Biomechanical Analysis of Screw Fixation in Cortical Bone Following Therapeutic Levels of X-Irradiation

Divakar N. Lal MD[1], Kenneth A. Mann PhD[1], Megan E. Oest PhD[1], Timothy A. Damron MD[1]
SUNY Upstate Medical University, Syracuse, NY
LalD@Upstate.edu

Disclosures: D.N. Lal: 4; Gilead Sciences, Centene Corporation. K.A. Mann: None. M. Oest: None. T.A. Damron: 3B; Cerament. 5; Cerament, OREF, Stryker, Wright Medical Technology, Inc.. 7B; eMedicine, Journal of the American Academy of Orthopedic Surgery, Up To Date, Wolters Kluwer Health. 8; BMC Musculoskeletal Disorders, Clinical Orthopedics and Related Research, eMedicine, Journal of Orthopedic Research, Journal of Surgical Oncology, Medicina, Open Journal of Orthopedics, PLoS One.

INTRODUCTION: Treatment of impending or acute fractures in orthopedic oncology patients often requires screw fixation in host bone which has been subjected to radiation. Fixation in these settings raises unique biological and mechanical considerations. Application of therapeutic levels of x-irradiation (20 Gy) results in cortical bone embrittlement (~25% reduction in fracture toughness with immediate/direct changes in bone matrix) [1], but it is not clear how this might affect screw fixation. The goal of this study was to determine if direct irradiation would substantially reduce robustness of screw fixation in using a preclinical rat femur model.

METHODS: Right femurs from fresh-frozen cadaveric feeder rats (n=14, 10M/4F, average: 296 grams) were irradiated ex-vivo with a single 20 Gy dose of x-irradiation (Faxitron, 225kV, 17 mA, 0.5mm Cu filter). Left femurs served as non-radiated controls. The diaphysis of femurs were drilled (0.9mm) and fitted to an alignment fixture for potting in PMMA, resulting in a screw orientation that was orthogonal to the pots. After insertion into the test fixture (**Fig 1**), femurs were tapped (1.0mm) followed by bicortical placement of 1.2mm stainless steel machine screws resulting in an interference fit. Uniaxial tensile tests to failure were performed in displacement control (1 mm/min). Force and global displacement were recorded using the test frame load cell and cross head displacement. Relative motion between the screw and cortical bone was measured using digital image correlation (DIC) methods. High resolution images of the screw-bone construct were captured at 20 frames per second. MicroCT imaging was used to quantify screw-bone contact area (**Fig 2**). Because screw contact area was not exactly the same for each femur pair, apparent shear stress (force/contact area) was calculated for each test. Peak shear stress, screw-bone shear stiffness, and energy to failure were calculated using the force-DIC displacement curves and compared between femur pairs using paired t-tests. Fracture patterns from the tensile tests were also categorized based on crack path near peak load.

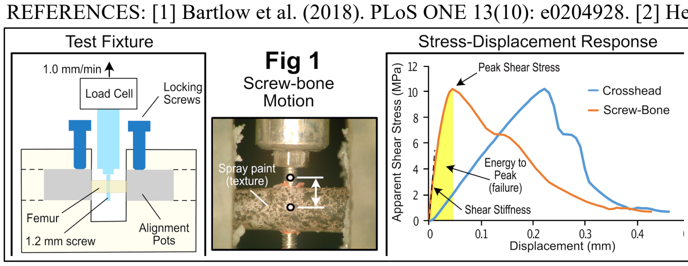
RESULTS SECTION: A single dose of 20 Gy irradiation reduced the energy to failure by a factor of two (p=0.02, **Table 1**). A smaller 18% reduction in peak shear stress (p=0.13) and 30% increased shear stiffness (p=0.17) was found with 20 Gy irradiation. There were two major fracture patterns with crack paths classified as either proximal cap fracture or transverse fracture (**Fig 2**). Thirteen of 14 irradiated femurs (93%) exhibited transverse cortex fractures, while only 6 of 14 of the control femurs (43%) had transverse cortex fractures (p=0.0046, Chi-Square test).

DISCUSSION: Therapeutic levels of irradiation (RTx) reduced the quality of screw fixation in cortical bone in this preclinical rat femur model. Bone embrittlement with RTx has been shown to diminish the normal toughening mechanisms in cortical bone through reduced ability to absorb high stress without crack growth [1]; this appears to be manifested here in less total energy required to cause screw pullout and reduced shear strength. The large transverse cracks that resulted during screw pull-out in irradiated femurs is also indicative of a more brittle fracture morphology. In the control femurs, a small cap fracture was often seen, while the adjacent diaphyseal cortex remained intact. This could explain the lower energy required to cause failure in the RTx-treated bones; with extensive cortical crack propagation, the screw threads at the screw-bone interface had reduced engagement with the bone due to lateral cortical displacement of the bone, resulting in less resistance to screw pull-out.

One important limitation of this study was that in vivo changes following irradiation were not included in this model but should be explored further. Previous work showed a further decrease in bone fracture toughness following in vivo implantation [1]. Also, despite efforts to carefully control screw placement and orientation, there was some variability in placement within each femur pair due to the small anatomic scale of the cadaveric femurs and screw instrumentation. Efforts to standardize screw placement orthogonally and as optimally centered with respect to cortical diameter in an in-vivo preclinical model would be an important consideration. While this experimental setup examined single cycle fatigue loading, another direction of future research that would be intriguing to explore includes biomechanical analysis under cyclical loading conditions.

SIGNIFICANCE/CLINICAL RELEVANCE: The effect of radiation-induced cortical bone embrittlement on screw fixation has not been explored, which particularly in the orthopedic oncologic patient population, has direct relevance and implications with respect to the operative stabilization, fixation, and reconstruction construct treatment options. Clinically, structural failure is the third most common mode of failure in orthopedic oncologic fixation (17%), so a better understanding of the biomechanical considerations in this unique patient population may render improved surgical treatment strategies and patient outcomes.

REFERENCES: [1] Bartlow et al. (2018). PLoS ONE 13(10): e0204928. [2] Henderson et al. (2011). J Bone Joint Surg Am. 2011;93(5):418-429.



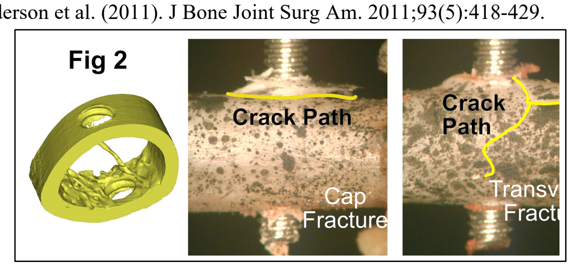


Table 1. Energy to failure (MPa-mm), shear stiffness (MPa/mm), and peak shear stress (MPa) of screw pullout in control and 20 Gy irradiated femurs. Results from paired t-test, mean and standard deviation shown.

	Energy to failure (MPa x mm) (p = 0.02)	Shear stiffness (MPa/mm) (p = 0.17)	Peak shear stress (MPa) (p = 0.14)
Control femur	0.59 (0.44)	402.2 (313.8)	11.5 (3.9)
20 Gy Irradiated femur	0.25 (0.21)	524.8 (200.8)	9.4 (2.2)
% Change from control femur	-57.6 %	30.4 %	-18.2%