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Review

Parameters affecting mechanical and thermal responses in bone drilling: A review

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ABSTRACT

Surgical bone drilling is performed variously to correct bone fractures, install prosthetics, or for therapeutic treatment. The primary concern in bone drilling is to extract donor bone sections and create receiving holes without damaging the bone tissue either mechanically or thermally. We review current results from experimental and theoretical studies to investigate the parameters related to such effects. This leads to a comprehensive understanding of the mechanical and thermal aspects of bone drilling to reduce their unwanted complications. This review examines the important bone-drilling parameters of bone structure, drill-bit geometry, operating conditions, and material evacuation, and considers the current techniques used in bone drilling. We then analyze the associated mechanical and thermal effects and their contributions to bone-drilling performance. In this review, we identify a favorable range for each parameter to reduce unwanted complications due to mechanical or thermal effects.

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1. Introduction

Bone drilling is a surgical procedure generally performed to create holes in the human skeleton to treat fractures, install implants, or for reconstructive surgery. In 1886, Carl Hansmann first introduced a modern surgical drilling procedure in an orthopedic surgical process (Karmani and Lam, 2004). Since then, bone drilling has been employed in various surgical contexts. For example, in orthopedic surgery, total knee arthroplasty for osteoarthritis treatment requires bone drilling to make holes in the intramedullary canal along the anatomical axis of the femur. In neurosurgery, craniotomy–the surgical removal of a section of the skull to expose the brain for brain-tumor resection or to relieve pressure on the underlying brain–involves drilling small burr holes into the skull. In stapedotomy–a surgical procedure in otolaryngological surgery of the middle ear to treat hearing loss due to abnormal bone growth in the middle ear (called otosclerosis)–bone drilling is performed to remove the abnormal bone and create a small hole in the stapes bone in the middle ear for replacement with a stapes prosthesis. Dental treatment involves drilling for placing dental implants. Drilling has also been used as a therapeutic treatment for osteoarthritis and osteonecrosis. As conceived by Pridie (1959), Pridie drilling is the therapeutic technique of drilling holes into the subchondral bone-marrow spaces underneath regions of damaged articular cartilage, thereby stimulating a spontaneous repair reaction. When treating necrotic bone, drilling multiple holes is effective for treating several stages of post-traumatic avascular necrosis of the femoral head. Additionally, core drilling, which is recommended to relieve intraosseous hypertension and to accelerate infract revascularization and repair, is used to prevent the collapse of the necrotic femoral head (Brown et al., 1993). In each of the aforementioned drilling procedures, the primary concern is to extract bone sections and create receiving holes without damaging the bone tissue either mechanically or thermally, thereby ensuring successful surgery.

Human bone is an inhomogeneous and anisotropic material comprising two types of bone tissues: cortical bone and trabecular bone. As shown in Fig. 1, the bone macrostructure comprises a dense cortical bone surrounding a porous trabecular interior; the interior part of a long bone is the medullary cavity, which is composed of marrow. In contrast, bone microstructure presents a hierarchy of different levels. As shown in Fig. 1, cortical bone consists of osteons, and each osteon comprises cylindrical collagen fibers that form lamellae, which are wrapped in concentric layers. The microstructural arrangement of the bone components directly influences the anisotropy of the human cortical bone. On the other hand, trabecular bone is a system of randomly fashioned rods and plates, known as trabeculae. Trabecular bone contains large spaces that are usually filled with marrow, resulting in porosity. Moreover, the structure and material characteristics vary between different bones, people, and age groups. Overall, the inhomogeneity and anisotropy of the human bone, combined with these variations, make bone drilling considerably complex.

For bone drilling to succeed, its mechanical and thermal aspects must be treated appropriately. Mechanically, the forces applied during bone drilling, which are associated with the mechanical work required to cut the bone material, can be used to characterize bone drilling and determine its efficiency, thereby significantly affecting its consequences (Jacobs et al., 1976; Krause, 1976; Wiggins and Malkin, 1978; Hobkirk and Rusiniak, 1977; Esen et al., 2003; Lee et al., 2012a). Two major forces, namely thrust force and torque, must be considered when analyzing bone drilling. The thrust force is due to the feed motion, whereas the torque is a twisting force related to both the thrust force and the radial distance from the center of the drill bit. When a bone is drilled, both the thrust force and torque increase up to certain levels until the drill bit is fully involved in the bone, whereupon the forces become steady in theory. The levels and trends of these applied forces significantly influence the outcomes of bone drilling. Several researchers have agreed that constant, sufficient, but not excessive forces, are critical to successful bone drilling (Hobkirk and Rusiniak, 1977; Esen et al., 2003; Lee et al., 2012a). Relatively large forces during bone drilling pose challenges to its application. One such challenge is drill-bit breakage, which occurs frequently during bone drilling (Bassi et al., 2008). Increased torque during bone drilling can induce shear stresses that exceed the strength of the drill bit, causing it to fracture (Farnworth and Burton, 1975; Hirt et al., 1992). Once breakage occurs, it can obstruct the placement of other devices or cause corrosive reactions with surrounding tissues, commonly necessitating follow-up procedures to remove the broken drill bit (Bassi et al., 2008; Fothi et al., 1992). Drill-bit breakthrough, another issue caused by excessive drilling forces, is when a drill bit protrudes excessively from the exit of the bone, resulting in considerable damage to the bone and surrounding tissues (Ong and Bouazza-Marouf, 1999). It has been reported that the nonuniform mechanical properties of bone associated with

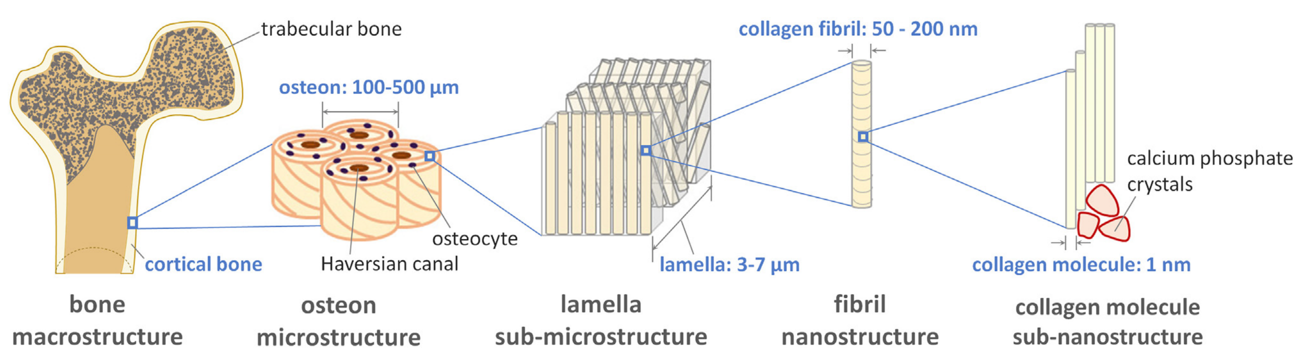

Fig. 1. Structure of bone over different scales.