Emerging Ideas

Soft Tissue Applications of Radiostereometric Analysis

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Abstract

Background Currently, the movement that occurs at the site of soft tissue repair cannot be measured accurately in vivo. Radiostereometric analysis (RSA) is the gold standard for measuring movement between two skeletal segments in vivo but its application to studying soft tissue migration has been limited by the unknown stability of tantalum beads in tendons and ligaments and their ability to define rigid bodies in these structures.

Hypothesis RSA can be used to accurately measure movement between two tendon segments or between a bony and a tendon segment in vivo.

Methods of Study The stability of tantalum beads and the ability to use such beads to define rigid bodies in some soft tissues will be investigated in animal models of tendon repair. Several tantalum bead insertion techniques will be tested using in vivo RSA measurements of bead movement followed by morphologic studies of the repaired tendon and soft tissue reaction to the tantalum beads.

Significance RSA performed on tantalum beads encapsulated in muscles and tendons could be a powerful new tool to study the in vivo motion at the site of soft tissue

repairs, for instance, the tendon gap formation. If RSA could be used to evaluate the efficiency of different tendon repair techniques in vivo, enhanced rehabilitation protocols could be developed and complications associated with prolonged protection or failure of repair could be reduced.

Hypothesis

We propose using RSA to study the migration of soft tissue segments in vivo. We hypothesize that tantalum beads can achieve and maintain immediate stability after insertion into muscles and tendons. Stable groups of tantalum beads will allow definition of rigid bodies in these tissues and therefore allow RSA to measure the migration, in vivo, between two tendon segments or between tendon and bony segments.

Background and Significance

Complications after soft tissue lacerations or surgical release include loss of function, instability, and deformity associated with the failure of repair; or stiffness, wasting, deformity, and systemic complications associated with prolonged immobilization. Such complications could be minimized if movement of the soft tissue at the site of disruption could be assessed in vivo during its repair.

RSA is the most accurate method to measure in vivo skeletal movement [5] and is commonly used in orthopaedics [14, 23]. The method is based on the determination of the three-dimensional coordinates of tantalum beads inserted into two skeletal segments captured in dual simultaneous radiographs taken above a calibration cage [13] and is dependent on the beads having a stable position

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[2, 4]. Although its importance is recognized primarily in the area of prosthetic implant migration [13], RSA applications continue to expand [7, 8, 14, 19].

Attempts have been made to measure soft tissue migration by modifying the traditional RSA method and using metal sutures or clips instead of tantalum beads as soft tissue markers [6, 18, 26]. In one of these studies, the implants migrated in the soft tissue investigated [6]. The accuracy of tracking motion with these implants was inferior to that with RSA using tantalum beads [6].

To date, the traditional RSA method, using tantalum beads, has been used to investigate soft tissues indirectly by measurements of migration between two bony segments on either side of the knee [12, 15, 16] or studying the migration of an ACL graft in and relative to its bony tunnel [1, 10, 17]. Despite the relative stability of tantalum beads in tendons during *in vitro* experiments [21, 24], tantalum beads inserted in the intraarticular segment of an ACL autograft migrated erratically in the graft for several months after implantation [17]. This suggests that *in vitro* testing [21, 24] does not reflect intratendinous stability of the beads *in vivo* [22]. In addition to instability, tantalum bead position in tendons is also subject to change as a result of bending, folding, and creep [11, 21, 24].

Despite these obstacles, there are reasons to believe soft tissue applications of RSA are possible. To date, *in vivo* testing involved devascularized tendons [1, 10, 17]. Tendon autografts take months to revascularize [3] in a process dependent on graft preparation technique [22]. Until such revascularization occurs, tantalum beads cannot be incorporated in the surrounding soft tissue and expected to remain in a stable position. Furthermore, in addition to its integration in bone [2, 4], the reaction of other musculoskeletal tissues to tantalum has not been investigated to date.

Proposed Program

For RSA to be used as a clinical tool to measure soft tissue migration, tantalum beads must maintain a stable position after insertion in the structures under investigation and groups of beads must maintain their relative positions in sequential RSA radiographs where they are assumed to be rigid bodies by the investigator in the RSA software. To investigate the feasibility of using RSA to measure soft tissue migration we propose a series of animal experiments that will aim to: (1) establish a tantalum bead insertion technique that ensures immediate bead stability and reduce erratic bead movement in tendons and muscles; (2) investigate the soft tissue reaction to tantalum beads with time; (3) optimize the configuration of tantalum beads to allow them to act as a rigid body; (4) optimize

positioning of the limb for radiographic examinations to reduce the effect of creep, bending, or folding of the soft tissue.

To perform these investigations we propose inserting tantalum beads of different sizes in different formations and different inter bead distances in several types of soft tissues: muscles, tendons, and ligaments, and in an adjacent bone structure in a sheep model of tendon repair. The beads will be inserted using different techniques, ie, with and without incision, with and without suturing, with and without biological glues. We also propose to insert several groups of beads into each structure investigated in the same side and on both sides of a repaired tendon laceration and a tendon/muscle reinsertion. We then will perform RSA examinations in several positions of tension of the structures investigated and at several times postoperatively. After the animals are euthanized at different times, we will determine the reaction of the soft tissues to tantalum beads by several histologic techniques. Models of the muscles investigated will be used to determine the limb position in which xrays should be taken for RSA, such that tendon and muscle are appropriately tensioned while folding and stretching are avoided.

Preliminary results from a study investigating the repair of the gluteus accessorius in sheep suggests that intramuscular tantalum beads, inserted through small unrepaired incisions and without biological glues, are surrounded by an envelope of fibrous tissue as early as 2 weeks after insertion and this process continues to 6 weeks when the envelope was more organized (Fig. 1). Migration of the gluteus accessorius was identified on the RSA radiographs taken at 2 and 18 weeks when compared with radiographs taken immediately after surgery (Fig. 2).

Fig. 1 A cross section through a 0.8-mm tantalum bead in the gluteus accessorius muscle is shown. There is a fibrous envelope surrounding the bead (black arrows) at the end of its insertion track (white arrows) (Stain, methylene blue; original magnification, $\times 40$).

Fig. 2A–C The resultant pairs of marked RSA radiographs taken (A) immediately after surgery, (B) at 2 weeks, and (C) at 18 weeks are shown. The beads in the gluteus accessorius muscle (GA) and greater trochanter (GT) are circled. The arrow between these circles, as seen in the 2-week and 18-week radiographs, identifies the migration of the gluteus accessorius muscle.

Software analysis using point motion of tendon/muscle beads relative to the bone beads correctly identified the failure of the repair (as shown at tissue retrieval), the tendon retraction/gap formation, and also that this failure occurred within the first 2 weeks after repair (Fig. 3).

Therefore, these preliminary results confirm RSA can be used to measure muscular point motion. Some erratic bead movement was observed within the first 2 weeks and these beads were excluded from analysis. It is anticipated that improved insertion techniques will provide the tantalum

Fig. 3 The three-dimensional migration is shown for three beads in the gluteus accessorius muscle of one sheep relative to the greater trochanter with time. The gluteus accessorius was tensioned for each radiostereometric analysis examination by placing the hind limb in external rotation. Radiostereometric analysis showed the failure of the repair occurred within the first 2 weeks postoperatively.

bead with initial stability until soft tissue integration and prevent erratic bead movement.

Limitations

A potential limitation is identification of an insertion technique that ensures tantalum bead stability before soft tissue encapsulation. The position of unstable beads in soft tissue is unknown, and measurements made using such beads may not reflect movement of the soft tissue of interest. Preliminary RSA studies showed that some beads were unstable within 2 weeks after insertion. Therefore, we will study improved insertion techniques, ie, use of fibrin glue that could stabilize the beads in soft tissue until encapsulation in 2 weeks.

Other potential problems include positioning the beads in the tissue of interest and positioning the limb while radiographs are taken to avoid creep, bending, or folding of the soft tissue. Positioning the limb should be investigated before clinical studies to determine if the tendon is adequately tensioned in a position that can be used repeatedly in numerous examinations with time. Placement of tantalum beads in tendons within 5 mm from each other is suggested to result in negligible viscoelastic creep between beads [24]. Placement of the tantalum beads circumferentially and close to a transverse plane through the tendon or muscle could avoid most or all of the unfavorable effects of soft tissue bending and folding.

Even if successful, clinical applications of soft tissue RSA might be limited by alternative imaging techniques like MRI and ultrasonography. These alternative techniques currently have problems with metal artifacts and the position of the structure investigated (ie, the direction of

the fibers of a tendon relative to the MRI unit). Such techniques also have a variable sensitivity and accuracy [9, 20] that is at least one order of magnitude bigger than that of RSA.

Next Steps

Future experiments will involve precision and accuracy tests to determine the number and position of the beads required to optimize the migration results. Such tests might need to be structured specifically to account for different tendon shape, tubular or lamellar. Another important aspect is the development of a standardized and reliable intraoperative tantalum bead insertion technique using a specialized insertion device that will ensure efficient insertion of beads in the desired position in a timely fashion and with minimal inadvertent bead delivery. The current tantalum beads for human insertion are either 0.5, 0.8 or 1 mm in diameter. Smaller bead sizes might be more optimal for soft tissue applications of RSA.

Because of the unknown excursions for some muscle and tendon groups, we suggest preclinical experiments that study the excursions of these muscles during different limb movements using string models before performing RSA analysis of these structures; such a study has been performed for the piriformis and obturator internus and externus [25]. This will not only help identify the best limb position in which radiographs for RSA should be taken, but also help identify the movements and arc of movements that particularly strain repaired soft tissue lacerations.

Other experiments will be directed to identify the effect of tissue degeneration and/or with a compromised blood supply on the stability and integration of tantalum beads and how these affect the ability to perform soft tissue RSA.

Vision of the Future

In the future we anticipate soft tissue RSA will be used in clinical trials, allowing exciting new research directions that potentially will bring solutions or improvements to the current management in numerous clinical scenarios. For example, RSA will allow in vivo measurement of tendon gap formation after different repair techniques and measurements of mechanical properties of healing tendons, thus enabling the establishment of improved postinjury and postsurgery rehabilitation protocols.

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References

- Adam F, Pape D, Schiel K, Steimer O, Kohn D, Rupp S. Bio-mechanical properties of patellar and hamstring graft tibial fixation techniques in anterior cruciate ligament reconstruction: experimental study with roentgen stereometric analysis. *Am J Sports Med.* 2004;32:71–78.
- Alberius P. Bone reactions to tantalum markers: a scanning electron microscopic study. *Acta Anat.* 1983;115:310–318.
- Arai Y, Hara K, Takahashi T, Urade H, Minami G, Takamiya H, Kubo T. Evaluation of the vascular status of autogenous hamstring tendon grafts after anterior cruciate ligament reconstruction in humans using magnetic resonance angiography. *Knee Surg Sports Traumatol Arthrosc.* 2008;16:342–347.
- Aronson AS, Jonsson N, Alberius P. Tantalum markers in radiography: an assessment of tissue reactions. *Skeletal Radiol.* 1985;14:207–211.
- Bragdon CR, Malchau H, Yuan X, Perinchief R, Karrholm J, Borlin N, Estok DM, Harris WH. Experimental assessment of precision and accuracy of radiostereometric analysis for the determination of polyethylene wear in a total hip replacement model. *J Orthop Res.* 2002;20:688–695.
- Cashman PM, Baring T, Reilly P, Emery RJ, Amis AA. Measurement of migration of soft tissue by modified Roentgen stereophotogrammetric analysis (RSA): validation of a new technique to monitor rotator cuff tears. *J Med Eng Technol.* 2010;34:159–165.
- Chehade MJ, Solomon LB, Callary SA, Benveniste SH, Pohl AP, Howie DW. Differentially loaded radiostereometric analysis to monitor fracture stiffness: a feasibility study. *Clin Orthop Relat Res.* 2009;467:1839–1847.
- Downing MR, Ashcroft PB, Johnstone AJ, Bach O, Mackenzie S, Ashcroft GP. Assessment of inducible fracture micromotion in distal radial fractures using radiostereometry. *J Orthop Trauma.* 2008;22(suppl):S96–S105.
- Festa A, Mulieri PJ, Newman JS, Spitz DJ, Leslie BM. Effectiveness of magnetic resonance imaging in detecting partial and complete distal biceps tendon rupture. *J Hand Surg Am.* 2010;35:77–83.
- Friden T, Ryd L, Lindstrand A. Laxity and graft fixation after reconstruction of the anterior cruciate ligament: a roentgen stereophotogrammetric analysis of 11 patients. *Acta Orthop Scand.* 1992;63:80–84.
- Haut Donahue TL, Howell SM, Hull ML, Gregersen C. A bio-mechanical evaluation of anterior and posterior tibialis tendons as suitable single-loop anterior cruciate ligament grafts. *Arthroscopy.* 2002;18:589–597.
- Jorn LP, Friden T, Ryd L, Lindstrand A. Simultaneous measurements of sagittal knee laxity with an external device and radiostereometric analysis. *J Bone Joint Surg Br.* 1998;80:169–172.
- Karrholm J. Roentgen stereophotogrammetry. Review of orthopedic applications. *Acta Orthop Scand.* 1989;60:491–503.
- Karrholm J, Gill RH, Valstar ER. The history and future of radiostereometric analysis. *Clin Orthop Relat Res.* 2006;448:10–21.
- Karrholm J, Selvik G, Elmqvist LG, Hansson LI. Active knee motion after cruciate ligament rupture: stereoradiography. *Acta Orthop Scand.* 1988;59:158–164.
- Karrholm J, Selvik G, Elmqvist LG, Hansson LI, Jonsson H. Three-dimensional instability of the anterior cruciate deficient knee. *J Bone Joint Surg Br.* 1988;70:777–783.
- Khan R, Konyves A, Rama KR, Thomas R, Amis AA. RSA can measure ACL graft stretching and migration: development of a new method. *Clin Orthop Relat Res.* 2006;448:139–145.
- Khan RJ, Yao F, Li M, Nivbrant B, Wood D. Capsular-enhanced repair of the short external rotators after total hip arthroplasty. *J Arthroplasty.* 2007;22:840–843.
- Madanat R, Moritz N, Larsson S, Aro HT. RSA applications in monitoring of fracture healing in clinical trials. *Scand J Surg.* 2006;95:119–127.
- O'Driscoll SW, Goncalves LB, Dietz P. The hook test for distal biceps tendon avulsion. *Am J Sports Med.* 2007;35:1865–1869.
- Roos PJ, Hull ML, Howell SM. How cyclic loading affects the migration of radio-opaque markers attached to tendon grafts using a new method: a study using roentgen stereophotogrammetric analysis (RSA). *J Biomech Eng.* 2004;126:62–69.
- Sckell A, Leunig M, Fraitzl CR, Ganz R, Ballmer FT. The connective-tissue envelope in revascularisation of patellar tendon grafts. *J Bone Joint Surg Br.* 1999;81:915–920.
- Selvik G. Roentgen stereophotogrammetry: a method for the study of the kinematics of the skeletal system. *Acta Orthop Scand Suppl.* 1989;232:1–51.
- Smith CK, Hull ML, Howell SM. Migration of radio-opaque markers injected into tendon grafts: a study using roentgen stereophotogrammetric analysis (RSA). *J Biomech Eng.* 2005;127:887–890.
- Solomon LB, Lee YC, Callary SA, Beck M, Howie DW. Anatomy of piriformis, obturator internus and obturator externus: implications for the posterior surgical approach to the hip. *J Bone Joint Surg Br.* 2010;92:1317–1324.
- Stähelin T, Drittenbass L, Hersche O, Miehke W, Munzinger U. Failure of capsular enhanced short external rotator repair after total hip replacement. *Clin Orthop Relat Res.* 2004;420:199–204.