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TECHNICAL NOTE

RANKING THE FRACTURE TOUGHNESS OF THIN MAMMALIAN SOFT TISSUES USING THE SCISSORS CUTTING TEST

Barry P. Pereira,*† Peter W. Lucas‡ and Teoh Swee-Hin¶

*Department of Orthopaedic Surgery, The National University of Singapore, 10 Lower Kent Ridge Road, Singapore 119074, Singapore; ‡Department of Anatomy, Faculty of Medicine, Li Shu Fan Building, The University of Hong Kong, 5 Sassoon Road, Hong Kong and ¶Centre for Biomedical Materials Application and Technology, The National University of Singapore, 10 Lower Kent Ridge Road, Singapore 119074, Singapore

Abstract—An instrumented pair of scissors with sharp high-carbon steel blades was used to measure the toughness of human and rat skin, human finger nails and bovine pericardium. Copyright © 1996 Elsevier Science Ltd.

Keywords: Essential work method; Fracture toughness; Mammalian soft tissue; Scissors cutting test.

INTRODUCTION

The tissues of any organism must have structural mechanisms for resisting fracture in order to withstand their environment. This resistance is at least partially quantified by measuring toughness, the energy required to make unit area of crack. The 'toughness' concept is recent (Griffith, 1921). As originally defined, it is restricted to materials that deform in a linear elastic manner. Non-linear elastic behaviour can be dealt with by the J-integral (Rice, 1968) but the theory of plastic fracture as required for understanding the fracture of viscoelastic materials is incompletely developed (Atkins and Mai, 1985). This matters because virtually all fracture tests do not measure toughness directly. Instead, they impart strain energy to a sharp-notched specimen and measure the loss of this energy when a crack extends from the notch in a controlled way. The assumption that all the lost energy is paying for crack growth is unlikely to be true in materials that can flow.

Thin mammalian tissues are usually subject to biaxial stress. When tested in uniaxial tension, they have a non-linear 'j-shaped' stress–strain curve (Mai and Atkins, 1989; Purslow, 1989). This behaviour has been attributed to the very low shear modulus of the ground substance between the collagen fibres in the connective tissue, which take the bulk of the tensile load (Gordon, 1978). This gives these tissues great resistance to cracking in tests such as trouser-tear or a single-edge notch tension (Isherwood and Williams, 1978). This resistance is likely to be due to the viscoelastic behaviour of the ground substance blunting the cracks (Mai and Atkins, 1989). However, to establish this, it is necessary to constrain crack sharpness. This can be done by using a razor blade (Lake and Yeoh, 1978) or the blades of a guillotine (Atkins and Mai, 1979) or scissors (Sim *et al*., 1993). The guillotine and scissors have the additional advantage that they do not calculate toughness indirectly by loading a specimen, thus storing strain energy within it, and then letting this pay for crack growth. Rather, they transfer the work of loading directly into crack growth (Atkins and Mai, 1979). This averts a major cause of concern with mammalian soft tissues, which is that they show large hysteresis when loaded and unloaded: much of the energy stored in them will not go into crack production.

The use of scissors have recently been advocated as a general toughness test for plant tissues (Choong *et al*., 1992; Lucas *et al*., 1995; Lucas and Pereira, 1990). Plant tissues do not crack-blunt though and the scissors test can produce similar values to other tests (leaves—Lucas *et al*., 1991; wood—Lucas, pers. comm.). The value of cutting tests on mammalian soft tissues may lie in establishing the resistance of tissues to sharp cracks, which is important in surgery and industrial accidents, and in ranking soft tissues in toughness. We attempt to demonstrate this here.

THEORY

Crack growth proceeds when the energy available from the release of stored potential strain energy is equal or exceeds the critical value required to create a new fracture surface (Griffith, 1921; Irwin, 1957). In a displacement controlled testing machine, stable cracking proceeds when

$$\frac{dR}{dA} \geqslant \left(\frac{\partial G_c}{\partial A}\right)_u,$$

where dR/dA is the rate of change of toughness with crack area and $(\partial G_c/\partial A)_u$ is the rate of change of strain energy at constant cross-head displacement u (provided by external work) and R is the work of fracture of the material.

In physical terms, G is the work required to propagate a crack by unit area, i.e. it is the total work, W, expended in propagating a crack from a length, a_1, to a new crack length a_2. Assuming a controlled and slow (quasi-static) crack propagation, then G is at a critical value G_c at all stages. Hence, the total input work required to create a new fracture surface is

$$\delta W = G_c b\, \delta a,$$

where $b\,\delta a$ is the new incremental fracture area, δA_f, through which the crack has propagated. So it follows that the critical strain energy release rate can be obtained from

$$G_c = \left(\frac{\delta W}{\delta A_f}\right)_u.$$

This work input can be evaluated graphically from the area under a load–displacement diagram after fracture (Gurney and Hunt, 1967). However, for most materials, the input work can be divided into essential work, W_e and non-essential work, W_p. The former quantity involves fracture of the material in the fracture process zone whereas the latter is the non-reversible deformation in the outer plastic zone. The total area under the curve would therefore represent both, i.e.

$$W = W_e + W_p.$$

In cutting systems like a pair of scissors, the deformation involved in cutting is concentrated at the blade tip and has been reported to have negligible non-essential work in the bulk of the material remote from

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†Author to whom correspondence should be addressed.

the tip allowing W to be estimated (Atkins and Mai, 1979). Another important consideration is the estimation of the work due to friction of the cutting system during cutting. However, this can be estimated if two passes are made, one with the material in place and one with the material removed. The latter pass gives the work due to friction alone, assuming that the friction of the cutting system during cutting of a thin flexible material is equivalent to the friction when the material is not in place (Atkins and Mai, 1979). The coefficient of friction is low for mammalian tissues; hence friction can be neglected.

A pair of standard tailoring scissors was used. In each test, two passes, using identical parts of the blade, were made in the following order: (i) cutting (fracture) of the specimen and (ii) an empty pass. The work done, W_{ii}, in the empty pass (ii) was deducted from the work done, W_i, in pass (i) to give the net energy needed to cut (or fracture) the specimen, W.

MATERIALS AND METHODS

Test design

A pair of tailoring scissors (A220, Dragonfly, Korea) with sharp high-carbon steel blades (Lucas and Pereira, 1990), were attached at their handles to a shaft hanger fitted with ball-bearings (Vincent, 1992) and then mounted on a universal testing machine (DCS-5000, Shimadzu, Japan). One handle was attached to the moving cross-head while the other was attached to a fixed support (Fig. 1). The distance between the loading points at both handles to the fulcrum was equal and fixed. A stiff wire frame used to hold the material in position was constructed and fitted on to the handle of the upper blade. The specimens were placed on the wire frame between the opened pair of blades against the point of intersection. With displacement of the handles constrained in the vertical plane, the wire frame rotated counterclockwise always allowing the material to be centrally placed between the blades. A 500 N capacity load cell was connected to the upper handle of the scissors. The cross-head displacement rate was 30 mm min^{-1}, giving a travel rate of 0.4 mm s^{-1} of the instantaneous intersection point of the two blades in the horizontal plane. A fixed cross-head displacement of 20 mm was used, which gave a length of cut of 14.9 mm in the empty pass. The work done in the test was given by integrating the product of the force and displacement at 50 Hz with a data processor (Dataletty 401, Shimadzu, Japan) and plotted as a load–cross-head displacement curve. The fracture toughness or work of fracture, R, was calculated as the net external work needed to fracture the specimen divided by the cut area (i.e. the product of the measured cut length l and thickness b)

$$R = \left(\frac{W_i - W_{ii}}{lb}\right).$$

The actual length of cut made, l, was measured from the surface of the material with a vernier calliper (Mitutoyo Co., Tokyo, Japan) with ± 0.1 mm accuracy and the thickness, b, with a micrometer (Mitutoyo Co., Tokyo, Japan) with ± 0.01 mm accuracy. The tissue was pressed against a glass plate (0.95-mm thick) to ensure that the tissue was laid out flat prior to measuring. Three measurements were taken for each measure and a mean and standard deviation were calculated.

All tests were carried out at room temperature (23 ± 2°C) and at a humidity range of 50–70%.

Materials

Human skin samples were obtained from two cadavers (males, aged 70) from the dorsal and palmar aspects of the hand. These specimens were stripped of adipose tissue leaving only dermal and epidermal layers. Finger nails were also obtained from the same cadavers. Bovine pericardium fixed in 0.45% glutaraldehyde used for fabricating tissue heart valves were obtained from a local heart-valve manufacturing company (St. Vincent's Meditech, Singapore). These various tissues were prepared in strips of 20 × 40 mm. For the dorsal skin, two groups were tested by distinguishing between cutting along the circumferential (radial–ulnar) and longitudinal (proximal–distal) directions. For the skin tissue from the palmar aspect, cutting along the skin creases was differentiated from across the creases. For pericardial tissue, toughness in the circumferential and longitudinal (radial) directions was compared.

The abdominal skin of adult Sprague–Dawley rats, cleared of free hairs, was tested with hairdressing scissors (Dovo, Germany). These scissors have a very much lower work of closure than Dragonfly scissors. However, these works are consistent for both scissors, even though the force record for the Dragonfly showed marked fluctuations (Fig. 1). Toughness estimates on a standard material, No. 542 filter paper (Whatman, U.K.), are almost identical: for one layer (0.14 mm) of No. 542 paper, Dragonfly: 3,165($\pm$281) J m^{-2}; Dovo: 3,119($\pm$251) J m^{-2}. The sharpness of the scissors would have an effect on the measured work of fracture if thickness were greater than 1 mm. In this case, the sharpness, which was measured as the radius of curvature of the blade (0.5 μm for the Dragonfly and 1.6 μm for the Dovo scissors), did not have any significant effect on the measure of the work of fracture.

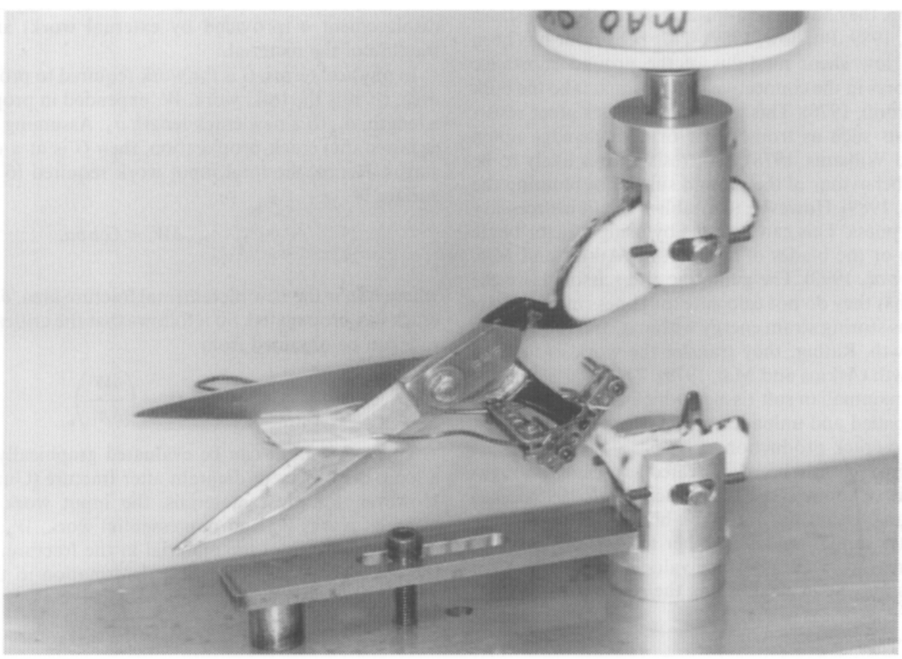

Fig. 1. Experimental set-up of the scissors cutting test comprising a pair of tailoring scissors mounted on a universal testing machine.

Atkins and Mai (1979) found that with the guillotine experiments, the work of fracture measured were about 12.7 $kJ\,m^{-2}$ for copier paper, relatively higher than that for No. 542 filter paper. We do not recommend using copier paper as a reference as it is usually filled with China clay—a powerful abrasive. The toughness of cellulosic materials depends on its thickness when this is less than 1 mm (Lucas *et al.*, 1995). Atkins and Mai (1979) did not find this in their experiments but Lucas and Pereira (1991) did.

RESULTS AND DISCUSSION

Typical load–displacement curves for the palmar and the dorsal skin are shown in Fig. 2. The curve was characterized by an initial slope that rose steeply (O–A). This represents the pre-load existing at the initial position of the scissors prior to each pass. In the initial phase, the blade tips deflect the surface of the material, resulting in the material storing energy (A–B). The wedge of the blade then cuts into the specimen and the elastic strain energy is fed to the cut surface (shear indentation). This results in a drop in force, indicated by the change in slope from the steep elastic slope to a more gradual slope (B–C). As the blade is angled into the material, there is a combined effect of shear indentation and a free running crack. The load increases with displacement as the applied load where the blades cuts into the material moves away from the fulcrum of the scissors. For different materials or tissues, a wide range of loads may be encountered. In this case using a 500 N load cell to measure loads of the range of 1 N may seem to compromise the accuracy. As a caution and to ensure a more consistent statistic of the results, it is recommended that a smaller capacity load cell be used, if available.

Table 1 summarizes the results. No significant differences were noted between the dorsal skin in the longitudinal and circumferential directions. Neither were there any difference between the palmar skin across creases and parallel to the creases. This would imply that the fibrous network in the dorsal and palmar skin generally has no preferred orientation in either of these directions. However, the toughness value of the palmar skin was found to be significantly greater than the dorsal skin. This could imply a difference in the quantity of collagen present. The result of Purslow (1983) on the trousers tearing of dorsally vs ventrally positioned rat skins are probably similarly explained. For the finger nails, the fracture toughness in the circumferential direction was greater than the longitudinal direction. This suggests that the arrangement of keratin in nails has a preferred orientation (Ditre and Howe, 1992; Dykyj, 1989). Cutting in the circumferential direction could have been cutting across the fibres while the longitudinal direction would mainly pass between the fibres (or across much fewer fibres). For the pericardial membrane treated with 0.45% buffered glutaraldehyde there was no significant difference between the radial and circumferential directions. This again implies a non-directional configuration and lends support to the fact that the glutaraldehyde buffered treatment not only acts as a sterilizing agent and reduces the tissue antigenicity but also stabilizes connective tissue by forming cross-links which are uniformly distributed within and between tropocollagen molecules (Purinya *et al.*, 1994). From our results on rat skins, it is notable that the values, regardless of orientation, are more than an order of magnitude lower than those of Purslow (1983). The only reasonable explanation is that crack-blunting, produced by the viscoelastic behaviour

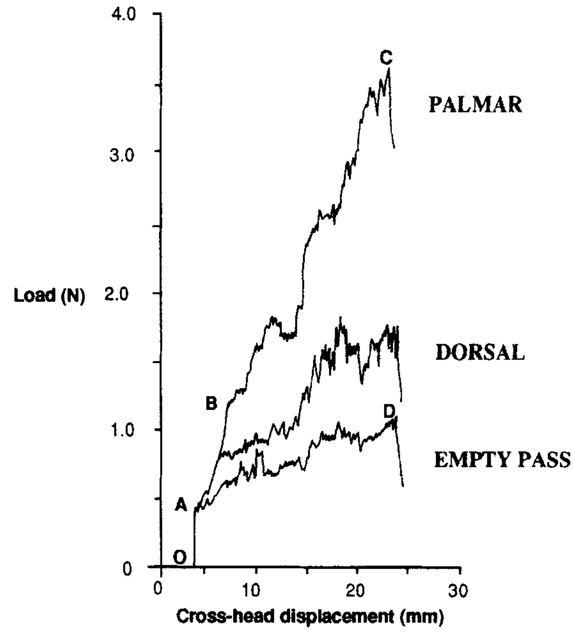

Fig. 2. Typical load–cross-head displacement curve obtained from the scissors test for the palmar skin (OABC) and the dorsal skin against the empty pass (OAD). The cross-head displacement was fixed at 20 mm which gave a length of cut of 14.9 mm in the empty pass.

Table 1. Fracture toughness values (mean ± S.D.) obtained from the scissors cutting test (a non-parametric Mann Whitney U-Wilcoxon Rank Sum test was used at a 0.05 level of significance)

Tissue tested	n	Mean thickness (mm)	Fracture toughness ($J\,m^{-2}$)	Statistics (non-parametric test used — Mann Whitney U-Wilcoxon Rank Sum Test. Treated as independent samples)	
Dorsal skin (hand)					
Longitudinal (proximal–distal) direction	4	0.55	1,777 ± 376	NS ($p = 0.77$)	
Circumferential (radial–ulnar) direction	4	0.69	1,719 ± 674		Significantly different ($p = 0.01$)
Palmar skin (hand)					
Along the skin creases	5	1.42	2,365 ± 234	NS ($p = 0.35$)	
Across the skin creases	5	1.34	2,616 ± 395		
0.45% *Glutaraldehyde fixed bovine pericardium*					
Longitudinal (radial) direction	8	0.25	1,263 ± 214		
Circumferential direction	8	0.29	1,160 ± 146	NS ($p = 0.51$)	
Finger nails					
Longitudinal direction	3	0.50	6,762 ± 2,958	Significantly different	
Circumferential direction	3	0.47	17,056 ± 2,428	($p = 0.02$)	
Abdominal skin of adult rats					
Random direction	12	0.7	588 ± 152		

Note: NS = not significant.

of the matrix of the connective tissue, was greatly restricted by the presence of the blade. The results show clearly that crack-blunting is the cause of the high toughness of such tissue and also that this is subverted, for example, by a surgeon's scalpel. Further work is needed to establish structural correlations of toughness in these tissues.

The scissors test is a quick and useful test for ranking the fracture toughness of thin flexible material as it is not limited by the size of the specimen (Choong *et al.*, 1992; Lucas *et al.*, 1995, Lucas and Pereira, 1990, 1991; Sim *et al.*, 1993). The blade localizes the applied stress to the crack tip and avoids any applied stress remote from the crack tip. Another advantage is that in scissoring, there is no need for grips because the work is concentrated at the crack tip. The test seems to provide an 'essential work of fracture' which is useful for ranking the fracture toughness properties of the material. It can potentially establish the general direction of fibres within these materials. The precise orientation of Langer's lines in connective tissue (Purslow, 1983) could be corroborated with this test. It appears to be the only type of test which can estimate the orthogonal toughness of tissue. If the crack is not driven, given the nature of the composite structure of the tissue, the crack will deviate, possibly with a zig-zag, towards the easiest (or least tough) path.

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