Fixation of canine tendons to metal

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For the purpose of developing a method to attach tendons directly to the prosthesis, canine supraspinatus tendons were attached in vitro to a metallic surface, using 3 different fixation devices: a spiked polyacetal washer (Synthes®), a spiked soft tissue fixation plate (Synthes®), and a newly designed Enhanced Tendon Anchor (ETA), which straddled the tendon with interlocking spikes oriented at a 20-degree angle. 2 methods were used: 1) the tendon was fixed directly to the metallic surface, or 2) a bone block containing the tendon insertion was fixed to the metallic surface. The specimens were tested for initial fixation strength in tension to failure; intact bone-muscle-tendon-bone units were used as controls.

Bone block fixations were stronger than direct tendon fixations when the spiked washer or the ETA was used; this was not true of the fixation plate. The ETA was stronger than the other techniques in ultimate strength in both direct tendon fixation and bone block fixation. The soft tissue fixation plate was found to be weaker than the other techniques in bone block fixation.

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Submitted 93-02-10. Accepted 93-11-05

Some endoprostheses now provide holes to suture soft tissue to the metal compression plates, or spiked plates, with or without porous coatings, at the insertion site (Chao and Sim 1985, Kotz et al. 1989). For reconstruction after tumor resection, the tendon is typically fixed directly to the prosthesis, because the bone serving as the tendon insertion site has to be resected to maintain safe surgical margins. In cases of revision surgery after failed total joint arthroplasty, the bone block at tendon insertions can usually be preserved and subsequently used for reattachment.

Data concerning the initial fixation strength of tendon insertion to implants are not yet available. Tendon attachment to bone, however, has been investigated. Consequently, a number of devices are in clinical use (Clancy et al. 1981, Hurson and Sheehan 1981, Shino et al. 1984, Kurosaka et al. 1987, Paulos et al. 1988, France et al. 1989). The limiting factor ub these devices has been the anchorage of the fixation device to the bone, rather than the fixation of the tendon to the device (Robertson et al. 1986, Bargar et al. 1987). Screw and washer fixation, as well as sutures, were consistently found stronger than staple fixations in in vitro studies (O'Carroll et al. 1983, Shino et al. 1984, Jones et al. 1987, Okuda et al. 1987, Straight et al. 1988, Hausmann et al. 1989). The purpose of this study was to test a new tendon fixation device for its in vitro performance in order to justify further investigation of this device in a living animal model.

Material and methods

The experimental model was the canine supraspinatus tendon. 60 intact motion units (scapula-muscle-tendon-humerus) from mixed-breed adult dogs weighing between 23 and 33 (27.6 ± 0.4) kg were used. Specimens were matched in animal weight, experimental limb (right or left), length of the muscle origin at the supraspinous fossa, and width or thickness of the tendon.

The supraspinatus tendon was detached from its insertion and reattached to a metal surface, using three different fixation devices (Figure 1). Each of the devices was used both for attachment of the bone block containing the tendon insertion and for direct tendon attachment. Therefore 6 groups, each containing 6 specimens, were tested (Table 1).

In all techniques, screws were applied under a controlled torque, measured by an electronic torque gauge (Newton Meter, Model 7000, DCI Inc., Olathe, Kansas) to assure comparable compressional forces underneath the device. The relationship between the torque applied and the morphological changes of the tissue which occurred underneath the device was evaluated in six pilot specimens evenly distributed among the fixation techniques (Table 1). A torque was considered adequate if all fixation devices (spikes, screws, pins) were fully buried in the tendon and morphological structures were not irreversibly altered (destruction of

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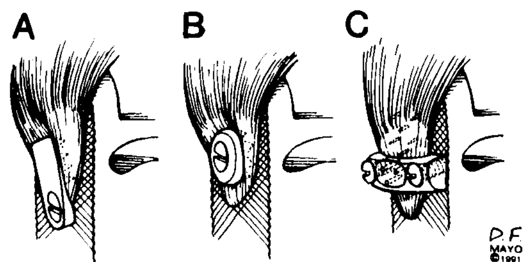

Figure 1. 3 techniques used for tendon fixation.
A. Soft tissue fixation plate (Synthes®).
B. Spiked washer (Synthes®).
C. Enhanced Tendon Anchor (ETA) (custom made).

Table 1. Experimental design and specimen preparation conditions for the mechanical pull-out test. No. of specimens used

Tendon attachment method	Pull-out test		Tightening torque test
	Bone block fixation	Tendon fixation	
Intact	18 (12[a], 6[b])		
Plate fixation	6[a]	6[a]	2
Washer fixation	6[b]	6[a]	2
ETA fixation	6[b]	6[a]	2

Muscle [a]fresh condition respecitvely [b]frozen condition.

cancellous bone trabeculae or shredding of soft tissues). The average torque for screw insertion to lower the fixation device onto the tendon was recorded for each technique, in order to achieve a comparable tissue compression.

For direct tendon attachment, the tendon was dissected from its insertion on the greater tubercle. If the bone block was preserved, the greater tubercle was osteotomized at the limits of the tendon insertion, sagittally at a 60-degree angle to the longitudinal axis of the humerus, using a micro reciprocating saw.

Fixation techniques (Figure 1)

Soft tissue fixation plate: A metal plate measuring 21.5 × 10.0 × 4.0 mm, with 14 teeth each 3.0 mm in length (Synthes Ltd., Paoli, Pennsylvania, U.S.A.), fixed with a 3.5 mm screw situated outside the tendon insertion, was used. The surface of the fixation plate contains crossed grooves to enhance tissue fixation and minimize sliding of the tendon under tension (Figure1). The following screw fixation torques were used:

Direct tendon attachment: Torque: 856 ± 8 Nm.

Bone block attachment: To accommodate the height of the bone block, a 2.5 millimeter thick washer was used to elevate the fixation plate. Torque: 1158 ± 45 Nm.

Spiked washer: 13.5 × 4.0 millimeters (Synthes Ltd., Paoli, Pennsylvania, U.S.A.) fixed with one 3.5 millimeter screw penetrating the tendon insertion.

Direct tendon attachment: A slit was cut into the tendon to accommodate the screw. Torque: 341.5 ± 17.5 Nm.

Bone block attachment: A hole 3.5 millimeters in diameter was drilled in the center of the tendon insertion for screw penetration. Torque: 463 ± 19 Nm.

Enhanced tendon anchor: A custom-made device consisting of a bridge plate with three spikes (0.8 mm in diameter, 1.5 mm in length) oriented at a 20-degree angle to the metal surface which contained ten spikes arranged in an interlocking pattern with the plate spikes. The two screws were alternately tightened.

Direct tendon attachment: Torque at screw 1: 316 ± 29 Nm; at screw 2: 305 ± 15 Nm.

Bone block attachment: Torque screw 1: 360 ± 11 Nm; at screw 2: 378 ± 12 Nm.

For normal controls, 6 pairs of specimens were tested under pull-out to failure (Figure 2).

Preparation of specimens

Canine front legs, including the scapula, were harvested. All soft tissues were removed, preserving only the supraspinatus muscle with its origin in the supraspinous fossa of the scapula and its insertion at the greater tubercle of the humerus. The motion units were wrapped in towels soaked in a solution of 0.9 percent saline, sealed in plastic bags and frozen to –20 °C. Specimens were thawed overnight at room temperature. For 2 hours before testing, the specimens were kept in a solution of 0.9 percent saline at 37 °C. The specimens were kept moist throughout the entire procedure. Bone block fixation with the spiked washer and with the ETA failed at the musculo-tendinous junction, which prevented an appropriate comparison of the properties of the tendon attachment techniques.

Consequently, we reinforced the muscles of 6 pairs of specimens by deep freezing to –20 °C. The distal 4 centimeters of the tendon was thawed at 37 °C in a 0.9 percent NaCl solution for 10 min. A precision stand was used to ensure repeatable depth of tendon immersion in the solution. For normal control with frozen muscle, 6 intact motion units were tested, using the same technique. This technique ensured that failure occurred under tension at the tendon attachment. Such muscle preparation was meant to allow a more reliable fixation to the test jig, without altering tendon and bone attachment to the prosthesis (the tendon and its attachment portion to the fixation device were well

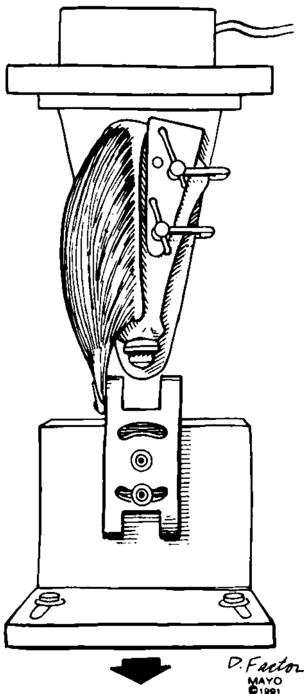

Figure 2. Experimental set-up for mechanical pull-out test to failure. The attachment jig for tendon fixation was allowed to self-align in the direction of the tensile force applied.

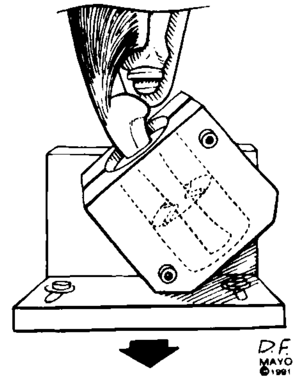

Figure 3. Fixation of the proximal humerus for mechanical testing of intact tendon attachment strength in the motion units.

thawed before the pull-out test). All specimens tested intact or fixed with bone block attachment using a washer and ETA were seen to fail at the musculo-tendinous junction, if tested with muscles in fresh condition, and therefore failed to produce reliable data for comparison. Hence, in studying test results of the entire experiment, we assumed that tendon or bone fixation strength to the attachment prosthesis would not be affected by muscle-freezing.

Mounting of specimens

Scapulae were mounted on a jig aligning the spine of the scapula parallel to the axis of tensional testing (Figure 3). Tendons were attached to jigs simulating the metallic prosthetic attachment site. Jigs for right and left specimens were used. The metallic surface was roughened with a 90-degree criss-cross groove pattern of 0.6 mm width and 0.5 mm depth.

For testing the intact motion units, two Steinmann pins 4.5 mm in diameter were inserted into the proximal part of the humerus, perpendicular to the shaft and to each other (Figure 3). The humerus was embedded up to 1 cm distal to the greater tubercle in a cylinder of Wood's metal (Cerrobend® alloy, Cerro Metals, Bellefonte, Pennsylvania) heated to just above its melting point of 70 °C. The humerus was oriented at a 45-degree angle to the testing axis.

Mechanical testing

Specimens were mounted on a MTS Universal Testing Machine (Model 312.1, MTS Systems Corp., Minneapolis, Minnesota), and tested in tension to failure in a single cycle. Tensional load was applied at a displacement rate of 10 cm per second until failure. Load versus displacement was recorded. The mode of failure was monitored by a high-speed video camera and analyzed after testing.

Data analysis

All groups were compared by performing analysis of variance (ANOVA) on the parameter of interest, regardless of the method of muscle preparation during the mechanical tests. If ANOVA revealed differences between the techniques, Tukey's studentized range post-hoc *t*-test and a Duncan grouping were performed. In order to provide a more reliable comparison, the two groups tested with frozen muscle were analyzed by the paired Student's *t*-test. All differences were considered significant at a probability level of 95 percent ($P < 0.05$). All statistical analyses were performed with commercially available software (SAS Institute, Inc., Cary, North Carolina).

Table 2. Ultimate pull-out strength (N) and stiffness (N/mm) of tendon fixation. Mean *SEM*

Tendon attachment method	Ultimate pull-out strength	Stiffness
Intact (fresh, n 12)*	(463 *46*)	(32 *2.0*)
Intact (frozen, n 6)	1734 *163*[a]	168 *21*[a]
Direct tendon attachment		
Plate (fresh, n 6)	170 *15*[b]	21 *3.3*[b]
Washer (fresh, n 6)	149 *15*[b]	26 *4.6*[b]
ETA (fresh, n 6)	399 *29*[b]	20 *3.2*[b]
Bone block attachment		
Plate (fresh, n 6)	266 *48*[c]	20 *2.7*[b]
Washer (frozen, n 6)	514 *15*[d]	67 *12*[c]
ETA (frozen, n 6)	729 *64*[a]	74 *8.5*[c]

* Failure occurred at the musculo-tendinous junction. These data were excluded from the statistical analysis.
In each column different superscripts indicate significant difference ($P < 0.05$) between the tendon attachment methods tested. For example, intact frozen is stronger than all other methods except bone block attachment using ETA device.

Results

Ultimate tensile strength

Unfrozen intact specimens (n 12), used as a control, failed at the musculo-tendinous junction with a mean force of 463 ± 46 Nm. Intact specimens with frozen muscle, used as a control (n 6), failed in the mid-portion of the tendon (n 3) or by avulsion fracture of the bone at the tendon insertion (n 3) with a mean force of 1734 ± 163 Nm. Regardless of the method of muscle preparation (fresh or frozen), all results reported here were obtained with fixation. Failure occurred either at the mid-substance of the tendon or at the bone/tendon insertion site on the prosthesis.

In direct tendon fixation with all specimens freshly tested, the ETA group had greater ultimate strength than when the other techniques were used. There was no difference between the spiked washer and the fixation plate (Table 2).

In bone block fixation, the plate group tested with fresh muscle failed at the tendon fixation site. The ultimate strength of this group was significantly weaker than the washer and ETA groups tested with frozen muscle. For better comparison, the washer and ETA groups tested with frozen muscle were further tested in paired fashion. The ETA group was stronger in ultimate strength than the spiked washer. Both were weaker than the intact control, using an identical muscle fixation method (Table 2).

Stiffness

There were no differences in stiffness of the tendon attachments between the techniques tested with the unfrozen muscle (Table 2). The 2 techniques tested with frozen muscles likewise showed no differences. All fixation techniques were less stiff than the controls, except the spiked washer fixation of the direct tendon.

Explanation of failure

In all techniques using direct tendon attachment, failure occurred with the tendon tearing off from beneath the device, without altering the fixation mechanism. The spikes of the fixation plate did not fully perforate the tendon and the tissue from beneath the plate was crushed but not shredded. With spiked washer fixation, the screw ultimately pulled through the tissue. The interlocking spikes of the ETA ultimately split the tendon lengthwise through the full thickness.

In bone block attachment, the fixation plate tendons were pulled out without failure of the bone block. The spiked washer was lifted from the metallic surface and failed when the screw broke through the bone block in 5 cases. In 1 case the washer broke. With ETA attachment, the bone block failed through fracture of the cancellous bone, without being lifted off the metallic surface.

Discussion

A tendon fixation device has to serve 2 purposes. First, it has to provide sufficient acute fixation strength to stabilize the reconstruction and, secondly, it has to allow tissue incorporation and remodeling to establish a biological anchorage necessary for ultimate long-term fixation.

Devices for tendon/bone attachment are available and the magnitude of initial fixation strength achievable is usually limited to the mechanical properties of the underlying bone (Robertson et al. 1986, France et

al. 1989). For tendon fixation to metallic implants, the device can be designed to withstand these forces, but care must be taken not to destroy the tissue by excessive compression. Tendon fixation to bone with sutures provides adequate tensile strength. However, it allows significant motion at the insertion between the tendon and the bone (Robertson et al. 1986). This may be an unfavorable scenario for tendon/metal attachment if biological anchorage by tissue ingrowth for long-term function is desired. We therefore used 2 devices for comparison which limit soft tissue motion at the point of insertion.

The mechanical properties of the intact motion units, which were used as controls, would behave differently in vivo. Stimulated muscle has a higher failure resistance than nonstimulated muscle (Garrett et al. 1987) and frozen storage probably causes further deterioration of mechanical properties. In mechanical testing, the tendon insertion of the canine supraspinatus muscle does not fail at the tendon/bone interface at room temperature because failure occurs in the muscle. If the muscle is kept frozen for reinforcement, the tendon fails in its mid-portion or by bony avulsion fracture. This also applies to clinical experiences in dogs where only supraspinatus muscle injuries are seen (Slatter 1985). We therefore used a frozen muscle reinforcement for the 2 fixation methods which were seen to be stronger than the fully thawed musculo-tendinous junction. Thus, it was ensured that failure occurred at the insertion site. For a better comparison between the two groups, we used paired specimens.

With the ETA design, initial fixation was achieved by the angled interlocking spikes which perforated the tissue and gained strength by piercing the structures, without relying entirely on tissue compression. This enabled placement of the bridge plate further distal to the insertion, minimizing the area under compression. Moreover, the angled spikes design resulted in a wedging action, creating a dynamic compression at the interface and preventing the lifting-off, as seen with the spiked washer.

The spiked washer provided a tendon attachment with high ultimate strength and stiffness. The perforating screw, however, weakened the insertion. The placement of the screw is technically difficult and may result in inconsistent fixation strength. The fixation plate provided inadequate fixation at the bone block attachment. The spikes did not penetrate the bone block, although a high-insertion torque for the eccentric screw was used with this technique. The ultimate strength of the bone block attachment was not significantly different from the direct tendon attachment. Therefore, this device was unsuitable as a bone attachment method. The new ETA design provides stronger initial fixation than the other existing comparable devices and it provides design features which may cause less damage to the attached tissues. The ultimate performance of this attachment concept will await an in vivo animal experiment, using the same model and test results obtained here.

Acknowledgement

The technical assistance of Linda Berge and Lawrence Berglund during this project was greatly appreciated. This study was supported by grants from N.I.H. (CA23751) and the Max Kade Foundation.

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