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The use of augmentation techniques in osteoporotic fracture fixation

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ABSTRACT

There are an increasing number of fragility fractures, which present a surgical challenge given the reduced bone quality of underlying osteoporosis. Particularly in aged patients, there is a need for early weight bearing and mobilization to avoid further complications such as loss of function or autonomy. As an attempt to improve fracture stability and ultimate healing, the use of biomaterials for augmentation of osseous voids and fracture fixation is a promising treatment option. Augmentation techniques can be applied in various locations, and fractures of the metaphyseal regions such as proximal humerus, femur, tibia and the distal radius remain the most common areas for its use. The current review, based on the available mechanical and biological data, provides an overview of the relevant treatment options and different composites used for augmentation of osteoporotic fractures.

Introduction

Fragility fractures are of increasing importance in orthopaedic trauma surgery given the demographic changes of our aging population. The National Osteoporosis Foundation estimates that there are approximately 2 million osteoporosis-related fractures in the U.S. each year, while additional studies suggest that the worldwide burden is closer to 9 million [1,2]. Thus, a majority of fractures are associated with osteoporosis, which result in 36% of the annual in-patient care costs, or 860 million €, in Germany alone [1]. Over the next few decades the incidence of osteoporotic fractures is expected to increase [2]. In these fragility fractures, surgical treatment can be challenging given the reduced bone quality that particularly affects the frequently fractured metaphyseal regions such as the proximal humerus, proximal femur, distal radius, spine, and proximal tibia. Postoperative non-union, screw cut-out, and implant migration are common complications adversely affecting patient outcomes. In the elderly patient population susceptible to fragility fractures, full weight bearing and early mobilization are of paramount importance in order to avoid the significant peri- and post-operative complications associated with frequently present comorbidities. The one-year mortality of hip fractures for example is up to 30% [3].

While advances in implant design such as locked plates have addressed some of the challenging issues, there is still need to promote fracture biology, augment bone defects, and improve surgical fixation in the osteoporotic patient. The aim of this review is to provide an overview of a history of bone augmentation, clinical problems associated with osteoporotic fractures, and potential solutions to these challenges through the use of various augmentation techniques.

Mechanical and biological characteristics in osteoporotic fractures

Age-related resorption of calcium from bone results in thinning of both trabecular and cortical bone and an associated increase in bone diameter [2]. These anatomic changes have a direct effect on mechanical properties. As the density of bone decreases, there is a commensurate decrease in the yield stress, elastic modulus of cortical bone, and compressive strength of cancellous bone [2]. Additional cellular and physiologic changes in the bone contribute to an impaired healing potential; there is a decrease in the number, responsiveness, and activity of mesenchymal progenitor cells, and signaling molecules. There also is a decrease in vascularity and impaired osteoblast function that affect both endochondral and periosteal osteogenesis [3].

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A comprehensive strategy for improved treatment of osteoporotic fractures should address biological and mechanical issues, and include the stimulation of fracture repair, removal of inhibitors to bone healing, application of augmentation materials, and improvements in surgical implants.

Biological stimulation or induction of bone growth can be facilitated by local techniques, systemic methods, or physical means. At the time of surgery, bone marrow aspirates, platelet gels, and bone morphogenetic proteins (BMPs) can be placed at the fracture site and have been shown to improve healing response [4–6]. Administration of vitamin D, calcium, bisphosphonates and parathyroid hormone (PTH), have also been shown to increase fracture healing [7]. Finally, physical modalities such as ultrasound, direct electrical stimulation, pulsed electromagnetic fields, and extracorporeal shock waves have been reported to affect fracture repair [8].

There are many well-recognized inhibitors to bone healing, and every effort should be made to remove these inhibitors to improve healing in osteoporotic fractures. This includes limiting exposure to smoking, alcohol, potent anti-inflammatory medications, and steroids. Maximized control of medical issues such as malnutrition, diabetes, infection, thyroid disease, and hormonal problems is essential for optimizing bone healing.

Evolution of bone augmentation techniques

Bone augmentation with biomaterials was first described in 1984, when Deramond injected polymethyl methacrylate cement into a cervical vertebral body to treat a painful intravertebral haemangioma [9]. In the three decades that followed, many studies have been published describing and critiquing the biomechanical principles, preclinical animal experiments, surgical techniques, and clinical outcomes of bone augmentation of the vertebral column [10–13].

Although the 1987 publication by Galibert and Deramond stimulated the field of vertebral augmentation, the biomaterial used in their case (polymethylmethacrylate; PMMA) was not novel, having been introduced as early as 1877 by Fittig and Paul. PMMA became commercially available in 1936 as an alternative for glass under the name of plexiglas of perspex. The first clinical application of PMMA was in odontology, followed by ophtalmology (after it was discovered in the Second World War that small fragments of PMMA from shattered warplane canopies did not induce inflammatory reactions in the eyes of pilots), and most famously, as a bone-implant bonding material in hip replacement surgery in the early 1960s. General acceptance of PMMA as a biomaterial for intravertebral applications was not established until the late 1990s when the original French work was introduced to the English-speaking medical community by French Canadian Jacques Dion. This lead to an increased interest in minimally invasive procedures such as vertebroplasty (transpedicular injection of PMMA cement in the vertebral body) and kyphoplasty (injection of PMMA cement after inflation of a balloon(s) in the vertebral body) [11]. In the 2000s, the indications for these procedures expanded from primarily symptomatic osteoporotic vertebral compression fractures to painful spinal metastases, vertebral osteolysis in multiple myeloma, and traumatic burst fractures [14,15]. Although the precise working mechanism of spinal augmentation for most of these indications has not been fully elucidated, it was (and still is) generally believed that the resulting increase of mechanical stability (and thus less movement of microfractures) in intravertebral cancellous bone after cement injection led to an immediate and long-lasting decrease of pain. To the current authors best knowledge, Nakano and coworkers published the first series of patients undergoing vertebroplasty for painful osteoporotic vertebral compression fractures using a different (i.e. calcium phosphate) type of cement with the secondary goal of promoting physiological bone remodeling after stabilization [16]. Since the clinical results from this study were not different from the studies using PMMA cement, several hypotheses on the working mechanism for PMMA (including the effects of local toxicity or thermal damage from polymerizing methacrylate) were subsequently considered less plausible. Another topic of debate was the risk for adjacent level fractures after vertebroplasty or kyphoplasty to treat painful osteoporotic vertebral compression fractures. Although a definitive conclusion or consensus has not been achieved, most researchers and clinicians have agreed that mismatched elastic properties (i.e. Young's modulus) between augmented and non-augmented vertebral bodies plays an important role in the etiology of adjacent level fractures [17].

The examples above illustrate the urgent need for a wider range of biomaterials that are better designed for the specific clinical conditions, taking into account factors that include biocompatibility/degradability (especially for younger patients), stiffness (relative to patient's own bone mineral density), and safety (in case of cement leakage). Moreover, since biomaterials are increasingly being used for augmentation of methapyseal fractures of various anatomic locations (e.g. humerus, femur, distal radius, and tibial fractures), there is a growing number of scientific reports on that topic. In spinal surgery, these reports focus on the attempt to reinforce pedicle screws in the osteoporotic spine or to fill (large) voids in cages after reconstruction of spinal defects. Additionally, characteristics specific for the bone-implant interface, such as crack formation and propagation, are also gaining interest from researchers [18].

Augmentation of the spine

Several studies have shown that increased amounts of PMMA injected during procedures such as vertebroplasty and kyphoplasty are associated with higher stiffness, higher risk of cement leakage (the most frequent complication after vertebroplasty/kyphoplasty procedures), and potential exothermal damage while not improving clinical outcome. The optimum amount of cement injected should therefore relate to the least amount needed for clinical efficacy. It has been demonstrated in several studies that this minimum amount corresponds to approximately 15% of the vertebral volume to be treated [19]. Other factors associated with a lower risk of cement leakage have also been identified: using balloons (as in kyphoplasty procedures Figure 1a) prior to cement injection; employing large-diameter needles to keep injection pressure low; using high viscosity cement; and visualizing/monitoring the region of interest with high-quality fluoroscopy equipment. It must be noted that for good clinical results, the careful selection of patients supported by the appropriate imaging techniques is still of greatest importance. When augmenting pedicle screws with biomaterials, some principles from arthroplasty cementing techniques may apply, including achieving an even cement mantle between pedicle screw and cancellous bone and allowing for undisturbed polymerization of the cement mantle until plastic cement deformation is no longer present. In larger spinal defects (e.g. after gross resections or when filling metallic cages), the benefits of using biocompatible/degradable cements may be limited, considering the large distances and volumes involved with respect to potential vascular ingrowth necessary for bone remodeling and creeping substitution.

Augmentation techniques for the humerus

Fracture fixation of the proximal humerus in patients with reduced bone quality still poses a great challenge to the surgeon. Despite the development of new and improved implants, secure anchorage of the implants with screws or blades in the trabecular bone of the proximal humerus remains the weak link for fixation and is mainly responsible for implant-related mechanical failures. Initial attempts to improve screw fixation in the humeral head used fibular grafts to augment the trabecular bone of the humeral head [20]. Later, biomechanical [21] and clinical studies [22] reported improvement in implant anchorage by using calcium phosphate cements to augment the central void in the humeral head. Recent developments of cannulated and perforated