THE INTEROSSEOUS MEMBRANE IN RADIO-ULNAR DISSOCIATION

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In severe forearm injuries, the diagnosis of disruption of the interosseous membrane is frequently delayed and sometimes missed, giving difficulties in the salvage of forearm stability.

We studied the structure and function of the interosseous membrane in 11 cadaver preparations, using mechanical and histological analysis. Seven of the specimens tested in uniaxial tension sustained a mid-substance tear of the central band of the membrane at a mean peak load of 1038 ± 308 N. The axial stiffness was 190 ± 44 N/mm with elongation to failure of 10.34 ± 2.46 mm. These results provide criteria for the evaluation of reconstructive methods.

A preliminary clinical investigation of the use of ultrasound suggests that this may be of value in the screening of patients with complex fractures of the forearm, and for investigating the natural history of tears of the interosseous membrane.

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The management of severe fractures of the proximal radius is still a problem. When anatomical reconstruction of the fragments is not possible, primary excision of the radial head has been recommended for comminuted Mason type-III fractures.¹ The role of prosthetic replacement of the radial head is still controversial.^{2,3}

Longitudinal dissociation of the radius and ulna is probably related to rupture of the interosseous membrane (IOM) at the time of injury. If the radial head is then excised, there may be proximal radial migration and subluxation of the

distal radio-ulnar joint (Fig. 1) as described by Essex-Lopresti and others.^{4,5} This has been regarded as an infrequent complication of fracture of the radial head,⁶ but the consequences of missing the diagnosis may be important. Trousdale et al⁷ reviewed 20 patients with radio-ulnar dissociation and found that only five had been diagnosed at first presentation, and the delay to diagnosis averaged seven years in the others. An objective scoring system showed that only 20% of patients with a delayed diagnosis of a ruptured IOM had a satisfactory outcome, despite attempts at salvage.

The site, extent and capacity for healing of the ruptured IOM are unknown, but an attempt at reconstruction using a graft from the palmaris longus tendon has recently been described by Hotchkiss.⁸ We report a mechanical, histological and ultrasound evaluation of the IOM, under controlled conditions. We aimed to investigate the pathomechanics, assess diagnostic methods and determine criteria for reconstructive procedures.

MATERIALS AND METHODS

Mechanical testing of structural properties. We studied the forearms of 11 human cadavers, ranging in age from 32 to 84 years. None had previous upper-limb injuries. The specimens were stored fresh frozen at -20°C until testing, then thawed at room temperature. The skin, subcutaneous tissue and muscle were removed exposing the shafts of the radius and ulna with the linking IOM. The central thickened band of the IOM was easily identified, running from the radius proximally to the ulna distally. Approximately 75 mm of the diaphysis of each bone were resected together with the origin and insertion of the central band of the IOM. These samples were stored in a bath of 0.9% NaCl at 25°C .

We performed mechanical testing in uniaxial tension along the longitudinal axis of the forearm with an MTS 858 Mini-Bionix materials testing machine (MTS, Minneapolis, Minnesota). The specimens were fixed to custom-made jigs by pins placed through drillholes in the bones with a fixed gauge length of 50 mm for each specimen (Fig. 2). To reproduce the presumed clinical mechanism of the Essex-Lopresti lesion of the IOM, the radial jig was displaced longitudinally and proximally relative to the fixed ulnar jig

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Fig. 1a

Fig. 1b

Fig. 1c

Anteroposterior (a) and lateral (b) views of a neglected comminuted fracture of the radial head. At three months the bone fragments were excised because of elbow pain. The patient then developed severe wrist pain due to proximal migration of the radius with subluxation of the distal radio-ulnar joint (c).

at a displacement rate of 50 mm/min. This is much slower than displacement during an injury, but allows more accurate determination of the components of the load-displacement curve, and is a recognised standard for testing bone-ligament-bone specimens.⁹ Load was plotted against displacement until failure, the site and mode of which were noted. We recorded the peak load and the elongation and energy absorbed at peak load. The tensile stiffness was determined from the linear portions of the plotted curves (Fig. 3).

Fig. 2

Diagram of the test jig on an MTS materials testing machine. A tensile load was applied to the radius at 50 mm/min until failure, either of the bone or the central band preparation.

Histological analysis. After mechanical testing, the failed samples were fixed in 10% phosphate-buffered formalin for 48 hours, decalcified in 0.5 M EDTA at pH 7.5, then dehydrated and embedded in paraffin. A series of transverse slices 5 μ m thick were cut across the long axis of the forearm and stained with haematoxylin and eosin or Masson trichrome. The sections were studied under an Olympus BH2 light microscope at 10, 50 and 200 times magnification.

Ultrasound imaging. One cadaver forearm including the elbow and wrist joints was thawed overnight at room temperature. A standard radiograph was made with the forearm in full supination, using two percutaneous hypodermic needles as proximal and distal reference markers. The distance between the two markers was measured directly on the radiograph to provide correction for magnification.

Fig. 3

An example of the load-displacement curve. There is a linear region before yield and failure, which in this case occurred through the mid-substance of the membrane.

The forearm was gently warmed in an isotonic saline bath to 37°C and then imaged on an Acuson 128XP/10 ultrasonographic device (Acuson, Mountainview, California), using a 7 MHz linear-array transducer transversely across its volar surface to locate the radius, ulna and IOM. The interosseous distance was measured at several levels in the forearm and compared with radiological measurements.

After ultrasonography of the intact IOM, a longitudinal incision was made over the dorsal surface of the forearm, which was still under saline to prevent air entering the tissues and producing artefacts during imaging. The extensor muscles were bluntly dissected from the dorsal surface of the IOM to allow a longitudinal incision through its mid-substance using a scalpel blade. The skin was closed by a watertight subcuticular non-absorbable suture, and ultrasound imaging was repeated from its volar surface.

RESULTS

Anatomy. The central band of the IOM was easily defined and had a thickness varying from 0.5 to 1.85 mm, as measured with a micrometer. In all our specimens, the fibres were not in parallel alignment but fan-shaped, with differing relative fibre lengths and angles of origin from the radius to insertion on the ulna.

Failure in tension. During mechanical testing, four of the 11 specimens failed by fracture through an ulnar pin site before there was failure of the IOM. In the other seven specimens, an extensive mid-substance tear appeared, starting at the distal margin of the central band (Fig. 4). No specimen failed by avulsion from either bone.

The sigmoid shape of the load-displacement curve (Fig. 3) was a typical result of tensile testing of soft connective tissues at a moderate displacement rate. The mean peak load at mid-substance failure was 1038 ± 308 N, compared with 548 ± 138 N for the bony failures through a pin site. The correspondingly lower energy absorbed before failure

Fig. 4

Specimen of radius (above) and ulna after testing, showing an extensive mid-substance tear of the IOM, which originated at the distal margin of the central band (arrow).

through the ulna was probably due to the stress riser effect of the pin hole in relation to the geometry and quality of adjacent bone. It was still possible to plot load against displacement in all specimens, and the mean tensile stiffness, calculated from the linear portion of the curves, was 178 ± 47 N/mm. Other data are summarised in Table I.

Histological examination. Histological sections of the IOM showed that the bases of the triangular-shaped insertion zones were thicker than the mid-substance, blending intimately with the periosteum at its margins (Fig. 5a). Higher magnification showed a thin collagenous sheet with layers of fibres arranged in parallel separated by interstitial layers running at a slightly oblique angle (Fig. 5b). These fibres were attached to the underlying lamellar bone through a 'tidemark' which defined a zone of mineralised fibrocartilage as described by Cooper and Misol.¹⁰ There were few vascular channels in the membrane itself, but skeletal muscle fibre bundles were prominent, in close apposition to the membrane.

Table I. Mechanical properties of radio-IOM-ulnar samples

Sample	Mode of failure	Peak load (N)	Tensile stiffness (N/mm)	Elongation at failure (mm)	Energy absorbed (J)
1	Tear	1397	196.5	13.43	7.092
2	Tear	1507	217.8	9.35	5.802
3	Tear	934	272.8	11.22	4.597
4	Tear	811	153.4	5.70	2.626
5	Tear	651	151.4	12.14	2.077
6	Tear	941	185.4	9.99	3.785
7	Tear	1027	153.3	10.57	3.694
	Mean $\pm$ SD	1038 ± 308	190.0 ± 44.5	10.34 ± 2.46	4.239 ± 1.755
8	Fracture	660	212.5	6.64	1.210
9	Fracture	373	91.7	12.48	1.396
10	Fracture	500	164.5	3.10	0.887
11	Fracture	658	157.6	4.17	1.757
	Mean $\pm$ SD	548 ± 138	156.6 ± 49.7	6.60 ± 4.19	1.312 ± 0.363

Fig. 5a

Fig. 5b

Transverse sections of the IOM showing its broad-based insertion on to the radius (Masson trichrome; $\times 27$ (a)). At a higher magnification ($\times 108$) (b) interleaved layers of collagen fibres are seen at oblique angles entering their insertion into bone through a zone of mineralised fibrocartilage (arrow).

Ultrasound studies. Ultrasound examination showed that the IOM was easily visualised as a highly echogenic structure, distinct from the adjacent muscles and lying between the echoic shadows of the radius and ulna. It was possible to trace the IOM proximally and distally and to determine its thickness at several points. The central band region was well-localised, with a thickness of 1.5 to 1.8 mm (Fig. 6a), in contrast to the thinner distal part which had a thickness of approximately 0.8 mm (Fig. 6b). These ultrasonic estimates confirmed those obtained by direct measurement of the dissected IOM.

Serial ultrasound measurements of the interosseous distance (9.9 to 14.1 mm) were within 0.1 mm of the radiological estimates, showing a high level of agreement between techniques. After surgical incision of the IOM, the images confirmed this discontinuity at several levels (Fig. 6c). The lesion was seen as a hypoechoic trace, which was even more apparent on continuous real-time images obtained during rotation of the forearm.

DISCUSSION

The longitudinal radio-ulnar dissociation described by Essex-Lopresti represents part of a complex fracture-dislocation of the forearm. The critical element is failure of the central band of the IOM, but this may be masked until excision of the radial head. After this, there is instability of the whole radio-ulnar rotary mechanism, with relative apparent lengthening of the ulna at the wrist. Surgical procedures which attempt to restore neutral ulnar variance at the level of the distal radio-ulnar joint,¹¹ fail to address this instability and may give poor results. Even when the IOM is intact, the replacement of the radial head by silicone rubber prostheses has been shown to be mechanically inadequate, with insufficient stiffness to withstand normal loads across the elbow without deformation.^{3,12}

Moore, Lester and Sarmiento¹³ studied the axial stability of the distal radio-ulnar joint in cadavers. They attempt-

Fig. 6a

Fig. 6b

Fig. 6c

Transverse ultrasound images of the IOM in a cadaver forearm. Figure 6a – The thick central band (markers) can be readily distinguished from the surrounding muscles and bones (R = radius, U = ulna). Figure 6b – More distally, the membrane is thinner but is still visible. Figure 6c – After division of the membrane, the defect is obvious (arrow).

ted to reproduce Galeazzi lesions by creating elbow dislocations and diaphyseal fractures of both radius and ulna. They showed that osteotomy of the radius allowed axial movement of 3 mm; the addition of division of the triangular fibrocartilage allowed movement of 6 mm. An additional division of the central band of the IOM was associated with proximal migration of the radius of more than 10 mm.

In the intact forearm, there are practical difficulties in reproducing these lesions. We isolated the central band with its radial and ulnar insertions and tested it separately as a distinct structure. The load-displacement curve which we obtained indicated that it behaved structurally as a strong ligament. The strength and stiffness values which we found broadly agreed with those recently reported by Boardman et al,¹⁴ although they used a smaller specimen of the central band alone and performed their tensile testing along the fibre axis, rather than the axis of the forearm.

The elongation of about 10 mm which we found before failure tends to support previous biomechanical studies based on the serial sectioning of soft-tissue structures in the forearm,^{13,15}; these have associated an IOM tear with this amount of proximal radial migration. The loads causing mid-substance failure are of the same order of magnitude as those which were found by Frykman¹⁶ to result in distal radial fractures, and in the mid-range of those recently reported by Amis and Miller¹⁷ for fractures of the radial head. This implies that partial, low-grade tears or a degree of attenuation of the IOM may occur more often in forearm injuries than is generally recognised.

The diagnosis of a tear of the IOM is difficult in an acute clinical setting since pain arising from the distal radio-ulnar joint is commonly associated with proximal fractures even when the IOM is intact.^{18,19} Radiographs and intraoperative fluoroscopy have been used to assess resistance to axial stress,² but these rely on relatively imprecise visual estimation of radial migration. MRI has also been used to demonstrate a mid-substance tear,⁸ but this is an expensive investigation and is not universally available. In the leg, ultrasound has been shown to be accurate and sensitive for the diagnosis of tears of the tibiofibular IOM associated with fractures about the ankle,²⁰ but to our knowledge has not previously been used to image the IOM in the forearm. Our initial results indicate that, in association with conventional radiography, ultrasound may be useful in acute cases since it is relatively inexpensive, portable and can provide both static and dynamic images of the integrity of the ligament. We are now assessing this method prospectively.

Both the histological structure of the IOM and its attachments, and the pattern of disruption in experimental studies, make it likely that clinical failure is usually due to mid-substance tearing of the central band, rather than bony avulsion. The precise natural history of these complex injuries remains unknown and it may be that reconstruction of the radial head by internal fixation, or replacement by a

prosthesis will prevent proximal migration of the radius and consequent instability and degeneration of the distal radio-ulnar joint. It seems possible that unless the IOM heals, its role in load transfer from wrist to elbow may be compromised.²¹ There is also some evidence that healing with a relative change in the length of the IOM may affect forearm rotation.^{22,23}

There are theoretical advantages for primary repair, augmentation or reconstruction of the central band of the IOM in association with fixation of a fractured radius in the control of residual longitudinal instability. Replacement of the radial head with a prosthesis is essentially a salvage procedure. As yet, methods of repair of the IOM or its reconstruction have not been developed. Our biomechanical data along with those of Regan et al²⁴ suggest that a graft of the palmaris longus tendon, shown to fail at approximately 350 N, may not be strong enough to act as an effective substitute at high physiological loads. Further work is needed to document the natural history and healing potential of the IOM, and to suggest appropriate reconstruction. The goals in the treatment of forearm fractures with radio-ulnar dissociation are to restore anatomical relationships, and to provide fixation stable enough to allow early active mobilisation and rehabilitation.

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