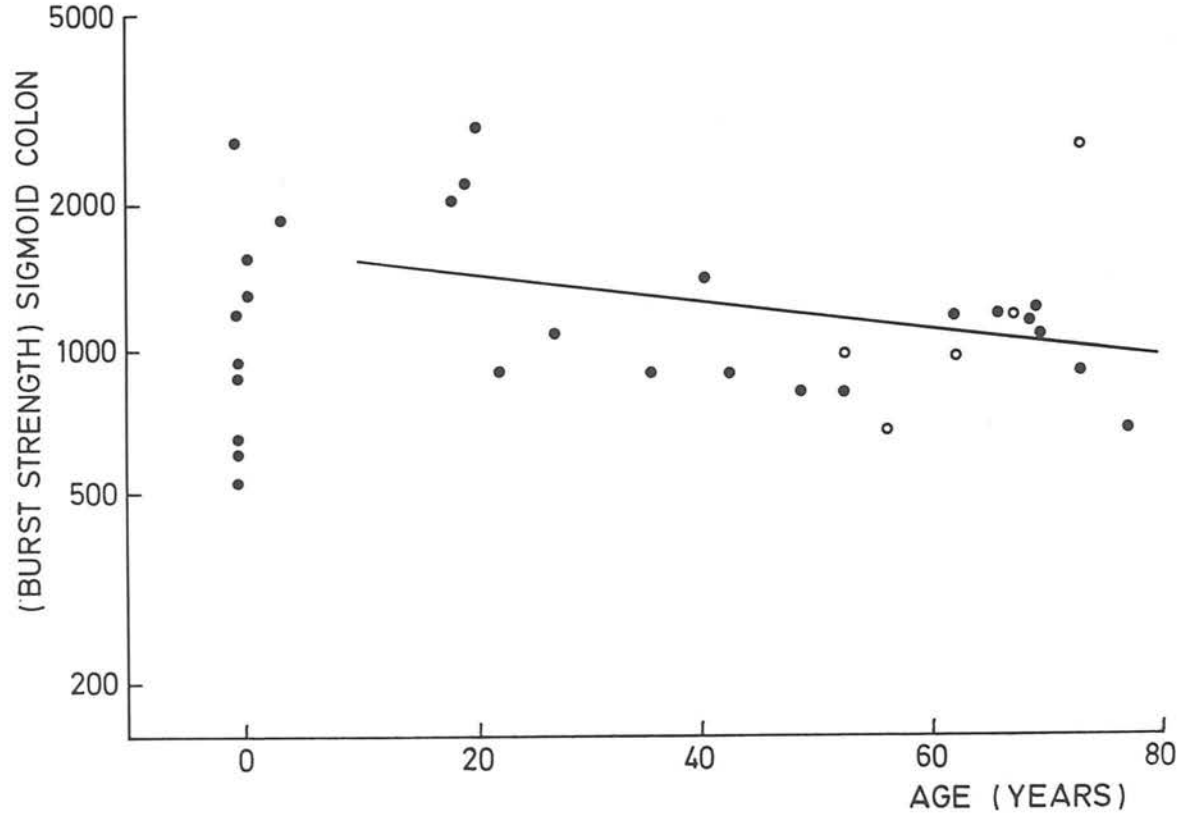


Figure 27 : Burst strength (grams–log scale) against age for Edinburgh sigmoid colons with (open circles) and without (closed circles) diverticular disease. The regression shown here just fails to be statistically significant. The diverticular disease specimens are similar to normals for their age.

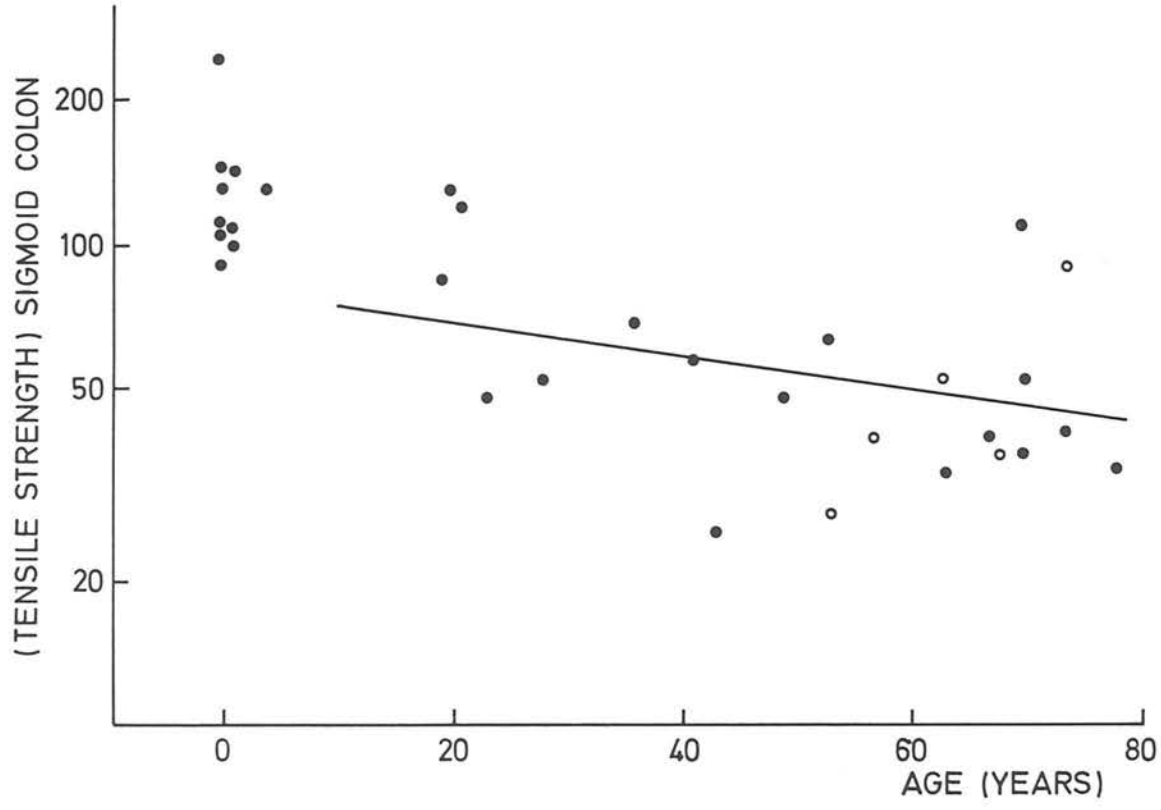


Figure 28 : Tensile strength (g/mm² – log scale) against age for Edinburgh sigmoid colons with (open circles) and without (closed circles) diverticular disease. The regression with age is statistically significant ($P < 0,05$). Specimens with diverticular disease were similar to normals from the same age group. The neonatal and infant colons had the greatest tensile strength.

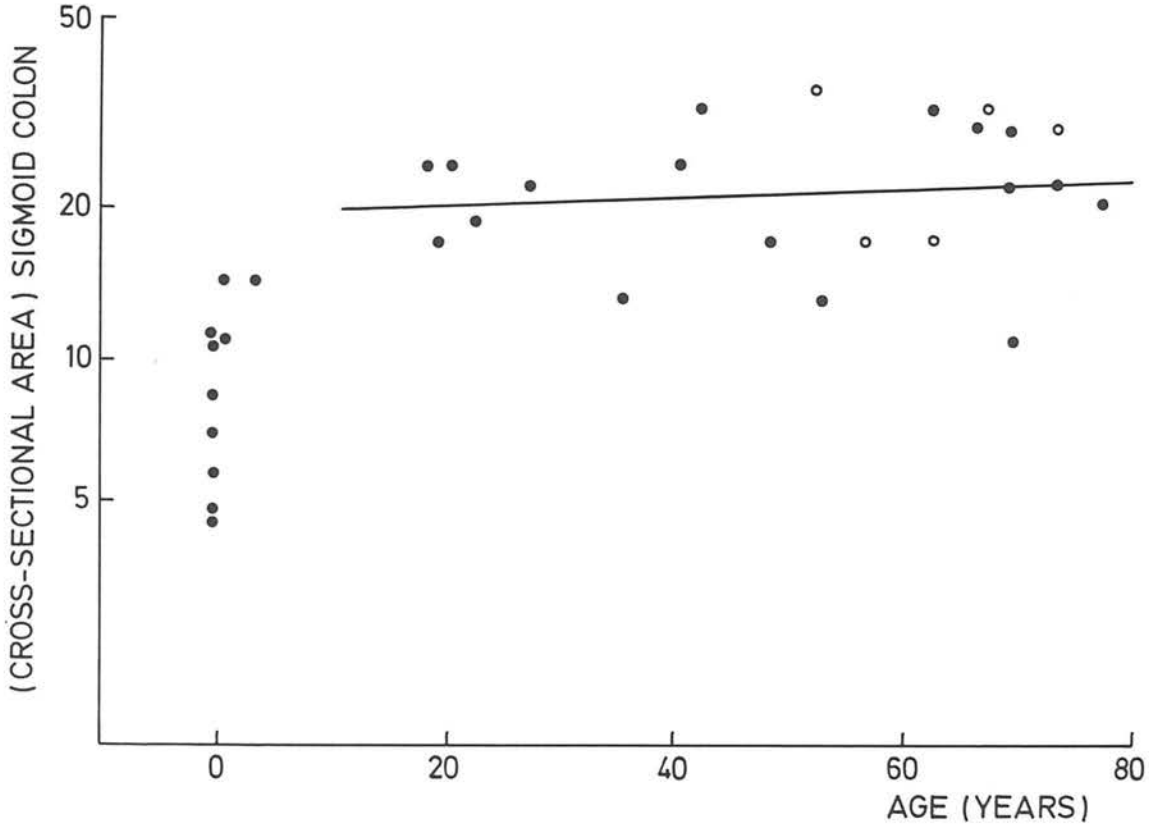


Figure 29 : Cross-sectional area (mm^2 – log scale) against age for Edinburgh sigmoid colons with (open circles) and without (closed circles) diverticular disease. The rise in cross-sectional area with age in adult life (regression line) was not statistically significant (Table XXXII) and the specimens with diverticular disease were similar to normals in the same age group. There is a rise in cross-sectional area associated with growth (0–20 years).

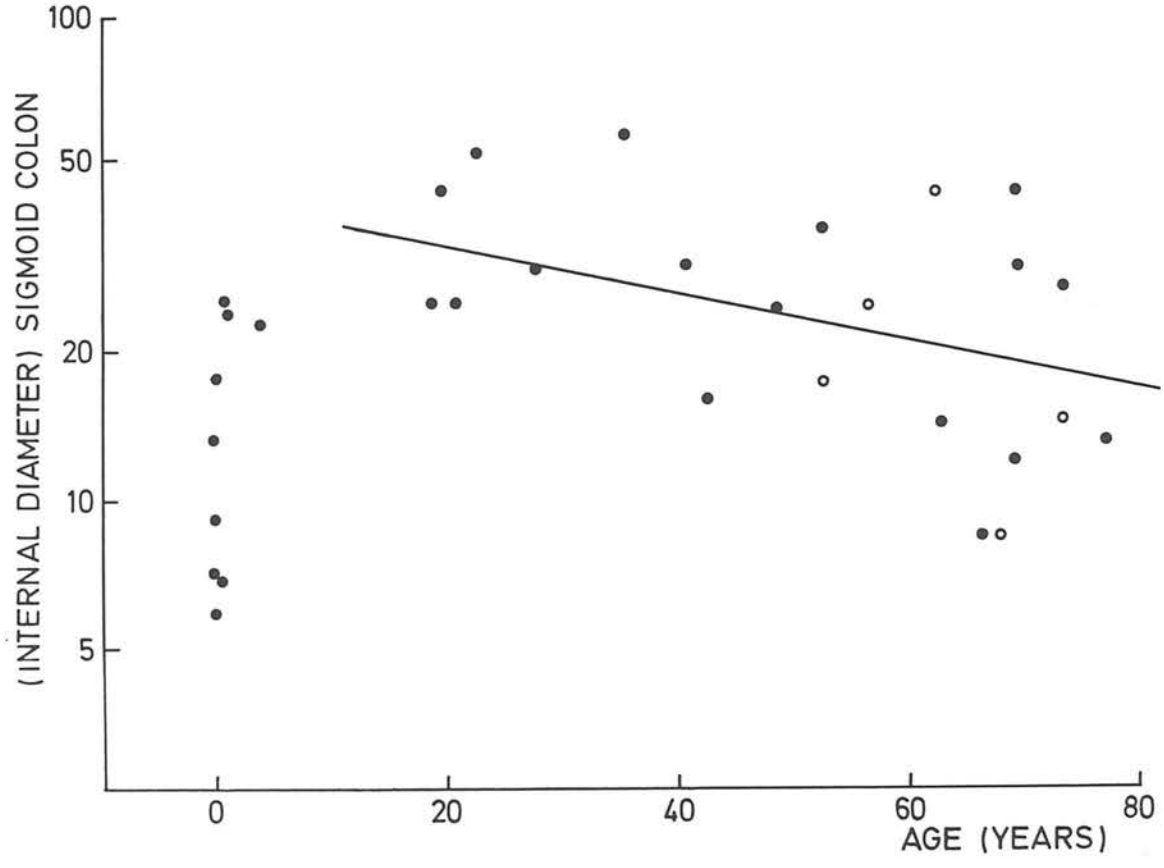


Figure 30 : Internal diameter (mm – log scale) against age for Edinburgh sigmoid colons with (open circles) and without (closed circles) diverticular disease. There is a significant fall in internal diameter with increasing age in adult life ($P < 0{,}01$). Specimens with diverticular disease were similar to normals from the same age group. There is a rise in internal diameter of the colon with growth (0–20 years).

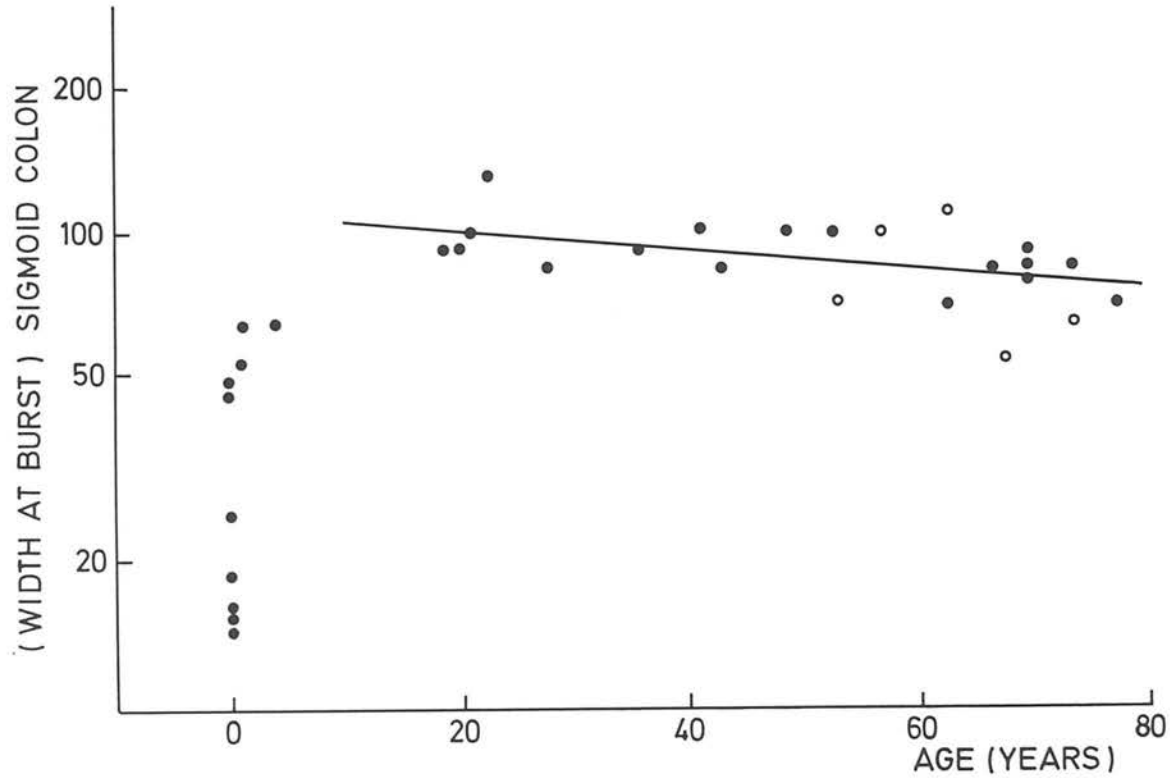


Figure 31 : Width at burst (mm – log scale) for Edinburgh sigmoid colons with (open circles) and without (closed circles) diverticular disease. There was a significant fall in the width at burst with increasing age in adult life ($P < 0{,}01$). Specimens with diverticular disease were similar to normals from the same age group. There was a rise in width at burst associated with growth (0–20 years).

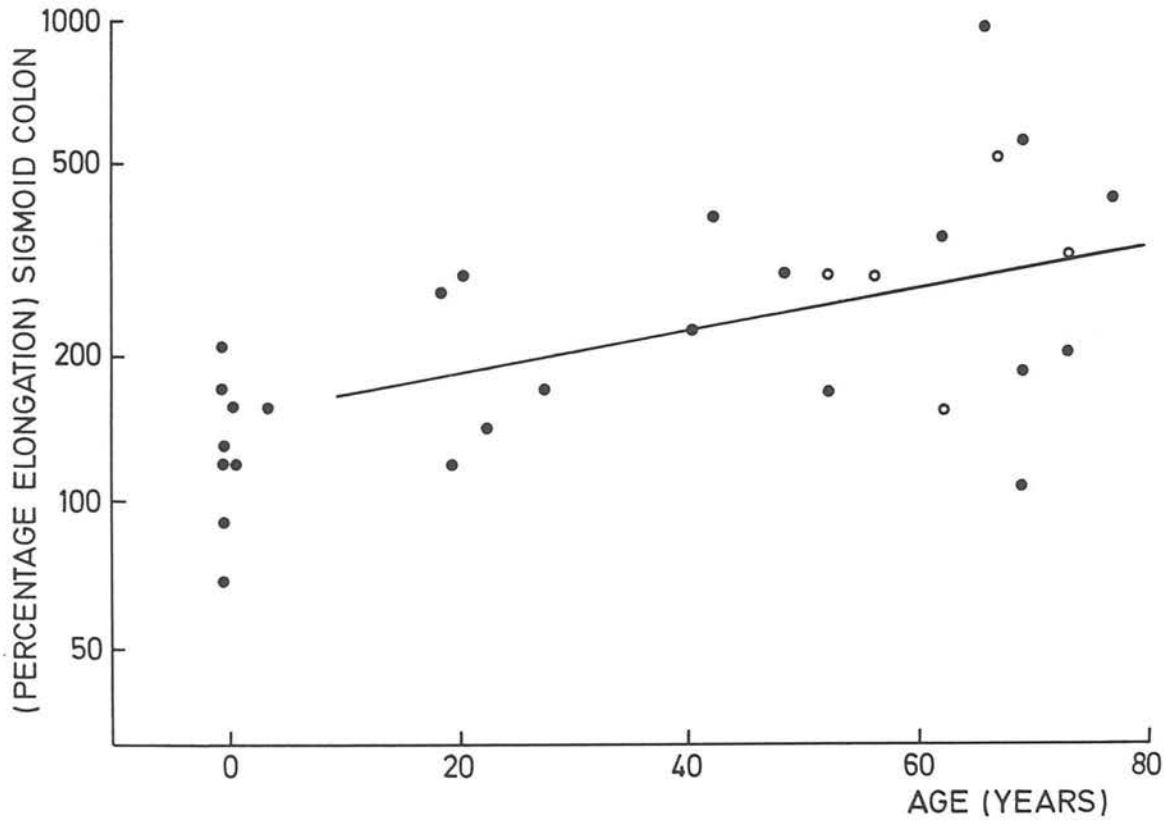


Figure 32 : Percentage elongation (log scale) against age for Edinburgh sigmoid colons with (open circles) and without (closed circles) diverticular disease. There was a significant rise with increasing age throughout adult life ($P < 0,05$). Specimens with diverticular disease were similar to normals from the same age group.

Discussion.

The mechanical properties of the bowel have been largely neglected to date, whereas the mechanical properties of skin (Daly and Odland, 1979), tendon (elliot, 1965), bone (Evans, 1973), blood vessels (Caro, 1978), ureter (Yin and Fung, 1971), uterine cervix (Harkness, 1968) and myocardium (Lee and Boughner, 1979) have been investigated to some extent. Iwasaki's work on Japanese post mortem colons has been the only detailed study (Iwasaki cited by Yamada, 1970), although Price *et al* (1977, 1979) described the mechanical properties of taenia coli smooth muscle in spontaneous contraction and the resting state.

Perhaps the most obvious reason why the mechanical study of the colon has been neglected is that there has been little clinical incentive to perform such a study.

However, Parks and Connell (1969) and Smith *et al* (1981) suggested there was a structural change in the bowel wall in patients with diverticular disease since balloon distension of the distal colon in diverticular disease did not produce the pressure change that occurs in normal subjects. Diverticular disease is prevalent in Western countries, affecting a substantial proportion (over 30%) of the over 60 age group of these populations (Eastwood *et al*, 1976). Its prevalence rises with age and in Western countries is most common in the sigmoid colon (Hughes, 1969). Iwasaki (Yamada, 1970) found that the tensile strength of the Japanese post mortem colon declined with age (Figure 10), as does the percentage elongation at burst. These findings suggested that a mechanical study of the human colon would have clinical relevance.

The close link between diverticular disease, the ageing process and diminishing strength of the colonic wall is an attractive theory, particularly since workers with other tissues such as skin (Daly and Odland, 1979) have shown age-related changes in mechanical properties.

In contrast to the prevalence of diverticular disease in the ageing Western world the incidence is low in Africa (Painter and Burkitt, 1975). It has been suggested that Africans have a shorter life expectancy and that this may be related to the low incidence of diverticular disease there (Eastwood *et al*, 1976). The more commonly accepted theory, however, is that diverticular disease develops secondary to years of low-fibre eating and high intraluminal colonic pressures (Painter and Burkitt, 1975). The generation of high intraluminal pressures may lead to wear and tear on the colon with consequent weakening of its wall. Attention in the past has been focused on the muscle thickening and contraction of the colon associated with diverticular disease (Morson, 1963), but the basic lesion might well be a weakness or loss of elasticity of its wall.

This study was therefore first concerned with the development of a method to test the mechanical properties of the colon and subsequently to measure any changes which occur with age. In view of the extreme difference in incidence of diverticular disease in Scotland (Eastwood *et al*, 1976) and Uganda (Painter and Burkitt, 1971), two groups of colons were studied, one from Edinburgh, Scotland and the other from Kampala, Uganda.

METHOD OF TESTING.

There is no established method for testing the mechanical properties of the colon. Iwasaki (cited by Yamada, 1970) cut transverse and vertical

strips from the bowel wall and tested these strips. Strips must be held in clamps with subsequent risk of clamping error. The clamps may damage the tissue if too great a clamp pressure is used and a dumbell shape must be cut to encourage the strip to break in themiddle. A gauge length to width ratio of at least 4:1 is usually recommended (Wainwright *et al*, 1976) to minimise error introduced by concentration of forces by the clamps. In this study the ring of colon was left intact since this would avoid any error introduced from interrupting the circumferential continuity in what is a tubular structure. This meant that tensile tests could be carried out by passing L-shaped hooks through the lumen of the bowel and there was no need to grip the colon in clamps. Testing was always carried out by deformation along the transverse axis of the bowel. Iwasaki found that the mechanical properties of the colon vary according to whether horizontal or vertical strips are tested, but differences with age and with race should be expected to be obvious whichever direction is tested, provided the same orientation is constant throughout the study. Another advatnage of using rings is that they are relatively easy to slip on to the hooks so avoiding time-consuming manoeuvres with clamps.

CHOICE OF MEASUREMENTS.

Strength : Strength was measured in tension since this is the most relevant means by which stress is experienced in the colon. Distension of the colonic wall by gas and faeces exerts a tensile stress whilst smooth muscle contraction and relaxation modifies the response of the colonic wall to distending forces. The pressures generated in the lumen by smooth muscle contraction exerts tensile stresses on the wall.

Tensile strength is therefore the most relevant means of measuring 'strength'

for the human colon. Its measurement depends upon the burst stress and the thickness of the wall. Burst stress is measured by extending the colon to burst. The region of the stress/strain curve prior to burst (Area C, Figure 8, p15) is almost linear because in this range of extension the collagen fibres are straight. Since collagen is the strongest material in the colonic wall, burst stress measures the burst stress of collagen rather than any other material. Watching a human colonic ring being extended one can see first the taenia splitting, followed by the circular muscle coat; there then follows a period when only the submucosa is intact and this is the last layer to rupture. Small blips occur on the stress/strain curve when the muscle layers tear, usually beginning around 500 g of stress but these are not consistent enough to allow one to estimate smooth muscle burst stress accurately. The value obtained for burst stress is the burst stress for the collagen fibres in the submucosa.

The thickness of the colonic wall is due to all the materials within it. Disorders of any of the layers individually will increase the wall thickness, eg. mucosal oedema, submucosal inflammation, muscle hypertrophy or hyperplasia. Thus a great deal more than collagen is contributing to wall thickness.

Dividing the burst stress for collagen by the thickness of the colonic wall to obtain a value for tensile strength is therefore an approximation. The strength of other materials is not being measured yet their presence in the colonic wall is increasing the thickness and thus reducing the actual value for tensile strength. One method of studying the layers of the colonic wall individually would be to separate them by microdissection. This was the method used both by Carvarlho (1973) to study the arrangement of collagen fibres and by Pace to examine the muscle layers. Pace (1968)

described interconnections between the muscle layers and therefore some of the integrity of the layers must have been lost in the separation process. Nonetheless this would be an interesting way of obtaining the layers individually for studies on their mechanical properties in the future. Orberg *et al* (1982) obtained the collagen in the submucosa in relatively pure form by treatment with hypertonic saline before scraping off the muscle and mucosa.

Another method would be to obtain collagen in a relatively pure form by enzymatic digestion of the rest of the colonic wall as is done in the manufacture of catgut from animal small intestine but this would require a large number of colons to provide a small amount of collagen. It would also destroy interconnections between collagen and other materials, though it would allow the collagen to be tested independently.

However, the colonic wall acts mechanically as a single unit and therefore it was deemed justifiable to study its mechanical properties as a unit in the first instance.

All tension tests were carried out uniaxially, ie. in one direction only. This was at right angles to thelongitudinal axis of the colon. In fact stresses and strains are experienced biaxially, since there are longitudinal stresses and strains acting on the bowel as well as transverse ones. The forces acting on a cylindrical tube have been described for blood vessels and are shown in Figure C, p161, (Caro *et al*, 1978). It was hoped that extending the tube of colon at right angles to the longitudinal axis was a reasonable approximation of its ability to withstand circumferential and radial stresses and strains. One factor affecting this approximation is that the circular muscle of the human colon is arranged as a tight spiral

(Pace, 1966), and therefore the vectors of force must be directed more diagnonally. Smooth muscle contraction may therefore introduce shear or twisting stresses and strains.

Yamada (1970) reported subtle differences between strips of colon obtained transversely and longitudinally. Vogel (1981) has shown differences in mechanical properties with strip orientation for skin as did Lee and Boughner (1981) for pericardium. In this study a constant direction was chosen, assuming that age and racial differences would be detected whichever direction was tested.

Stretch and viscoelasticity : The colon as other biological tissues is not truly elastic since it does not return to its original dimensions once a stress is removed. On cyclical loading and unloading experiments the stress/strain curve is not reproducible until a number of cycles have been carried out. Once a reproducible stress/strain curve is obtained the tissue is said to be preconditioned (Fung, 1981). Preconditioning alters the internal arrangement of the tissue and thus preconditioned tissue is different from that in the natural state. Lee and Boughner (1981) found that strips of canine pericardium less than 0,5 cm in width could not be preconditioned because each cycle progressively damaged the tissue. However, the bowel is an intact tube subject to cyclical stresses and strains with peristaltic, segmentation and mass action activity, so that it is in one sense 'preconditioned' in the living animal. Preconditioning can be achieved in blood vessels very quickly (in two or three cycles) if blood flow via the vasa vasorum is interrupted (Fung, 1981). Since preconditioning involves movement of tissue water it would be expected that an intact blood supply is important for this process as well as to viscoelastic properties in general.

Initially it was hoped that a measure of elasticity could be made by calculating L-values, a Young's modulus between set points of stress and the energy under the curve at burst. However, the colon is not elastic and the stress/strain curve is not reproducible without pre-conditioning so that L-values, energy under curve and Modulus calculations are subject to large variations and the relevance of change is difficult to interpret. Therefore the conventional practice of studying the visco-elastic properties after preconditioning was adopted and stress-relaxation was studied in the human and the rat.

The L-values obtained from the early part of the stress/strain curve (L0, L1, L2) were easier to obtain in the rat colon than the human. This was because the rat colon has a constant diameter compared with the human. L-values depend upon accurate measurement of tissue dimensions. Because the colon collapses when air is removed, it is extremely difficult to measure its internal diameter without subjecting it to a small stress. Therefore the internal diameter of the human colon was measured at the point where stress began to be registered, which is the take-off point on the stress/strain curve. The internal diameter of the colon includes the distance L0-L1 which Daly and Odland (1979) used to show age-related changes in elasticity.

L-values are also dependent upon drawing a tangent to the steep part of the stress/strain curve. It is harder to draw an accurate tangent for the human colon because of the blips which occur due to muscle tearing.

For these reasons modulus and L-values were not measured for the human colon and were considered to be of doubtful meaning in assessing elasticity in the rat colon. In addition to stress relaxation and internal diameter at

stress 0, the width at burst and percentage elongation were measured.

The width at burst was less variable than percentage elongation because it does not depend upon the measurement of internal diameter. It was the variability of the internal diameter that made the percentage elongation so variable, ranging from 100 to 500% or more in the human colon.

The stress-relaxation slope would not be expected to be significantly altered by variation in the internal diameter since Pinto and Fung (1973) showed that the viscoelastic properties of rabbit papillary muscle were independent of strain rate. Yin and Fung (1971) also demonstrated a similar stress-relaxation slope between ranges of 9 to 30% strain in dog ureter. Therefore, inaccuracies due to measurement of internal diameter and thus the calculation of 80% strain are unlikely to have significantly affected values for stress relaxation.

ESTABLISHMENT OF METHOD.

The method was first established in the rat.

Rat Experiment 1 : It is standard practice to avoid error due to dehydration when making mechanical measurements on biological tissues (Wainwright *et al*, 1976). Initially this study was concerned with the stress/strain curve obtained when a ring of colon was fairly rapidly (within a minute or two) extended until rupture occurred. Tissue hydration is not likely to have been significantly altered over such a short period of time. In order to check this assumption three segments were excised from each of six rats and the segments were either (a) left in air; (b) kept moist in physiological saline; or (c) in Earl's solution. A balanced design was used to minimise any effect due to segment site. Over the two hours

required to prepare the test the rings there was no difference between the rings allowed to dry and those kept moist in physiological saline or Earl's solution. Earl's solution is a tissue culture medium and as such is more expensive than physiological saline but it conferred no advantage over the saline. Although this was a small experiment and larger numbers might have shown significant differences there was no cause to be concerned over possible dehydration in a matter of minutes when no differences were detected in two hours. Significant differences might have been detected had viscoelastic properties been examined, since these properties are dependent upon tissue hydration (Fung, 1981). Physiological saline appeared adequate to keep the tissue moist until testing occurred, and the use of a better balanced electrolyte solution which was more expensive did not seem justified.

There was only one significant segment effect in this experiment. The Young's modulus between 25 and 100 g fell from segment A to C. Since A was the most proximal segment and C the most distal this suggested that the proximal colon may be stiffer than the distal. However, the range of stress over which the modulus was measured was large and the stress/strain curve in this range is not linear so that this result might equally be misleading. The segment effect was studied further in Experiment 2.

Rat Experiment 2 : Since in Experiment 1 physiological saline appeared to be the most practical method of keeping the rat colon moist, Experiment 2 was designed to determine how long the mechanical properties of the rat colon can be preserved in physiological saline. Yamada (1970) reported that a mechanically stabilised state existed whereby the colon could be stored in physiological saline at 4°C for two days.

Rat Experiment 2 confirmed the existence of a mechanically stabilised state with regard to testing the burst characteristics of the rat colon. Stress relaxation was significantly altered after 24 hours of storage in physiological saline at 4°C, the slope of the regression of stress with log time becomming steeper. Thereafter it remained constant for a further six days but by Day 17 it had changed again, the regression line becoming steeper still. The time course of the change in stress-relaxation and presumably other viscoelastic properties within the first 24 hours is unknown, although Matthews and Ellis (1968) suggested there was no change in the viscoelastic properties of cat tendon within three hours.

The other significant results in Experiment 2 were due to segment effects. In this experiment five segments were excised from the rat colon. Segments A to C corresponded to the three segments tested in Experiment 1 and two more distal segments were also tested. It was these two distal segments which were significantly stronger and more extensible than their more proximal counterparts. The L2 value was greater in these distal segments (and also segment C) which suggested that distal segments were more extensible at low ranges of stress. This was not confirmed for L0 and L1 values. The stress-relaxation curve which describes the viscoelastic properties at 5-30 g of stress was steeper in the distal segments, implying a greater ability to relax in terms of stress at a fixed strain (100%). The overall picture obtained is that the distal colon is stronger and more extensible than the proximal. However, in Experiment 3 where colon and rectum were compared, the colon was stronger than the rectum. There was no difference in percentage elongation between colon and rectum but L1 and L2 were significantly greater for the colon implying that at low stress ranges the colon is the more extensible.

Variation and reproducibility : As can be seen from Table XVI the coefficients of variation for testing adjacent segments are reasonably small when it is considered that it was biological tissue which was being tested. The variation was greatest in testing burst strength with a range of 16-24% depending on site. Burst strength is an absolute depending upon no other measurement and therefore the variation relates the variability of the tissue itself as well as the method of testing. One might expect greater variation in post mortem than live tissue, and also the variability may increase with storage since changes due to death and storage will increase the variation. Statistically significant results are thus harder to obtain, since larger numbers are required to confirm apparent differences. The coefficient of variation (between adjacent segments) for width at burst (WB) and stress relaxation were small, being only 5-7%. Percentage elongation at burst is calculated from width at burst and internal diameter so that its value depends upon the variation of both these two measurements. This explains why its coefficient of variation is greater, ranging from 9-13% for testing adjacent segments.

Choice of post mortem tissue : Colonic tissue is not readily obtained from the living human being. Only specimens resected at operation for underlying bowel disease are readily available and in any case are only available in quantity from the older age groups. Post mortem tissue is therefore the only ethical means of obtaining material from individuals without bowel disease across the whole spectrum of age. Fortunately, material is rarely available from infants and children, since those in the age range 1-15 rarely come to post mortem. Post mortem tissue is subject to a number of known and probably many unknown limitations: The tissue has had its blood supply cut off, changes occur due to rigor mortis and autolysis occurs at a rate dependent upon temperature and possibly the bacterial flora.

Effect of death : There was therefore no alternative to post mortem tissue. Some measure of the effect of death was made by comparing five pieces of colon resected from four patients. Two patients had severe diverticular disease, one had a carcinoma of the transverse colon and the other had revision of a pelvic colectomy. Two specimens of transverse colon and three of sigmoid colon were thus obtained and these were comapred with 13 colons obtained from those over the age of 50 in the Edinburgh group.

There was no difference in mechanical properties between the two groups. The only difference was that the operative specimens were considerably thicker. The above statement is obviously limited by the numbers being small in the operative group and the operative specimens having underlying bowel disease and therefore more prone to have thicker colons, particularly in the case of diverticular disease. Conclusions must be guarded, but still no differences were found which suggests that the use of post mortem colon for mechanical testing is reasonable.

Time after death : The effect of time after death was studied on the rat (Experiment 3). As can be seen from Table VIIIb, p48, the colon becomes stiffer after death up to 48 hours as reflected by reduced L values. This effect was probably due to rigor mortis in the smooth muscle of the colon. Had the experiment been continued longer than 48 hours the effects of rigor mortis would have been expected to have diminished with the colon becoming less stiff. This would need to be confirmed by a longer experiment. The time after death did not affect burst strength, percentage elongation or width at burst measurements.

The time after death was also recorded for each human colon obtained.

In view of the concern that mechanical properties would be drastically altered by changes after death regression analyses for time after death against each mechanical measurement was performed and failed to show any statistical significance in all four parts of the colon. Kendall's Rank correlations were also performed for time after death between Edinburgh and Kampala colons for each mechanical measurement. The only significant difference obtained was that the Kampala group became thinner with time after death compared with the Edinburgh group. Figure 21 shows the reason for this. There were two Edinburgh colons obtained over 80 hours after death and these were thicker than any of the other colons. Up to 60 hours the Edinburgh colons had a similar regression to the Kampala group. The two outliers at 80 hours may be thicker because of changes that occurred with death in this period.

It seems therefore whatever changes develop with time after death are not sufficiently advanced within the first three to four days to affect the mechanical properties that were measured.

Matthews and Ellis (1968) found no change in the elastic modulus of cat tendon within 3 hours of death. Vidik *et al* (1965) found no change in mechanical properties of rabbit ligament 96 hours after death kept moist, but there appears to be no study of tissue left *in situ* after death.

Storage : There is no means of testing the mechanical properties of the colon in Africa by the described method immediately after death, since there is no Instron tensile tester in the continent. The machine is not transportable in any practical sense sothat the tissue had to come to the machine rather than the machine going to the tissue. Colons obtained in Kampala therefore had to be stored in such a way that their mechanical

properties would be preserved. The standard method for transportation of pathological specimens is to use formalin. Quite apart from the fact that there was no formalin in Uganda in June 1982, formalin irreversibly stiffens the tissue and was therefore deemed inadequate as a means of preserving mechanical properties.

Salt is used to preserve the collagen of the submucosa for commercial transportation as it was used to preserve meat in the Middle Ages. It is readily obtainable and relatively cheap, heavy for airline travel but otherwise convenient. No equipment is required for storage except a polythene bag, which made this the most practical means of storage investigated in this study. The results of the storage experiments confirmed that salt is a reasonable storage medium. It was the best means of preserving burst strength (a collagen test) although ultimate percentage elongation tended to rise with salt storage and this rise continued with the length of storage. Other measurements such as L values and the Young's modulus were not affected by salt storage. The temperature of storage (whether at 4°C or 20°C) did not appear to alter the preservative qualities of salt over the 7-35 days tested. Storage at -185°C (liquid nitrogen) and -20°C (deep freezing) had detrimental effects on the strength of the colons.

Salt storage for 24-35 days was compared with 24 hours storage in physiological saline in both the rat and the human colon. In the rat there were no gross differences in the salt and saline groups. Six human colons were tested at the standard four sites, with seven measurements being made for eachsite. Only two sites had any statistically significant difference between the salt and saline groups. Otherwise there were no significant effects. Two out of 28 tests significant at the 5% level is almost what one would expect to occur by chance.

Workers with other tissues have described the preservative qualities of a number of different storage mediums. Vidik *et al* (1965, 1966) examined preservation of rabbit ligaments in saline at 20°C, 4°C, tanned and in the frozen state (-10°C for two weeks). For each method of storage they found at least one parameter changed. Cronkite (1936) found no difference in the tensile strength of human tendons which had been embalmed and those examined within 48 hours of death. Van Brocklin and Ellis (1965) found no difference between the mechanical properties of the extensor tendons of amputated toes when examined fresh or after being frozen. Later Matthews and Ellis (1968) repeated these tests on cat extensor tendons and found that the mechanical properties were similar whether the tendon was fresh or frozen, although the average elastic modulus was lower for the frozen group. Lanir and Fung (1974) found no degradation of viscoelastic properties in preconditioned rabbit skin stored in saline at 10°C for 24 hours. Van Noort *et al* (1981) found that the mechanical properties of human dura mater were unaltered by glycerol preservation. Human dura mater is used for heart valve replacement. At present little is known about the effect of storage on mechanical properties, even of tissues that require to be stored for clinical use. It seems that each storage medium will affect some mechanical measurement and that therefore in the absence of an ideal storage medium one must test the desired medium for the specific tissue to be stored. Salt appeared to be an adequate means of preserving the mechanical properties of the colon for up to 35 days.

Despite having failed to demonstrate convincing significant differences with salt storage, both Edinburgh and Kampala groups of colon were stored in salt for 28-35 days before testing, so that the storage conditions were similar for both groups. The only difference was that after 7 days the Kampala

group were kept at 20°C rather than 4°C, but this is unlikely to have had a significant effect since Experiment 3 failed to demonstrate any advantage in the lower temperature with salt storage.

Irradiation : In accordance with the health and safety regulations at Ethicon Research Laboratories human tissue was irradiated before testing. Ranu (1981) demonstrated significant alterations in collagen fibre anatomy and alterations in the stress/strain curve 120 days after irradiation. These changes increased with increasing doses of irradiation. In Experiment 3 only one out of 12 measurements was statistically different in the irradiation group compared with the non-irradiated group. Since this was significant only at the 5% level it could easily have been a spurious result. The measurement affected was the Young's modulus calculated between 10 and 25 g of stress. It was decided not to measure Young's modulus in the human colon, thus there is a reasonable degree of confidence that irradiation has not significantly altered the human results. In Experiment 4 irradiation had no great effect on burst strength, L values or percentage elongation between the saline non-irradiated and salt irradiated group. There was a 9% reducation in percentage elongation, 19,8% reduction in L_1 (ie. became stiffer) and 17,2% reduction in burst strength between the saline irradiated and non-irradiated groups. The first two were statistically significant and the last almost significant. These effects are similar to the coefficient of variation and at any rate are not confirmed in the salt irradiated group. In Experiment 3 irradiation was carried out 7-28 days before testing, whereas in Experiment 4 , the colonic segments were irradiated the day before testing so that irradiation up to 28 days before testing seems to have little effect.

All human colons were tested within a week of irradiation. Had they

been tested months after irradiation there may have been a significant effect on mechanical properties. What effect irradiation did exert on the colons would be to equalise groups. Stronger colons would be expected to be greater affected than weaker colons and therefore the effect of ageing and difference between races would be dampened. However, it seems unlikely that irradiation has significantly altered the results of this thesis in view of the results obtained in the rat experiments.

MECHANICAL PROPERTIES OF THE RAT COLON.

The mechanical properties of the rat colon have not been previously reported with the exception of Yamada (1970), who gave figures only relating to the burst properties of the rat caecum, ascending colon and rectum. The method used was different from the one in this study and placed the rat between the dog and rabbit in terms of burst strength.

Tensile strength : The tensile strength of the rat colon in this study was in the order of 50 g/mm^2. Compared with Yamada's figures for dog, rabbit, cat and domestic fowl, this places the rat between dog and rabbit, approximately the same as the cat and domestic fowl. Yamada (1970) gave no figures for rat tensile strength or percentage elongation at burst.

The tensile strength of the rat colon is similar to the aged human as well as the cat and domestic fowl.

The 24-30 week human fetus has a colon which is nearest to the rat colon in dimensions but the former has approximately twice the tensile strength. Since measurement of ultimate burst and expansion is a test of the collagen meshwork in the tissue, it seems that either collagen, or at least

its internal arrangement and cross-linkages are species specific.

A scanning electron microscopy study of rat intestine suggested that collagen fibres are arranged in undulating arrays, mighty parallel to each other with smaller fibres linking the bundles (Orberg *et al*, 1982). The authors did not state whether they were examining small or large intestine but certainly the arrangement of rat submucosal collagen was different from that of human which is arranged in criss-cross bundles (Cavarlho, 1973). A proper study of differences between species requires detailed ultrastructural studies.

Age and sex : There were significant differences between old and young female rats in that the colons of young rats were stronger and more expansile. This age difference was not confirmed in the male rats but the old male group was younger than the old female group by at least three or four months. The old females were in poor condition in that they were losing weight and some of their number had already died when mechanical testing was carried out. A further difference was that the old females had eaten a different diet from the old males for the first six to nine months of their lives. The females ate an unrestricted diet until the age of 6 to 9 months. The diet also had subtle differences, such as a barley base in the males compared with an oats base in the females. Other differences are shown in Table IV, materials and methods.
The one year old males were not a comparable group with the 14-17 month females and therefore no conclusions can be drawn about the influence of gender in the aged rat. There were no significant differences between seven week males and females. The stronger colons of one year old males compared with seven week old males suggessts an increase of

strength throughout life in the first year. The results for burst strength in Experiment 1 (3 month males) shows that the values are between those for 7 week and one year old males. This effect was not merely due to increasing colonic thickness with growth (rats continue growing until they die) since the tensile strength was also greater in the one year old group of males.

These results suggest that the rat colon increases in strength and stretchiness throughout the first year of life. Once old age is reached there is a weakening of the tissues and loss of stretchiness. There were no sex differences at the age of seven weeks.

Orberg *et al* (1982) studied the effect of age on rat intestine collagen fibres. The length of large fibre undulations increased during the first three months of life (during maturation), but thereafter remained constant throughout the next 22 months. As the intestine aged the association of collagen fibres into bundles increased, suggesting greater organisation of the fibres.

Pre-strain : The pre-strain longitudinally in the rat colon was 10%, which is less than the 30% reported in blood vessels (Caro *et al*, 1978). The colon does not normally have to cope with such high pressures and tensions as blood vessels which may be why its pre-strain is less.

Segment site : The distal colon was stronger and more stretchy than the proximal colon. This may reflect differences in the consistency of the faeces that the bowel must propel at each site. There are liquid faeces proximally where possibly less pressure is generated to propel the liquid whereas distally the faeces are solid and thus a greater propulsive force is required. The rectum was weaker than the colon. There was no

consistent difference in 'stretch' properties. L values were reduced in the rectum compared with the colon but percentage elongation was the same. The rectum is a storage organ and thus may not need to generate such high pressures for propulsion. Nonetheless, in the rat, it is a long structure and some degree of propulsion must be necessary.

TABLE XXXXI. **Comparison of different species' tensile strengths. The Yamada (1970) study did not specify ages.**

	Mean tensile Strength (g/mm^2)	Reference
Human fetus	173	Present study
Young adult	96	Present study
Dog	93	Yamada, 1970
70 year human	74	Present study
Rat (7 weeks)	50	Present study
Cow	45	Yamada, 1970
Cat	43	Yamada, 1970
Domestic fowl	42	Yamada, 1970
Rabbit	13	Yamada, 1970

AGEING IN THE HUMAN COLON.

Strength : In the sigmoid, descending and transverse colon there was a significant decline in burst strength with increasing age. Burst strength is basically a collagen test since it is the collagen which is the last to rupture and which ruptures at a higher stress than any other material in the colonic wall (Wainwright *et al*, 1976). Pace (1966) demonstrated an increase in the amount of connective tissue in the colonic wall with age but observed that the quality of the elastin, collagen and reticular fibres

declined by histological criteria. From the age of 10 onwards he also observed a progressive reduction in the connective tissue layer between the two muscle coats with increasing age. He noted that the collagen bundles of the submucosa, but not elsewhere, begin to show fraying of their ends. There is therefore some histological support for the reduction of burst strength with age.

This trend was not found for the ascending colon. This may be because it was the most difficult part of the colon to test, being the most prone to deterioration, possibly because it was harder to clean out all the liquid faeces before storage. Another methodological difficulty with the ascending colon was that it was harder to cut an accurate ring of bowel than from other regions. This is emphasised by the fact that the coefficient of variation was 24% for adjacent segments of the ascending colon. The possibility that the ascending colon may not age at the same rate as the rest of the colon should also be considered. Certainly, the faeces in this region are most fluid and thus the intraluminal pressures lowest with reduction of 'wear and tear' over the years.

When burst strength is divided by cross-sectional area (10 mm by the thickness of the colon) a value is obtained for tensile strength. There was a significant decline in tensile strength in the sigmoid and transverse colons with age. There was also a tendency for the tensile strength in the descending and ascending colons to decline with age, but this was not statistically significant. This lack of statistical significance with age is probably due to both a wide scatter of values for tensile strength in the older age-groups and also a relatively small sample size.

The thickness of the colon showed a marked rise in the first few years of

life. Thereafter a plateau was reached where there were no significant changes over the age of 14. Pace (1966) has shown a progressive increase in the muscle wall of the colon with age. His study was extremely detailed and careful, concentrating on the muscle coat.

The method used in this study was crude, but the most practical available, since it gave a quick measure of whole wall thickness, whilst minimising error in measuring. It may be that the thinning of the intermuscular connective tissue compensates for an increasing muscle thickness, but further elucidation of this issue would require detailed histological, electron microscopic and micro-dissection techniques.

Tensile strength was highest in the first year of life. The neonatal colon was remarkably strong compared with the adult colon gram for gram of tissue. The burst strength appeared to increase throughout intrauterine life with a tremendous increase in strength after birth possibly related to use of the colon. By nine months of age the infant's colon had its greatest burst strength. Indeed, the strongest colon tested belonged to a nine month old infant.

The declining strength of the colon with age did not appear to be due to changes in the thickness of the colon. These results agree with those of Iwasaki (Yamada, 1970) who demonstrated a similar change with age in the ascending, transverse and descending regions. The rectum also declined in strength. He found that burst strength increased until the 10-19 age group and then decreased, whereas tensile strength fell steadily throughout adult life. It is suggested that the collagen component of the colonic wall deteriorates with age, either in its arrangement as a matrix or by weakening of the individual fibres.

Further support for this tendency of the colon to weaken with age is suggested by the fact that the old female rats had significantly reduced burst strength compared with their young female counterparts.

Stretch : The width at burst is the extent to which the colon can be stretched before bursting apart. It is an absolute measurement, independent of the internal diameter at zero stress. Therefore it is not subject to inaccuracies due to smooth muscle contraction before or after death. It simply describes the extent to which the colon can expand.

The width at burst increased tremendously after birth which simply relates to growth and is not a remarkable finding. Throughout adult life there was no significant change in width at burst in the ascending, transverse and descending colon, but in the sigmoid colon there was a highly significant fall in width at burst with age. The trend in the other parts of the colon was also for width at burst to fall with age but the tendency was not as great.

Percentage elongation is calculated from the internal diameter at stress 0 and the width at burst. Percentage elongation increases with age although this was only statistically significant for the Edinburgh colons. In contrast Yamada (1970) reported that the percentage elongation fell with age, although the decrease was small. The results presented for young and old female rats (Table XVII) also showed a fall with age. One year old male rats however had a greater percentage elongation than seven week old males.

The rise in percentage elongation with age may be due to testing the colon ring intact since the diameter of this ring falls with age. Percentage elongation being based on this diameter must rise if the width at burst is

constant which it was in the proximal colon. In the distal colon there is a tendency for the fall in width at burst to be disproportionate to the fall in internal diameter (the latter being greater), particularly in the Edinburgh group of colons. Thus the percentage elongation rose with increasing age.

Iwasaki (Yamada, 1970) only did mechanical tests on strips. A predetermined strip of tissue was cut out regardless of the internal diameter of the colon. In this case percentage elongation may be the only way to measure the ability of the colon to stretch, since each strip represents a different proportion of the intact colonic ring. Keeping the colonic ring intact may give a better indication of the ability of the colon to stretch because internal diameter and width at burst can be measured separately. Percentage elongation may even be a misleading entity when the starting dimensions of the tissue are variable. By contrast the internal diameter of the rat colon was remarkably consistent and therefore percentage elongation and width at burst measured the same entity.

Vogel (1982) studied the ultimate extension in rat skin obtained perpendicular to the body axis and found that the extensibility increased until the age of four months and decreased thereafter. Samples obtained longitudinal to the body axis, however, showed much smaller changes. Daly and Odland (1979) demonstrated a decline in elastic deformation with age in adult human skin. Thus ageing appears to be associated with a loss of extensibility. In the colon this was apparent in the decline of internal diameter and width at burst in the distal colon.

Viscoelastic properties : The viscoelastic property tested was stress relaxation, the ability of the colon to relax when a fixed stress or strain is applied. The decay of stress with time at 30% strain was plotted on a semilogarithmic scale of log time against stress decay. Daly and Odland (1979)

demonstrated a fall in stress relaxation to compression in the live anterior tibial skin in humans with age. It was expected that there would be an age related change in stress relaxation. However, in the post mortem tissue there was no change in stress relaxation related to age. This did not seem to be due to the method of storage since stress-relaxation was similar before and after salt storage when compared with testing after 24 hours in physiological saline. Nor did irradiation appear to affect stress relaxation.

There was a significant difference in stress relaxation between the group of young and old (14-17 months) female rats, stress relaxation falling with age. These rats were tested within 3 hours of death and it may be that the viscoelastic properties change disproportionately with age in 24 hours of saline storage. The mechanically stabilised state experiment (Experiment 2) was designed to examine the effect of saline storage and there was a significant rise in stress-relaxation properties with saline storage at 4°C in the first 24 hours.

The presence of an intact vascular supply is obviously vital to the viscoelastic properties of a tissue, since the viscoelastic properties are related to elastin and ground substance integrity and these have many hydrophobic bonds. Viscoelastic properties may therefore decline rapidly after death so that they can be studied more meaningfully *in vivo*. Smooth muscle is also a structure that exhibits viscoelasticity but rigor mortis may influence this, as may smooth muscle autolysis.

I am therefore reluctant to conclude that viscoelastic properties do not change with age in the human colon. I suspect that post mortem bowel is not the best for testing viscoelastic properties and that this would be

better done on living colonic tissue. A method has been described using balloon distension for the rectum with this purpose in mind (Martelli *et al*, 1978). Smith *et al* (1981) and Parks (1970) showed balloon distension could be used in the living sigmoid colon. The results for young and old female rats suggested that the viscoelastic properties of the colon may decline with age, but this remains to be confirmed in the human.

COMPARISON OF EDINBURGH AND KAMPALA COLONS.

Stretch : There was a tremendous increase in the width of the colon at burst in both groups over the first few years of life. This was related to growth. The width at burst remained fairly constant thereafter in the proximal colon in both groups, but the distal colon (both descending and sigmoid) had significantly lower width at burst in the Edinburgh group. Figure 24 shows fitted parallel lines for the width at burst over the age of 10 in the sigmoid colon. Both groups demonstrated the significant ageing effect of a fall in width at burst with age, but the Kampala sigmoid colon had a significantly greater capacity to stretch.

The overall picture that emerged was one of a more distensible distal colon in the African. It is the distal colon which is the most prone to develop diverticular disease in Western countries so that the impaired stretch capacity in the Edinburgh group may reflect pre-diverticular change. Alternatively, diverticular disease develops secondary to an impaired stretch capacity. Diet may well be an important factor in either of these possibilities.

Some evidence which would support either of these views comes from *in vivo* studies of balloon distension in the human colon. Parks and Connell (1969) found that the sigmoid colon with diverticular disease is

less able to withstand a stretching force than is the normal bowel. Parks (1970) later confirmed that the descending colon in those who had had their sigmoid colon resected for diverticular disease also had an impaired stretch capacity. This descending colon was probably 'pre-diverticular' in that it was noted to be free of diverticula at surgical resection of the diseased sigmoid. This was later confirmed by Smith *et al* (1981) who also showed that subsequent treatment with bran did not lead to recovery of the ability to stretch.

Another factor to be considered in the Kampala group is the large volume required to provoke colonic and rectal sensation in balloon distension experiments (Shepherd and Wright, 1967) in the normal Ugandan (150-400 ml). It is enormous in those who have recently had reduction of a sigmoid volvulus (1000-3400 ml).

The incidence of sigmoid volvulus is high in Uganda (Shepherd, 1968) and volvulus is normally associated with a form of megabowel which involves the distal colon and upper rectum (Shepherd and Wright, 1965). A greater tendency to develop volvulus may be in part related to an increased ability to stretch and deform. Thus the Ugandan colon may be mechanically predisposed to sigmoid volvulus. One would not expect the thickened, contracted, stiff diverticular diseased colon to be likely to undergo volvulus.

Painter and Burkitt (1975) suggested that the African colon is wider, since it copes with a larger faecal volume (Wells, 1949; Carlson and Hoezel, 1949). The wider colon segments less efficiently and would therefore be expected to generate lower intraluminal pressures. The increased transit time in the African (Walker, Walker and Richardson, 1970) compared with the British (Burkitt, Walker and Painter, 1972; Eastwood *et al*, 1981)

means that the African stool is softer, since less time is available for water absorption. The faeces may be propelled along the colon with less propulsive pressure and ultimately passed with less straining. The weaker Edinburgh colon may therefore be due to 'wear and tear' secondary to years of generating high intraluminal pressures. The increased thickness may relate to increase in colonic smooth muscle though this would have to be confirmed by study of the individual layers. Some support for this comes from animal experiments. Rats (Wierda, 1943) and Rabbits (Hodgson, 1972) fed long-term on a low fibre, high fat diet develop colonic diverticula which may be due to weakening of the wall in relation to pressures generated to propel faeces.

Viscoelasticity : There was no consistent difference between the two groups of colons. As previously discussed, this may represent a methodological problem related to testing viscoelastic properties in dead and devascularised tissue. On the other hand the viscoelastic properties at the level of strain tested may be similar for colons of all races and diets. *In vivo* studies might provide the answer.

Strength : The significantly greater tensile strength in the Kampala group was related to an increased burst stress and reduced thickness though neither of these measurements were statistically significant in their own right.

Reference to Table A1-4 (Appendix A) shows that over the age of 15 the Kampala colons were stronger and thinner in most age groups and sites.

The only exceptions were those age groups where there was only one or two colons representing Uganda or Edinburgh.

Although statistical comparison is impossible if there is only one sample in a group, values may still be included in a regression analsyis which is a better method of presenting data when numbers are small or unevenly balanced.

The standard deviations were large in many cases, suggesting great variability between individual colons. The variation between adjacent segments from the same colon was much smaller (16-24%), suggesting that it was not primarily the method which gave variable results but rather the large individual variation. This variability makes statistically significant results less likely, particularly with small numbers.

Despite these difficulties, there was a definite trend for the Kampala group to be stronger, thinner and thus more efficient mechanically. The possible increased thickness of the Edinburgh samples may be a means of compensating for decreased strength - a greater amount of tissue being needed to cope with the colonic work load.

This difference in strength between Edinburgh and Kampala colons must be due to either genetic or environmental factors. Possibly the most important environmental factor is the diet which is likely to have been deficient in fibre and excessive in fat and sugar in the Edinburgh group. There was no statistical difference between the Edinburgh and Kampala chidlren's colons which favours an environmental cause for the differences in strength in developing later in life. There were, however, only three

colons in the Kampala group. Larger numbers would be needed to prove conclusively the proposal that it is environmental factors such as diet and not genetic factors that are responsible for the differences in strength between the two groups. Other tissues could also be studied to determine whether there are any genetic differences in connective tissue.

The possible reasons for the Edinburgh colons tending to be thicker than those from Kampala are legion but include differences in mucosa, submucosa, muscle and serosal layers due to a number of causes such as hypertrophy, hyperplasia, oedema, degeneration or autolysis of any or all of the colonic wall elements. It is tempting to theorise that the African bowel is thinner because it requires to generate less pressure to propel the faecal mass and therefore the muscular layers are less well developed. Histological and electron-microscopic studies would help to test this theory. The increased strength of the Kampala colons is compatible with a difference in collagen but it is not known whether this difference is qualitative or quantitative.

NEONATAL AND INFANT COLONS.

The small numbers meant that non-parametric statistical analysis had to be carried out using Wilcoxon Rank Sums. There was sufficient variation, particularly in tensile strength and burst strength measurements to make statistically significant results hard to obtain without larger numbers.

The crucial finding was that there was no difference between Edinburgh and Kampala neonatal colons other than in the transverse colon which was stronger in the Kampala group. The small numbers, especially in the Kampala group, limit the confidence with which one can state that at birth there was no difference in the mechanical properties of the colon between the two races. The other limitation was that even in the Edinburgh group there

was gestational age ranges of 24 to 41 weeks. Children's colons were simply not available in nicely clustered age groups. Nonetheless, these results are consistent with the theory that both races start off equal and that the differences between them in adult life are acquired rather than hereditary.

The increase in thickness and internal diameter after birth was undoubtedly due to growth. The increase in width at burst without a similar increase in percentage elongation suggests that growth was responsible rather than an inherent change in the structure of the colonic wall.

The reduced stress relaxation in the descending colon after birth was probably a chance result since there was no trend in any other region of the colon.

The tensile strength of the neonatal and children's colons tended to be greater than that of the adults (Tables A1-4, Figure 19). The burst stress increased into early adult life (Tables A1-4, Figure 18) due to an increasing mass of colonic tissue with growth. It is remarkable, however, that the collagen of the colonic wall and possibly of other tissues too is strongest *in utero* and the first few months of life. The strongest colons tested in the whole study belonged to the five and nine month old babies.

The neonatal colons, particularly 24 to 30 weeks gestational age, were similar in dimensions to the rat colon. The human colons were three to four times as strong which implies species differences at least in the arrangement of collagen bundles if not also in the structure of the collagen itself.

DIVERTICULAR DISEASE.

There was no evidence to suggest that the Edinburgh colon with diverticular disease was any different mechanically than the Edinburgh colon without diverticular disease. The colons with diverticula only had mild to moderate disease without obvious muscle thickening and contraction such as was evident in the operative specimens. It is tempting to suggest that whatever damage there is to the colon in diverticular disease occurs throughout life due to many years and decades of low-fibre eating associated with high intra-luminal pressures. The average colon from Edinburgh is thus likely to be 'pre-diverticular' by the age of 50. The muscular changes associated with diverticular disease have been well described (Hughes, 1969). Collagen changes are reflected in the significantly lower tensile strength of the Edinburgh group of colons throughout adult life. The sigmoid colon was also the part of the colon least capable of expansion as well as being the weakest. The distal colon in Kampala also had a greater capacity for expansion (width at burst) than in Edinburgh. The arrangement of collagen fibres may be different between the two races rather than the strength of the fibres themselves, or else, the amount of collagen may be different. Further elucidation of these points awaits a detailed microscopic comparison of the African and Western colons.

STATIC MECHANICS APPLIED TO THE COLON.

The colon is a muscular tube. Although its dimensions continually vary with muscular contraction and distension by faeces and flatus, static mechanical considerations still have some application to its mechanical properties.

The radical force balance acting as a section of bowel wall may be simplified (see Appendix C for fuller explanation and Caro *et al*, 1978) according to the formula :

$$p_i r_i - p_e r_e = Sh$$

where p_i is the internal pressure

r_i the internal radius (half the internal diameter)

p_e is the external pressure (approximately equal to atmospheric pressure)

r_e the external radius (r_i + thickness)

h is the thickness of the colon

s the circumferential or hoop stress of the colon.

The values obtained in this study for the internal diameter and thickness of the colon allow us to calculate the circumferential stress. Painter (1975) reported that the basal pressure in the human colon is 5-10 mmHg above atmospheric pressure. Atmospheric pressure is 10^5 Nm^{-2} and 5 mmHg is equal to 650 Nm^{-2}.

Example :

Kampala sigmoid colon aged 30-39.

Internal radius 15 mm (0,015 m), thickness 1,5 mm (0,0015 m), assume internal resting pressure of 5 mmHg (100,650 Nm^{-2}).

$$\frac{(100{,}650 \times 0{,}015) - (100{,}000 \times 0{,}0165)}{0{,}0015}$$

$$= S = -9{,}4 \times 10^4 \ Nm^{-2}$$

The circumferential stress here is negative which means there is a compressive rather than tensile stress in the bowel wall at rest. A

compressive stress means that the bowel tube would collapse if restraints such as faeces did not hold it open.

The three variables affecting the circumferential stress are the internal radius, the wall thickness and the internal pressure. The atmospheric pressure will be constant if one remains at sea level. A reduction in internal radius or an increase in wall thickness will increase the compressive circumferential stress (increase the negative value). Both these changes occur in diverticular disease (Morson, 1963). An increase in internal pressure will reduce the compressive circumferential stress, but high pressures are required before the value of the stress would be positive (ie. tensile). Reference to Table XXXXII shows the equation solved for a range of dimensions and pressures.

Within the range of pressures normally generated in diverticular disease, ie. up to 90 mmHg (Painter, 1975), the circumferential stress is always compressive. The changes of muscle thickening and contraction of the colon increase the static circumferential stress. Fibrosis and scarring of the colon associated with longstanding or severe diverticular disease would make the colon less distensible. Morson (1963) reported that there is increased folding of mucosa of the colon in diverticular disease since the wall contracts with resultant excess mucosa. This leaves mucosa available to be squeezed out through the other layers of the colonic wall. Painter's (1975) analogy of a fist squeezing a lump of clay which then herniates through the gaps between the fingers is therefore consistent with the static mechanics inherent to the changes of diverticular disease since there is excess mucosa and a greater compressive circumferential stress.

TABLE XXXXII. **Calculated values of circumferential stress under different conditions.**

Internal pressure	Internal radius	Wall thickness	Circumferential stress	Relevance
5 mmHg	15 mm	1,5 mm	$-9,4 \times 10^4$ Nm^{-2}	Kampala group sigmoid, 30 year old, basal
15 mmHg	15 mm	1,5 mm	$-8,1 \times 10^4$ Nm^{-2}	Kampala group sigmoid, 30 year old, stimulated
15 mmHg	9 mm	1,5 mm	$-8,8 \times 10^4$ Nm^{-2}	Edinburgh group 60–69 year old, sigmoid, stimulated, r_i reduced
15 mmHg	15 mm	2,0 mm	$-8,5 \times 10^4$ Nm^{-2}	(hypothetical sigmoid, increased thickness)
70 mmHg	5 mm	3,0 mm	$-8,5 \times 10^4 Nm^{-2}$	(hypothetical sigmoid, diverticular disease, stimulated)
5 mmHg	5 mm	3,0 mm	$-9,9 \times 10^4$ Nm^{-2}	(hypothetical sigmoid, diverticular disease, basal)
5 mmHg (guess)	3 mm	0,6 mm	$-9,6 \times 10$ Nm^{-2}	Rat colon

The increased negative value when solving the equation for the circumferential stress when the internal radius is small is another way of stating the law of Laplace $P = \frac{Sh}{r_i}$. Thus, the pressure required to distend a spherical structure is greatest when the radius is small. This may be easily proven by blowing up a balloon. It is always hardest to get the distension started.

The circumferential stress in a tubular structure is twice the longitudinal (Gordon, 1978) thus, the values obtained by calculating the circumferential stress may easily be converted to longitudinal stress by halving.

The colon is not a static structure. Thus, much of the theoretical arguments I have applied from static mechanics are limited. Smooth muscle contraction and relaxation with continuing pressure changes makes the colon a dynamic structure, but nonetheless, the principles provide a framework from which the mechanical forces acting on the bowel may be understood.

Conclusions.

1. The mechanical properties of both the rat and human colon may be tested by cutting intact rings and stretching these in the transverse axis of the bowel.

2. The colon may be stored in salt for at least 28 days before testing without significantly altering its mechanical properties.

3. Irradiation with 2,5 megarads over 9 hours did not alter the mechanical integrity of the tissue.

4. The rat colon has a tensile strength of around 50 g/mm² which places it between the dog and the cat. The rat colon increased in strength from proximal to distal, although the rectum was weaker than the colon. The pre-strain was 10% and the rat colon was capable of stretching to around 200% of its original dimensions.

5. The strength and ability to stretch fell in extreme old age in the rat, although strength increased in the first year of life.

6. Gender did not affect the mechanical properties of either rat or human colon.

7. The tensile strength of the human colon was greatest in infancy, declining throughoutlife.

8. The tensile strength was greater in the proximal colon than distal colon.

9. The ability of the colon to stretch increased markedly in the first few years of life and then remained constant in the proximal colon. This ability declined with age in the sigmoid region. The human colon is capable of stretching to at least 150-200% of its original dimensions.

10. Viscoelastic properties remained unchanged throughout life in the post mortem colon.

11. There was no difference in mechanical properties between Kampala and Edinburgh neonatal colons.

12. Kampala colons were stronger than Edinburgh ones, throughout adult life.

13. The distal colon but not the proximal had a greater capacity for stretch in the Kampala group compared with the Edinburgh group.

14. Viscoelastic properties were similar in both race groups.

15. Colons with mild to moderate diverticular disease were similar to age and race matched counterparts.

16. Colonic specimens removed at operation appeared similar to post mortem colons in terms of their mechanical properties other than the operative specimens being thicker.

17. Applying static mechanical formulae for the stresses acting on the bowel wall the Edinburgh group of colons appeared to experience greater compressive stresses in the wall of the bowel which might encourage the herniation of mucosa through the colonic wall.

18. The differences between Edinburgh and Kampala colons lend strong support to the theory that environmental factors such as diet are more important than genetic ones in the aetiology of diverticular disease.

19. The wider, more "stretchy", sigmoid colon in the Kampala group is consistent with the high incidence of sigmoid volvulus in that area.

Appendix A.

Tables A1-4 show means ± standard deviation for each measurement by age group and race. These groupings were not the basis of the statistical analysis since each individual measurement was plotted on the regression graph.

TABLE A1. Means ± standard deviations for each measurement made for Edinburgh and Kampala ascending colons.

Age Group (yrs)		Burst Strength (g)	Cross Sectional Area (mm^2)	Tensile Strength (g/mm^2)	Internal Diameter (mm)	Width at Burst (mm)	Percentage Elongation	Stress Relaxation
0–1	E	1391 ± 1262	8,0 ± 2,9	150,0 ± 81,9	15,1 ± 10,7	32,3 ± 21,5	120,7 ± 59,6	0,186 ± 0,022
	K	1752 ± 212	7,0 ± 1,4	252,1 ± 20,6	9,0	20,2 ± 1,1	125,0 ± 11,8	0,170 ± 0,018
1–15	E	1850	17,0	108,8	27,0	77,0	185,2	0,166
	K	1200	14,0	85,7	83,0	169,0	103,6	0,145
16–29	E	1547 ± 737	16,2 ± 8,3	110,5 ± 67,4	60,6 ± 13,8	134,3 ± 9,1	131,6 ± 59,5	0,156 ± 0,045
	K	2529 ± 998	15,2 ± 3,3	164,1 ± 40,3	51,0 ± 11,3	137,7 ± 15,1	179,1 ± 67,2	0,166 ± 0,005
30–39	E	1065	M	M	45,0	120,5	167,8	0,136
	K	1570 ± 501	15,25 ± 2,3	101,6 ± 19,5	61,9 ± 7,0	153,8 ± 21,0	152,6 ± 53,8	0,153 ± 0,026
40–49	E	1145 ± 168	21,3 ± 3,8	54,7 ± 5,3	34,3 ± 18,2	136,0 ± 12,2	452,5 ± 450,5	0,191 ± 0,028
	K	1849 ± 780	17,3 ± 5,7	111,6 ± 42,2	31,7 ± 7,8	123,7 ± 42,0	304,1 ± 139,5	0,188 ± 0,010
50–59	E	1020 ± 511	13,6 ± 1,2	73,9 ± 35,8	53,3 ± 14,4	127,8 ± 43,1	137,8 ± 32,3	0,175 ± 0,028
	K	M	M	M	M	M	M	M
60–69	E	1352 ± 840	20,0 ± 5,6	63,5 ± 27,0	30,3 ± 15,4	124,5 ± 31,3	351,1 ± 153,5	0,184 ± 0,019
	K	1775 ± 177	12,8 ± 3,2	145,5 ± 50,2	52,0 ± 31,1	127,2 ± 4,6	201,3 ± 189,1	0,151 ± 0,053
70+	E	1503 ± 673	17,6 ± 4,2	89,4 ± 45,1	40,1 ± 14,3	122,4 ± 14,5	244,5 ± 143,1	0,187 ± 0,020
	K	M	M	M	M	M	M	M

E = Edinburgh
K = Kampala

TABLE A2. Means ± standard deviations for each measurement made for Edinburgh and Kampala transverse colons.

Age Group (yrs)		Burst Strength (g)	Cross sectional Area (mm^2)	Tensile Strength (g/mm^2)	Internal Diameter (mm)	Width at Burst (mm)	Percentage Elongation	Stress Relaxation
0–1	E	1172 ± 1011	7,7 ± 3,5	144,5 ± 52,3	16,7 ± 11,0	29,0 ± 19,8	95,3 ± 55,8	0,205 ± 0,017
	K	1548 ± 356	7,0 ± 1,2	223,7 ± 24,4	13,0 ± 4,6	24,0 ± 7,8	88,0 ± 46,8	0,187 ± 0,012
1–15	E	1835	9,0	203,9	40,0	87,0	117,5	0,139
	K	2175	12,0	181,2	54,0	119,0	120,4	0,172
16–29	E	1689 ± 531	16,0 ± 4,3	105,4 ± 21,2	43,8 ± 10,4	114,2 ± 6,7	174,4 ± 74,2	0,161 ± 0,039
	K	2537 ± 530	15,3 ± 3,2	165,6 ± 4,7	41,3 ± 18,9	129,2 ± 28,4	239,1 ± 100,1	0,171 ± 0,013
30–39	E	650	11,0	59,1	68,0	126,0	85,3	M
	K	1457 ± 574	12,5 ± 2,0	116,3 ± 45,0	62,7 ± 13,2	129,7 ± 9,3	116,0 ± 56,6	0,159 ± 0,026
40–49	E	1021 ± 190	20,7 ± 10,8	54,9 ± 15,7	32,8 ± 19,6	124,5 ± 6,8	458,7 ± 461,4	0,205 ± 0,006
	K	1695 ± 400	18,2 ± 3,3	97,4 ± 36,9	27,7 ± 4,1	110,2 ± 39,0	319,6 ± 220,2	0,186 ± 0,008
50–59	E	950 ± 229	16,7 ± 3,5	59,9 ± 25,1	30,3 ± 9,7	106,3 ± 18,6	272,2 ± 130,5	0,202 ± 0,036
	K	1125	13,0	86,5	49,0	122,5	150,0	0,164
60–69	E	1508 ± 991	15,5 ± 3,3	104,1 ± 82,1	28,5 ± 6,9	108,1 ± 11,2	294,5 ± 91,1	0,175 ± 0,032
	K	1450 ± 353	14,5 ± 7,1	120,2 ± 83,0	28,5	113,0 ± 28,3	226,3	0,174 ± 0,027
70+	E	942 ± 277	18,2 ± 3,1	53,4 ± 20,0	31,8 ± 9,3	106,8 ± 10,0	273,4 ± 165,6	0,190 ± 0,009
	K		M	M	M	M	M	M

E = Edinburgh
K = Kampala

TABLE A3. Means ± standard deviations for each measurement made for Edinburgh and Kampala descending colons.

Age Group (yrs)		Burst Strength (g)	Cross sectional Area (mm^2)	Tensile Strength (g/mm^2)	Internal Diameter (mm)	Width at Burst (mm)	Percentage Elongation	Stress Relaxation
0–1	E	1206 ± 1001	6,4 ± 3,1	172,8 ± 60,9	13,4 ± 7,9	28,4 ± 17,6	118,6 ± 65,0	0,178 ± 0,023
	K	1308 ± 321	6,3 ± 1,5	222,3 ± 98,2	13,0 ± 4,6	25,5 ± 12,8	94,4 ± 87,4	0,190 ± 0,009
1–15	E	1350	11,0	122,7	17,0	59,5	250,0	0,164
	K	1800	13,0	138,4	40,0	81,0	102,5	0,166
15–29	E	1838 ± 635	19,6 ± 6,7	95,6 ± 27,8	30,0 ± 6,4	86,9 ± 9,9	202,4 ± 85,7	0,198 ± 0,016
	K	2100 ± 319	15,0 ± 3,6	146,6 ± 43,9	40,0 ± 2,0	105,5 ± 3,9	164,5	0,159 ± 0,013
30–39	E	1050	12,0	87,5	65,0	98,5	51,5	M
	K	1594 ± 589	15,0 ± 2,5	110,3 ± 50,4	46,3 ± 7,4	112,7 ± 10,1	147,7 ± 35,6	0,176 ± 0,006
40–49	E	868 ± 163	22,3 ± 5,8	39,8 ± 8,9	26,7 ± 11,3	91,8 ± 17,6	278,4 ± 121,3	0,203 ± 0,029
	K	1858 ± 520	23,5 ± 5,4	80,5 ± 24,5	18,3 ± 5,7	105,8 ± 25,5	494,1 ± 109,9	0,201 ± 0,004
50–59	E	1275	19,0	67,1	20,0	102,5	412,5	0,166
	K	1150	14,0	82,0	47,0	93,5	98,9	0,197
60–69	E	1133 ± 272	20,75 ± 6,1	61,0 ± 31,8	19,5 ± 8,1	82,3 ± 18,2	365,5 ± 151,1	0,185 ± 0,014
	K	1419 ± 457	14,5 ± 6,4	100,7 ± 13,1	39,2 ± 15,2	101,2 ± 18,0	169,3 ± 58,3	0,194 ± 0,027
70+	E	1064 ± 161	15,3 ± 3,6	73,5 ± 25,4	23,1 ± 8,3	86,5 ± 10,8	250,0 ± 62,2	0,182 ± 0,011
	K	M	M	M	M	M	M	M

E = Edinburgh
K = Kampala

TABLE A4. Means ± standard deviations for each measurement made for Edinburgh and Kampala sigmoid colons.

Age Group (yrs)		Burst Strength (g)	Cross sectional Area (mm^2)	Tensile Strength (g/mm^2)	Internal Diameter (mm)	Width at Burst (mm)	Percentage Elongation	Stress Relaxation
0–1	E	1157 ± 692	8,7 ± 3,2	130,8 ± 48,9	13,6 ± 7,8	33,2 ± 19,0	132,3 ± 45,2	0,192 ± 0,024
	K	1135 ± 92	6,5 ± 0,7	174,9 ± 4,9	15,0 ± 5,7	23,0 ± 10,6	50,7 ± 13,9	0,213 ± 0,016
1–15	E	1875	14,0	133,9	23,0	60,5	163,0	0,170
	K	2325	14,5	160,3	33,0	118,5	259,1	0,171
16–29	E	1882 ± 869	21,6 ± 3,6	87,2 ± 38,9	34,8 ± 11,3	100,8 ± 16,4	206,3 ± 77,7	0,182 ± 0,021
	K	2326 ±1265	20,3 ± 3,1	122,7 ± 83,0	30,0 ± 7,2	131,0 ± 22,6	369,9 ± 207,3	0,175 ± 0,011
30–39	E	900	13,0	69,2	57,0	93,0	63,2	0,152
	K	1498 ± 475	15,0 ± 3,1	103,1 ± 33,9	49,3 ± 15,0	123,4 ± 10,9	170,6 ± 78,7	0,165 ± 0,014
40–49	E	1035 ± 344	25,0 ± 8,5	44,1 ± 17,1	24,0 ± 7,2	93,7 ± 11,8	307,3 ± 84,9	0,205 ± 0,013
	K	1486 ± 457	22,7 ± 4,0	67,6 ± 28,3	26,3 ± 4,0	125,1 ± 32,3	380,1 ± 140,4	0,187 ± 0,016
50–59	E	846 ± 127	22,7 ± 12,7	43,8 ± 19,6	25,3 ± 9,1	86,7 ± 16,6	257,4 ± 69,5	0,217 ± 0,011
	K	1100	25,0	44,0	20,0	86,0	330,0	0,189
60–69	E	1122 ± 107	28,5 ± 7,3	41,1 ± 8,9	18,3 ± 16,1	79,1 ± 23,0	507,2 ± 351,2	0,170 ± 0,020
	K	1567 ± 152	14,75 ± 7,4	118,7 ± 49,5	41,0 ± 12,7	110,7 ± 23,0	174,7 ± 29,2	0,173 ± 0,009
70+	E	1301 ± 704	23,0 ± 7,2	60,2 ± 31,6	23,5 ± 12,9	78,5 ± 11,5	302,9 ± 169,6	0,188 ± 0,017
	K	M	M	M	M	M	M	M

E = Edinburgh
K = Kampala

Appendix B.

Computer programme used to convert the stress relaxation curved regression line to a straight line of ratio of stress to initial stress against log time (language : basic).

```
 5 ! *****GRAPH PLOT*****
10 DIM X(32),Y(32),Z$[20],R$[20
   ]
15 PEN 1 @ SCALE LGT(.2),LGT(20
   0),-.3,1.4 @ LDIR 1
20 IOBUFFER Z$
25 ON KEY# 4,"END" GOTO 275
30 CLEAR @ DISP "WHAT IS THE SC
   ALE OF THE TRACING(mm/min)"
   @ INPUT L
35 LET N,I1=1 @ X1=0 @ GCLEAR
40 DISP @ DISP "PLACE TRACING O
   NTO TABLET &"
45 DISP "PRESS CURSOR AT POINT
   OF ORIGIN"
50 I=0 @ GOSUB 380 @ BEEP
60 V=0 @ CLEAR @ DISP "ALIGN GR
   APH BY PRESSING CURSOR  ON T
   HE OPPOSITE"
65 DISP "END OF X AXIS (ORIGIN
   OF NEXT SECTION)" @ DISP
70 I=31 @ DISP "PLEASE ENTER PO
   INT" @ GOSUB 380
75 S1$="SHIFT" @ S2$=" X AXIS"
   @ GOSUB 550
80 IF Y(I)<=Y(0)+5 AND Y(I)>=Y(
   0)-5 AND V=0 THEN GOSUB 395
   @ GOTO 135
85 IF Y(I)<=Y(0)+5 AND Y(I)>=Y(
   0)-5 AND V>0 THEN GOSUB 395
   ELSE 70
90 V=0
95 DISP "DOUBLE CHECK ORIGIN PO
   SITION" @ I=32 @ GOSUB 380
100 IF X(I)>X(0)+5 THEN BEEP @ D
   ISP S1$;S2$;(X(I)-X(0))/10;"
   mm LEFT"
105 IF X(I)>X(0)+5 THEN V=V+1
110 IF X(I)<X(0)-5 THEN BEEP @ D
   ISP S1$;S2$;(X(0)-X(I))/10;"
   mm RIGHT"
115 IF X(I)<X(0)-5 THEN V=V+1
120 GOSUB 550 @ X=X(0) @ Y=Y(0)
125 IF X(I)<=X+5 AND X(I)>=X-5 A
   ND Y(I)<=Y+5 AND Y(I)>=Y-5 A
   ND V>0 THEN GOSUB 395 @ GOTO
    60
130 IF V>0 THEN 95
135 DISP @ DISP "TRACING ALIGNED
   "
140 IF N>1 THEN GRAPH @ GOTO 245
145 DISP @ DISP "PRESS AT TOP OF
    REFERENCE PEAK"
150 I=1 @ GOSUB 380 @ BEEP
155 R=(Y(1)-Y(0))/10
160 GCLEAR @ XAXIS 0 @ YAXIS LGT
   (.4),.1,0,1.09
165 PEN -1 @ MOVE LGT(.2),0 @ DR
   AW LGT(.4),0
170 PEN 1 @ FOR I=10 TO 180 STEP
    10
```

```
175 IF I<180 AND I>120 THEN 190
180 IF I=60 OR I=120 OR I=180 TH
    EN MOVE LGT(I),.04 @ IDRAW 0
    ,-.08 @ GOTO 190
185 MOVE LGT(I),.02 @ IDRAW 0,-.
    04
190 NEXT I
195 FOR I=1 TO 3
200 MOVE LGT(60*I),-.2 @ LABEL V
    AL$(I)
205 NEXT I
210 FOR I=.1 TO 1 STEP .1
215 MOVE LGT(.25),I-.03 @ LABEL
    VAL$(I)
220 NEXT I
225 MOVE 0,-.2 @ LABEL "TIME (mi
    n)"
230 LDIR 90 @ MOVE LGT(.24),0 @
    LABEL "RATIO TO REF PEAK"
235 LDIR 1 @ MOVE 0,1.1 @ LABEL
    "ENTER POINTS. PRESS"
240 MOVE 0,1 @ LABEL "KEY#4 WHEN
     FINISHED"
245 IF N>1 THEN X=X1 ELSE X=0
250 FOR I=I1 TO 30
255 I1=I @ BEEP 10,100 @ GOSUB 3
    80
260 X(I)=6*(X+ABS(X(I)-X(0)))/L
    @ Y(I)=(Y(I)-Y(0))/(10*R)
265 PENUP @ MOVE LGT(X(I))-.02,Y
    (I)-.0325 @ LABEL "+"
270 NEXT I
275 CLEAR @ BEEP 70,50 @ ALPHA @
     DISP I-1;"POINTS ENTERED" @
     DISP USING "2/"
277 X1=X1+ABS(X(0)-X(31))
280 DISP "ADD ANOTHER SECTION OF
     THE GRAPH(Y/N)";@ INPUT R$
285 IF R$[1,1]="Y" THEN N=N+1 @
    GOTO 40
290 IF R$[1,1]#"N" THEN BEEP @ G
    OTO 280
295 PRINT "REFERENCE PEAK HEIGHT
    =";R;"mm" @ PRINT USING "//"
300 PRINT " I       X       Y" @ PR
    INT
305 FOR I1=1 TO I-1
310 PRINT USING "DD,XX,4D.D,XX,.
    4D" ; I1,X(I1),Y(I1)
315 NEXT I1
320 GOTO 415
325 ! ***TABLET INPUT AREA***
330 DISP "TABLET I/O FAILURE";ER
    RL;ERRN
335 GOSUB 345
340 GOTO 355
345 SET TIMEOUT 7;4000 @ REMOTE
    708 @ LOCAL LOCKOUT 7 @ RETU
    RN
350 ON ERROR GOTO 325
```

```
355 IOBUFFER Z$ @ ABORTIO 7 @ Z$
    =""
360 TRANSFER 708 TO Z$ INTR ; DE
    LIM 10
365 ON ERROR GOTO 355
370 ENTER Z$ USING "#,#K" ; X(I)
    ,Y(I),Z
375 OFF ERROR @ RETURN
380 GOSUB 350 @ IF Z#0 THEN 380
385 GOSUB 350 @ IF Z=0 THEN 385
390 RETURN
395 FOR I2=20 TO 40
400 BEEP I2,20
405 NEXT I2
410 RETURN
415 ! ***LINEAR REGRESSION***
420 CLEAR @ DISP "COMPUTING!"
425 R1,R2,R3,R4,R5=0 @ N=I1-1
430 FOR I=1 TO N
435 X(I)=LGT(X(I))
440 R1=R1+X(I) @ R2=R2+Y(I)
445 R3=R3+X(I)*Y(I) @ R4=R4+X(I)
    ^2 @ R5=R5+Y(I)^2
450 NEXT I
455 R6=(R3-R1*R2/N)/(R4-R1^2/N)
460 R7=(R2-R6*R1)/N
465 R8=(R3-R1*R2/N)^2/((R4-R1^2/
    N)*(R5-R2^2/N))
470 CLEAR @ PRINT USING "//"
475 PRINT USING "K,D.4D" ; "r²="
    ,R8
480 PRINT USING "K,D.4D,K,DD.4D,
    K" ; "Y=",R7," + ",R6,"LGT(X
    )"
485 PENUP @ PEN -1 @ MOVE 0,1.1
    @ LABEL "ENTER POINTS. PRESS
    "
490 MOVE 0,1 @ LABEL "KEY#4 WHEN
     FINISHED"
495 PEN 1 @ MOVE LGT(.4),R7+R6*L
    GT(.4) @ DRAW LGT(200),R7+R6
    *LGT(200) @ WAIT 1500
500 CLEAR @ ALPHA @ DISP "LABEL
    GRAPH";@ INPUT R$
505 IF R$[1,1]="N" THEN 530
510 IF R$[1,1]#"Y" THEN BEEP @ G
    OTO 500
515 DISP "ENTER LABEL ( <=20 CHR
    S )" @ INPUT R$
520 ON ERROR GOTO 515 @ OFF ERRO
    R
525 MOVE LGT(1.5),1.05 @ LABEL R
    $
530 GRAPH @ PRINT USING "3/" @ C
    OPY @ PRINT USING "4/"
535 CLEAR @ ALPHA @ DISP "CONTIN
    UE PROGRAM WITH SAME SCALE(Y
    /N)";@ INPUT R$
540 IF R$[1,1]="Y" THEN V=0 @ GO
    TO 35
545 DISP @ DISP "FINI" @ END
550 IF Y(I)>Y(0)+5 THEN BEEP @ D
    ISP S1$;S2$;(Y(I)-Y(0))/10;"
    mm DOWN"
555 IF Y(I)>Y(0)+5 THEN V=V+1
560 IF Y(I)<Y(0)-5 THEN BEEP @ D
    ISP S1$;S2$;(Y(0)-Y(I))/10;"
    mm UP"
565 IF Y(I)<Y(0)-5 THEN V=V+1
570 RETURN
```

Appendix C.

STATIC MECHANICS APPLIED TO COLON

The colon is a muscular tube.

The static balance of forces acting on a small section of the wall of a tube is shown in Figure C (Caro *et al*, 1978). The net forces acting on this segment of bowel wall result from the normal stresses on its six faces. The three vectors of stress at righ angles to each other are balanced by stresses acting in the opposite direction. The three vectors are :

1. parallel to the long axis of the colon.
2. radially out from the centre.
3. tangential to the tube in a plane perpendicular to the axis.

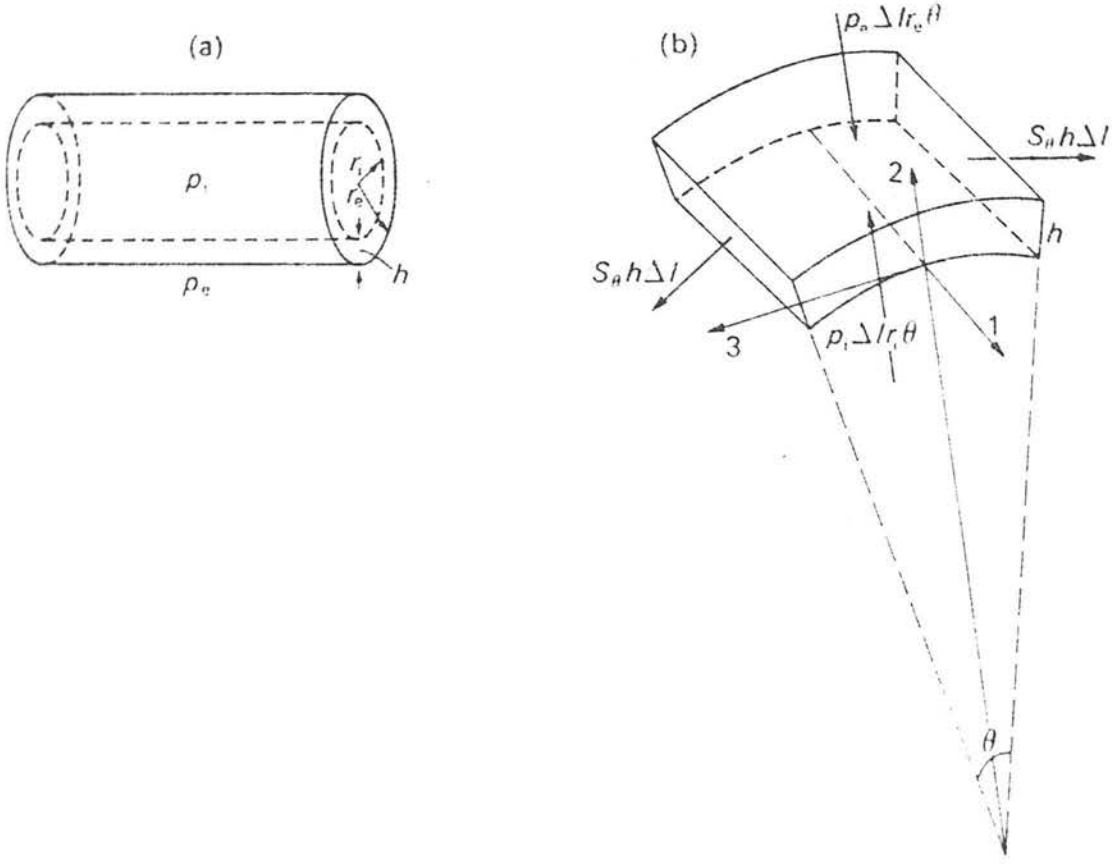


Figure C : Showing forces acting on a small section of the bowel wall at rest.

The force balance in each of these three directions is zero. However, because the two flat faces of the section of the wall incline towards each other and hence to the radial axis (2) they also have a component inwards of $2xs\vartheta h\ell \times \sin\frac{1}{2}\vartheta$. The other contributions to the radial components of stress are the internal and external pressures. The outward stress is the internal pressure (p_i) times the area of the curved inner face of the section ($\ell r_i \vartheta$). The inward stress is similarly the external pressure (p_e) which is approximately atmospheric times the area of the curved outer face ($\ell r_e \vartheta$). Thus, the radial force balance is :

$$p_i \ell r_i \vartheta - p_e \ell r_e \vartheta = 2s\vartheta h\ell \sin\tfrac{1}{2}\vartheta$$

If the section of wall we are studying is small then $\sin\frac{1}{2}\vartheta$ is approximately equal to $\frac{1}{2}\vartheta$ (this is accurate within 1% for values of $\frac{1}{2}\vartheta$ up to 0,24 rads or about 14°). Thus $\ell\vartheta$ can be cancelled from either side of the equation leaving us with :

$$p_i r_i - p_e r_e = s\vartheta h.$$

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