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Research Paper

Effects of gamma radiation sterilization and strain rate on compressive behavior of equine cortical bone

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ABSTRACT

Objectives: Gamma radiation has been widely used for sterilization of bone allograft. However, sterilization by gamma radiation damages the material properties of bone which is a major clinical concern since bone allograft is used in load bearing applications. While the degree of this damage is well investigated for quasi-static and cyclic loading conditions, there does not appear any information on mechanical behavior of gamma-irradiated cortical bone at high speed loading conditions. In this study, the effects of gamma irradiation on high strain rate compressive behavior of equine cortical bone were investigated using a Split Hopkinson Pressure Bar (SHPB). Quasi-static compression testing was also performed.

Methods: Equine cortical bone tissue from 8 year old retired racehorses was divided into two groups: non-irradiated and gamma-irradiated at 30 kGy. Quasi-static and high strain rate compression tests were performed at average strain rates of 0.0045/s and 725/s, respectively.

Results: Agreeing with previous results on the embrittlement of cortical bone when gamma-irradiated, the quasi-static results showed that gamma-irradiation significantly decreased ultimate strength (9%), ultimate strain (27%) and toughness (41%), while not having significant effect on modulus of elasticity, yield strain and resilience. More importantly, contrary to what is typically observed in quasi-static loading, the gamma-irradiated bone under high speed loading showed significantly higher modulus of elasticity (45%), ultimate strength (24%) and toughness (26%) than those of non-irradiated bone, although the failure was at a similar strain.

Significance: Under high speed loading, the mechanical properties of bone allografts were not degraded by irradiation, in contrast to the degradation measured in this and prior studies under quasi-static loading. This result calls into question the assumption that bone allograft is always degraded by gamma irradiation, regardless of loading conditions. However, it needs further investigation to be translated positively in a clinical setting.

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1. Introduction

Bone fractures are a leading health problem with enormous social and economical consequences (Burge et al., 2007; Bonafedea et al., 2013). Bone allografts are widely used as a natural substitute to repair the defects in skeletal system such as bone fractures, spinal fractures and bone tumor. Due to its effectiveness and convenience, terminal sterilization of bone allografts by gamma radiation is very important to minimize disease transmission and infection (Bright et al., 1983; Nemzek et al., 1994; Kennedy et al., 2005; McAllister et al., 2007). However, the mechanical properties of gamma-irradiated cortical bone are affected by the destruction of collagen and it is made brittle by irradiation because of the destruction of collagen alpha chains (Hamer et al., 1996a, 1996b; Akkus and Rimnac, 2001; Nguyen et al., 2007a). Clinical findings have indicated that the rate of fracture in allografts sterilized with gamma radiation may be higher than that in non-irradiated allografts (Lietman et al., 2000). The degree of this destruction depends on dose of the radiation (Hamer et al., 1996b; Nguyen et al., 2007a; Mardas et al., 2012). The dose employed in many of tissue banks is 30 kGy, with a tolerance of 5 kGy, which is sufficient to minimize any risk of disease transmission (Angermann and Jepsen, 1991; Hamer et al., 1999; Nguyen et al., 2007a, 2007b). Despite findings of Komender (1976) that there was no significant effect of gamma irradiation with a dose between 25 kGy and 35 kGy, there are numerous studies stating that gamma irradiation even at these doses significantly reduces the mechanical properties of allograft bone (Triantafyllou et al., 1975; Hamer et al., 1996b; Currey et al., 1997; Akkus and Rimnac, 2001; Mitchell et al., 2004; Akkus and Belaney, 2005; Nguyen et al., 2007a; Russell et al., 2012; Kaminski et al., 2012).

As engineering materials, bone might also be subjected to high rates of loading in some instances such as sports accidents, traffic accidents involving vehicles, cyclists and/or pedestrians, falls from a height, sudden falls, gun shots and drilling processes in orthopedic surgery. The strength of bone is known to be dependent on the rate of loading and, over a range of loading rates consistent with normal physiological loads, the mechanical properties such as modulus of elasticity, yield strength, ultimate strength and toughness, vary modestly with rate (Wright and Hayes, 1976; Currey, 1989; Evans et al., 1992). Nevertheless, in high speed loading situations, ultimate strength can increase considerably while the ultimate strain, a measure of ductility, can decrease considerably (McElhaney, 1966; Lewis and Goldsmith, 1975; Katsamanis and Raftopoulos, 1990; Shazly et al., 2005; Adharapurapu et al., 2006; Ferreira et al., 2006; Shunmugasamy et al., 2010; Kulin et al., 2011a, 2011b). However, there are contradictory results for modulus of elasticity in previous studies. While most studies indicated a significant increase in modulus of elasticity (McElhaney, 1966; Shazly et al., 2005; Adharapurapu et al., 2006; Shunmugasamy et al., 2010; Teja et al., 2013), there are a few studies that indicated either smaller increase (Lewis and Goldsmith, 1975) or a significant decrease (Ferreira et al., 2006) in modulus of elasticity.

Understanding the response of bone under high rates of loading is critical to accurately model mechanical behavior of bone, and to predict where and how bone injury might occur in case of sports or traffic accidents. For instance, development of computational models in predicting mechanical behavior of bone under high rates of loading is very important in some industries such as automotive (Yang and Kajzer, 1994; Bermond et al., 1994; Yang et al., 1996; Tamura et al., 2001; Nagasaka et al., 2003; Yang et al., 2006; Kerrigan et al., 2009; Laporte et al., 2009), sports, personal protective equipments and orthopedics (Tsai et al., 2007; Lughmani et al., 2013; Pandey and Panda, 2013). Because, the success of the computational models is highly dependent on the bone models employed. While data exists for the mechanical behavior of non-irradiated bone at low and high strain rates to develop constitutive models, there is no data of gamma-irradiated bone at high strain rates since radiation-induced embrittlement of bone has only been studied for quasi-static and cyclic loading conditions. However, most clinical bone fractures occur under high speed loading conditions. In view of this, the present study is undertaken to examine the compressive behavior of gamma-irradiated cortical bone under high speed loading using a Split Hopkinson Pressure Bar (SHPB) and comparing compressive behavior to that of non-irradiated cortical bone. Quasi-static compression is also performed to compare the effects of gamma-irradiation on cortical bone in both quasi-static and high speed loadings.

The SHPB, also called Kolsky bar, is the most commonly used method for determining the mechanical properties of various materials at high strain rates (Namet-Nasser, 2000; Ramesh, 2008; Weinong and Chen, 2010). However, the SHPB has mainly been used to test metals, ceramics and other hard materials including cancellous (Laporte et al., 2009; Prot et al., 2012; Teja et al., 2013) and cortical bone (McElhaney, 1966; Tennyson et al., 1972; Lewis and Goldsmith, 1975; Katsamanis and Raftopoulos, 1990; Tanabe et al., 1994; Shazly et al., 2005; Adharapurapu et al., 2006; Ferreira et al., 2006; Cloete et al., 2009; Shunmugasamy et al., 2010; Kulin et al., 2011a, 2011b; Teja et al., 2013). One of the main problems in testing soft materials with the SHPB is the impedance mismatch between a soft material specimen and metallic bars. The introduction of polymeric bars in the SHPB apparatus (Salisbury, 2001) has overcome the impedance matching problem, thereby allowing proper reflection and transmission of strain wave by the specimen. Recent studies have shown that modifications to the traditional SHPB allow for the successful characterization of mechanical properties of soft materials including biological soft tissues at high strain rates that exceed alternate soft tissue testing techniques. In the last ten years, there have been several studies using modified SHPB for soft tissues such as muscle, ligament and brain (Sligtenhorst et al., 2006; Chawla et al., 2006; Lennon et al., 2007; Saraf et al., 2007; Trexler et al., 2011; Rashid et al., 2012; Ott et al., 2012; Rashid et al., 2013). Explanation of SHPB compression system and the equations of stress, strain rate and strain used for SHPB compression system are included in Appendix A, which were provided by Namet-Nasser (2000).

2. Materials and methods

2.1. Specimen preparation

Cortical bone of larger animal species such as goat, sheep, cow, pig and horse is often used for comparative biomechanical