**Name of Journal:** *World Journal of Stem Cells*

**Manuscript NO:** 56054

**Manuscript Type:** MINIREVIEWS

**Isolation and characterization of mesenchymal stem cells in orthopaedics and the emergence of compact bone mesenchymal stem cells as a promising surgical adjunct**

Anastasio A *et al.* Isolation and characterization of MSC in orthopaedics

Albert Anastasio, Marina Gergues, Michael S Lebhar, Pranela Rameshwar, Joseph Fernandez-Moure

**Albert Anastasio,** Department of Orthopedic Surgery, Duke University Health System, Durham, NC 27710, United States

**Marina Gergues,** Department of Medicine, Hematology/Oncology, Rutgers University, New Jersey Medical School, Newark, NJ 07103, United States

**Michael S Lebhar,** School of Medicine, Duke University School of Medicine, Durham, NC 27710, United States

**Pranela Rameshwar,** Department of Medicine-Hematology/Oncology, Rutgers School of Biomedical Health Science, Newark, NJ 07103, United States

**Joseph Fernandez-Moure,** Department of Surgery, Division of Trauma, Acute, and Critical Care Surgery, Duke University School of Medicine, Durham, NC 27710, United States

**Author contributions:** Fernandez-Moure J conceived the original main idea of this review; Lebhar MS, Rameshwar P, Anastasio A, and Gergues M contributed to developing and revising the drafts.

**Corresponding author: Joseph Fernandez-Moure, MD, MSc, Surgeon,** Department of Surgery, Division of Trauma, Acute, and Critical Care Surgery, Duke University School of Medicine, 2301 Erwin Rd, Durham, NC 27710, United States. joseph.fernandezmoure@duke.edu

**Received:** April 17, 2020

**Revised:** September 26, 2020

**Accepted:** October 13, 2020

**Published online:**

**Abstract**

The potential clinical and economic impact of mesenchymal stem cell (MSC) therapy is immense. MSCs act through multiple pathways: (1) as “trophic” cells, secreting various factors that are immunomodulatory, anti-inflammatory, anti-apoptotic, proangiogenic, proliferative, and chemoattractive; (2) in conjunction with cells native to the tissue they reside in to enhance differentiation of surrounding cells to facilitate tissue regrowth. Researchers have developed methods for the extraction and expansion of MSCs from animal and human tissues. While many sources of MSCs exist, including adipose tissue and iliac crest bone graft, compact bone (CB) MSCs have shown great potential for use in orthopaedic surgery. CB MSCs exert powerful immunomodulatory effects in addition to demonstrating excellent regenerative capacity for use in filling boney defects. CB MSCs have been shown to have enhanced response to hypoxic conditions when compared with other forms of MSCs. More work is needed to continue to characterize the potential applications for CB MSCs in orthopaedic trauma.

**Key Words:** Compact bone; Mesenchymal stem cells; Stem cells; Trauma; Orthopedic; Regeneration

Anastasio A, Gergues M, Lebhar MS, Rameshwar P, Fernandez-Moure J. Isolation and characterization of mesenchymal stem cells in orthopaedics and the emergence of compact bone mesenchymal stem cells as a promising surgical adjunct. *World J Stem Cells* 2020; In press

**Core Tip:** The use of stem cell therapies continues to emerge as available therapy for tissue engineering of orthopedic trauma. Compact bone mesenchymal stem cells (MSCs) have been studied for many years and have been found to have a greater orthopedic regenerative capacity compared to other autologous sources. Herein, we describe and review a novel source of MSCs from compact bone and their uses in orthopedic regeneration. This review is best suited for the traumatologist in search of a comprehensive review of this novel sources of MSCs and their potential uses *in vitro*, *in vivo*, and clinically.

**INTRODUCTION**

***Background on mesenchymal stem cells***

The osteogenic ability of bone marrow aspirate was first demonstrated by Jones *et al*[1,2] in 1869. This ability was later attributed to the presence of mesenchymal stem cells (MSCs), which are a heterogeneous population of cells defined by surface markers[1,3,4]. MSCs isolated from animal models have consistently demonstrated capacity for multi lineage differentiation, pluripotency, and myriad MSC surface markers[5]. MSCs have also been extracted from human sources, and can be harvested from bone marrow, blood, or mesenchymal tissues (including bone, cartilage, meniscus, ligaments, and tendons). After harvest, they undergo isolation, expansion, and differentiation to create a lineage aimed at modulating the immune system and the regenerative response[6-9]. A common harvest site is from the bone marrow (iliac crest), and this specimen contains mixtures of mesenchymal progenitors with variable differentiation potential[10]. Hernigou *et al*[11] reported concentrations of approximately 400 mesenchymal stem cells/mL of iliac crest aspirate. Another site for harvest of MSC is adipose tissue, which is obtained through standard liposuction methods[12-15]. While these sites are capable of generating a robust number of MSCs, they are both surgically morbid procedures with their own sets of complications.

MSC isolation began in the 1970s, where initial investigations demonstrated that bone, cartilage, muscle and other mesenchymal tissue could be differentiated from embryonic stage chick limb bud mesenchymal progenitor cells[16,17]. MSCs were found to have the capacity to differentiate into cartilage, muscle, marrow stroma, tendons, ligaments, fat, and other connective tissues[15]. Recent technology developments for isolating and culture expanding adult marrow-derived MSCs has led to an explosion of research opportunities with current and future clinical applications[18-20]. Most recently, MSCs isolated from trabecular and cortical bone portions, referred to as cortical bone fraction MSCs (CB-MSCs), have emerged[4]. CB-MSCs have shown to have higher biosynthetic activity *in vitro* under hypoxic conditions when compared to MSCs of other sources[21]. These findings have profound implications since CB-MSCs have the unique ability to withstand the harsh conditions that may exist in recipient tissue. The mechanisms behind enhanced survivability in the hypoxic condition are numerous, and may include the enhanced production of a variety of protective cytokines[21,22]. Regardless, post-traumatic inflammation, reactive oxygen species, and compromised blood flow inducing hypoxic tissue state complicate the *in vivo* environment after fracture, and thus, CB-MSCs may be better suited for orthopedic tissue engineering than their bone marrow-derived counterparts[21].

From enhancing current techniques used to treat fractures or bolster fusions, to tissue engineering and the opportunity to impact genetic diseases such as Osteogenesis Imperfecta or muscular dystrophy in cell replacement therapy, the number of patients that could be positively impacted by use of MSCs is wide-ranging. Prior to exploring current uses of mesenchymal stem cells in orthopaedic surgery and discussing emerging evidence in support for further research of CB-MSCs within orthopaedics, we will survey current source isolation and characterization techniques of MSCs.

***Sourcing of MSCs***

Today we have many sources of MSCs, including the two most commonly discussed – iliac crest bone marrow aspirate and adipose tissue. These have shown some benefit in achieving osseous regeneration in some clinical applications. However, there is a wide variation in refining methods and administration techniques within the current literature, and there has yet to be a standardized volume or concentration of MSCs within published data, which has led to varied results[23-25].

Mesenchymal progenitor cells have a prevalence of approximately one per 30000 nucleated cells from iliac crest bone marrow aspirate in some studies[9]. This calculates to around 600 progenitor cells per milliliter. This could be further increased to 2500 per milliliter by concentration techniques, such as centrifugation or freezing, or by small volume aspiration[4,9]. Large amounts of progenitor cells are required for most orthopedic applications, though, which makes bone marrow aspiration impractical. Thus, alternative sources of MSC where yield and osteogenic potential are greater is sought.

Adipose tissue, dental pulp, and umbilical cord MSCs are additional sources that have proven reliable sources of MSCs[16]. All these sources have their own advantages and disadvantages, but one common drawback shared by these sources is donor site surgical intervention required to acquire the cells. Further, while many sources have been identified and used experimentally in orthopedic regeneration what lacks is a consensus on what source is best suited for bony repair. Some studies have shown bone marrow MSCs to be equal to umbilical MSCs, but superior to adipose MSCs[26]. However, there is newer research showing extraction of MSCs from compact or cortical bone[27]. The benefit of this therapy is that it can harvested intra-operatively and can potential yield a population of cells predisposed to promoting an osteogenic niche. Compact bone has been identified as a viable and reliable source for MSCs. Using discarded bone from laminectomy specimens, Fernandez-Moure *et al*[28] demonstrated that CB-MSCs were found in the spine.

Given their origin, this unique population of cells holds significant potential for orthopedic regeneration. With intra-operative refinement techniques, this harvested compact bone could be a source of MSCs that could be administered during the same operative procedure[28]. Theoretically, a surgeon could derive cells from extracted bone and reimplant in the same procedure from the same source, thus overcoming many of the regulatory hurdles associated with a donor procedure. This will decrease costs, anesthesia time, and patient morbidity while giving improved outcomes in skeletal reconstruction. While determination of an ideal source remains an ongoing debate, isolation techniques once a source has been identified is an additional hurdle to the effective implementation of MSCs from various sources.

***Isolation techniques of CB-MSCs***

Since Friedrichstein identified the isolation of cells of the mesenchymal lineage, many methods for the isolation of mesenchymal progenitor cells have been described (Table 1). The isolation of bone derived MSCs was first described by Robey *et al*[29]. In this study human bone cell cultures were established by maintaining collagenase-treated, bone fragments in low Ca2+ medium and the technique described provided a useful system for the study of osteoblast metabolism *in vitro.* This method of isolation has been adapted for use in clinical samples. Tuli *et al*[30] described a method where reaming debris was taken from the intramedullary canal of femurs undergoing total hip arthroplasty. Reaming debris was then taken and underwent collagenase XI digestion for 3-4 d until cellular material had disappeared. Boney fragments were then transplanted into new flasks and allowed to culture so that cells would migrate out from the bone and onto the plastic surface. Those cells underwent multilineage characterization and immunohistochemical analysis. Similarly, others have used mono-enzyme digest using collagenase I or II as the sole processing agent for MSC isolation[4,31,32]. In order to enhance the selectivity of the cell population isolated Gangji *et al*[33] coupled a Collagase and Dipase digest with fluorescent assisted cell sorting for MSC specific makers. This method of characterization lead to a homogenous population of MSCs as defined by the standards of the International Society for Cellular Therapy[34]. Relied solely on cellular migration outward from the boney reamings and the inherent property of stem cell plastic adherence to isolate their cell population. They used the bone reamings of patients with closed diaphyseal femur fractures who were undergoing internal intramedullary nail fixation for cellular extraction without any additional agents. Cells adherent after ten days were transferred to a new flask and grown to confluence prior to phenotypic characterization. While no comparison was made to other methods of isolation the authors did demonstrate the capability of the bone reaming derived cells to transform into both neuron-like cells and functional osteoblasts. This suggested that cells derived from the bone itself were capable of transdifferentiation, a characteristic of MSCs.

Various processing agents and isolation methods have been described for the isolation of CB MSCs as well. Zhu *et al*[25] 2010 described a protocol for the isolation and culture of large numbers of murine MSCs (mMSCs) from compact bones in contrast to mMSCs culture from bone marrow, the bone marrow cavities are flushed at least three times in order to thoroughly deplete hematopoietic cells[35-37]. The mouse compact bones are then dissected into fragments of 1-3 mm3 and digested with collagenase II. The released cells are discarded and the digested bone fragments are cultivated in an MSC culture medium. In contrast to the frequent medium changes in primary culture required in the mouse bone marrow culture technique, the culture medium is not changed until the third day after the initiation of culture[35]. During cultivation, fibroblast-like cells are observed around the collagenase-digested bone fragments within 48 h of cultivation. The mMSC cultures reach 70%-80% confluence within 5 d in the first passage and significant numbers (> 107) of mMSC can be harvested in a short time from one mouse.

This protocol has been modified from the original description by Guo *et al*[24]*.* Where muMPC, murine mesenchymal progenitor cells, culture was developed by addition of bone fragments with mouse bone marrow cells in the presence of basic fibroblast growth factor and bone fragment-conditioned medium. They postulate that murine counterparts were able to be purified with adherent culture of either enzyme-treated bone fragments or the released cells[38-42]. In the protocol the femurs and tibiae were collected from 2 to 3-wk old C57BL/6 female mice. The epiphyses were removed, bone marrow was flushed out, and the bone cavities were washed thoroughly. In the presence of collangease II the cells were allowed to migrate out and seed culture plates. Cai *et al*[43] expanded upon these methodologies by obtaining compact bone fragments, culturing them, and isolating CB-MSCs. After trypsinization of these cell lines, the cultured fragments exhibited significantly higher proliferation and were accompanied with less CD45 expression but more CD90 and CD44 expressions. Moreover, the capacity for osteogenic and adipogenic differentiation of the MSCs obtained from the cultured compact bone was enhanced when compared to the cells harvested from bone marrow[43].

Varying methods of cell isolation have been described yet none has been shown to be superior to another. After isolation of MSCs from a donor source, characterization of the obtained cells is necessary to maximize downstream utilization as well as to be able to standardize methodology for future investigation (Table 1).

***Characterization techniques***

Techniques have been developed to source, isolate, and experimentally assess CB-MSCs.

Many laboratories have developed methods for the extraction and expansion of MSCs from bone. Once isolated, the characterization of the cell population is critical to its downstream uses and potential. The variation of methods used and the variety of tissue sources used has lead to significant differences in the cell population isolated and the need for minimal criteria for the definition of a mesenchymal stromal cell was required to standardize investigation. To address this need, the Mesenchymal and Tissue Stem Cell Committee of the International Society for Cellular Therapy established the minimal criteria by which a cell could be characterized and thus named a mesenchymal stromal cell[44]. Three criteria were proposed: (1) cell adherence to plastic; (2) specific surface antigen expression; and (3) multipotent differentiation.

These criteria allowed for a standard to be set for those working in isolation of CB-MSCs. First, the isolated cells must be adherent to plastic; Second, > 95% of the isolated cells must express CD 105, CD73, and CD90 measured with flow cytometry. In addition, the absence of CD45, CD34, CD14 or 11b, CD79 or CD19 and human leukocyte antigen class II must be documented in < 2% of the cell population; Lastly, the cells must be able to differentiate, under appropriate conditions, into adipocytes, chondrocytes, and osteocytes. Prior to the establishment of the aforementioned standard by the International Society for Cellular Therapy many characterized the cell isolated from the bone by their ability to tri-lineage differentiate. While this proved useful for their translational potential it underestimated the true potential and full character of the cell itself. CB-MSC identified have shown all these characteristics. Further, studies into source specific markers for MSC in addition to those identified are currently underway.

***Clinical applications of MSCs in orthopaedic surgery***

MSCs have long been utilized in orthopaedic surgery, and their clinical applications are robust. The economic impact that these therapies have the potential to affect is immense. Public health investigations have shown that osteoarthritis is associated with an economic burden of approximately $150 billion (2007 dollars), and is projected to affect 25% of the adult United States Population by 2030[11,45]. From the standpoint of orthopedic trauma, it has been estimated that 100000 fractures will go onto non-union each year in the United States alone[17]. Zull *et al*[46] looked at direct and indirect costs of reamed intramedullary nailing for tibial fractures compared to casting, casting plus ultrasound, and non-reamed intramedullary nailing. They found that reamed intra-medullary nailing led to significant reduction in non-union rates, and calculated an approximate cost of $11800 (Canadian) per non-union case[46]. Beaver *et al*[47] looked establish tibial non-unions and calculated their surgical and medical care to cost United States $ 11333 per case. From increasing union rates, enhancing fusions, minimizing bone stock defects after total joints to treating articular cartilage defects, tendinopathies, avascular necrosis or bone cysts, the full impact of applications of MSCs is difficult to quantify both clinically and economically. The possibilities are as diverse as they are fascinating, and the ability to consistently improve even one of these complications or disease processes would have a great impact on the patients that are involved and the healthcare system.

While the field of orthopaedic surgery has pioneered the use MSCs many other fields within medicine have the potential to benefit from the knowledge gained from working with MSCs (Table 2). Within the field of head and neck surgery, animal research has shown promise with the use of MSCs along with mandibular distraction osteogenesis producing improved total bone production and compact bone ratios in the “regenerate” or bone formed at the distraction site[48]. Liu *et al*[49] published a case report of their success using bone marrow aspirated MSCs to treat a patient with poorly controlled diabetes mellitus and a severe post-traumatic infection causing non-healing skin defect in the hand. The wound demonstrated complete healing 10-d after treatment saving the patient from wrist amputation[49]. Using a rat-model of ischemic cardiomyopathy, Tano *et al*[50] showed improved cardiac function after application of a pericardial MSCs embedded within a biodegradable carrier membrane.

The use of MSCs for regeneration of the musculoskeletal system is an area of much basic science research and evolving clinical applications[51-54]. Over the past twenty years, MSCs have been used clinically in a variety of scenarios to enhance the outcome for orthopedic patients from the standpoint of both wound healing and pain[55]. Dating back to the 1980s, bone grafting and bone marrow injection into fracture sites has been utilized to enhance union[4]. The use of MSCs in the setting of non-unions and critically sized defects, where bone’s natural regenerative capacity to heal without scarring is impaired due to poor biology and/or biomechanical environment, was the focus of early investigations[6,16]. Connolly *et al*[32] published a case series of 20 tibial non-unions treated with unprocessed bone marrow with 90% demonstrating union at 6-8 mo follow-up. Hernigou *et al*[56] discussed the use aspirated iliac crest marrow with centrifugation to separate out osteoprogenitor cells (based on fibroblast colony forming units, CFU-F) for re-injection in sixty tibial non-unions. Fifty-three of the 60 patients went on to union at an average of twelve week[56]. Clinical applications of MSCs have since expanded to include healing of high-tibial osteotomies, large bone defects after total hip arthroplasty and trauma, distraction osteogenesis, treatment of avascular necrosis, articular cartilage defects, tendinopathy (patellar, lateral epicondylitis), spinal fusion, and treatment of bone cysts[2,4,31,55,57-60]. These findings paved the way for future use and investigations to understand the mechanisms underlying the observed wound healing effects. While MSCs have certainly proved to have widespread efficacy in orthopaedics, CB-MSCs, remain underutilized and under-investigated within the field.

***The potential of CB-MSCs***

MSCs have widespread uses within orthopaedics, but traditionally, the cortical bone fragment remains underutilized. Emerging developments have allowed for the isolation and characterization of CB-MSCs. Thus, investigation of the efficacy of CB-MSCs in murine models has been undertaken with very promising results. CB-MSCs appear to have beneficial immunomodulatory properties, which indicates that they may have great potential for utilization in cases requiring boney augmentation.

Repair of large bone defects still poses a major challenge for the orthopedic surgeon. For instance, it is widely known that these defects cannot heal on their own or repair themselves to a fully functional tissue. To overcome these issues, orthopedic surgeons generally implant a section of bone tissue. Unfortunately, this can lead to immune rejection or infections. The severity of these potential complications necessitates careful consideration of the immunological milieu surrounding the boney defect. With their diverse biological properties and efficacy, MSCs have long been considered as the ideal cells for cellular therapy. MSCs have the potential of secreting factors such as cytokines and exosomes, to produce varied effects within a specific microenvironment[61-64]. Once educated, a process also called “licensing”, MSCs turn into anti-inflammatory cells within their niche, which can exert immunosuppressive functions to affect other cells within the immune system[6,7,65,66].

MSCs have obvious beneficial effects on the inflammatory milieu, and traditionally, these cells have been isolated from bone marrow and adipose derived MSCs. Emerging techniques have allowed for the additional isolation of MSCs from the cortical or compact bone. MSCs harbored within these tissues have been shown to be isolated in large quantities making re-transplantation a clinical reality. Once isolated their osteogenic regenerative potential has been measured and, *in vitro*, has been shown to be superior to adipose or bone marrow derived MSCs. Blashki *et al*[67] demonstrated that MSCs isolated form the cortical bone had greater potential for colony forming unit formation *in vitro* and greater osteoid generation *in vivo*. Similarly, Murphy *et al*[68] demonstrated an enhanced potential for CFU formation when cortical bone MSCs were cultured on bioactive osteogenic scaffolds. While the potential for osteogenesis was demonstrated in these studies a direct comparison had not established which tissue surface was ideal for osteogenic regeneration.

Moreover, like MSCs obtained from other sources, CB-MSCs appear to have excellent immunomodulatory properties. Previously, Guo *et al*[24] performed skin grafting in a mouse model (C57BL/63BALB/c) with or without murine CB-MSCs pre-transfusion in order to determine if these cells had immunosuppressive effects *in vivo*. Their findings indicated that the delivery of these cells caused a significant increase in survival of allogeneic skin grafts further ascertaining the anti-inflammatory role that these cells exert on the *in vivo* immune response. Recently, some studies have shown that CB-MSCs are both multipotent and capable of extensive *in vitro* expansion similar to BM-MSCs, enhancing their therapeutic appeal in the field of orthopedics[69,70]. Besides phonotypical properties, CB-MSCs have been shown to share with BM-MSCs functional properties such as tri-differentiation potential in adequate conditions and immune suppression both *in vitro* and *in vivo*[71-73]. For instance, in a mouse model of acute graft-versus-host disease, Zhu *et al*[25] reported a decrease in tissue damage after transfusion of murine CB-MSCs, potentially altering the phenotype and function of splenic lymphocyte[74]. Similarly, these authors inferred that CB-MSCs also affected functional properties of T lymphocytes and dendritic cells by modulating their migratory behavior leading to a delayed lethal acute graft-versus host disease reaction[75]. Furthermore, Qiao *et al*[76] demonstrated a significant protective benefit of CB-MSCs in a radiation-induced hematopoietic toxicity mouse model. CB-MSCs acted to alleviate lymphocyte-mediated CFU-GM, colony-forming unit granulocyte/macrophage, inhibition and expand regulatory T cell lineages. They also mitigated T cell chemokine receptor expression and shifted the Th1/Th2 balance toward anti-inflammatory Th2 polarization[76].

In another study, authors investigated the impact of CB-MSCs in airway remodeling and inflammation in experimental ovalbumin-induced mouse model of chronic asthma. The authors infused GFP-labeled murine CB-MSCs which were located in the lungs of OVA group 2 wk after intravenous induction accompanied with a significant Treg response in ovalbumin-treated mice. It is worth noting that increase in Treg cell numbers along with other factors such as cytokines, to be linked to MSC-mediated immunomodulation[77]. Thus murine CB-MSCs could be effective at reducing an allergic inflammation. Furthermore, Shan *et al*[78] demonstrated mitigation of prion disease in brain extracts from infected mice after administration of CB-MSCs by enhancing microglial activation. Remarkably, the Intra-hippocampus transplantation of CB-MSCs had a small but statistically significant effect on prolonging the survival of mice inoculated with the Chandler prion strain[78].

CB-MSCs appear to not only have efficacy from an immunomodulatory standpoint, but may serve as an ideal scaffold material adjunct to repair boney defects. CB-MSCs when compared with BM-MSC, are bigger in size, show a lower proliferation rate at early passages, and have a greater commitment toward the osteogenic lineage. This cell source has been shown *in vitro* to generate greater alkaline phosphatase and calcium deposition in both normoxic and hypoxic conditions[23]. MSCs attached to three-dimensional scaffold designed to mimic the biological and mechanical role of extracellular matrix can be a faster approach to promote bone regeneration[79]. To date, several scaffolds have been used in MSC-based bone augmentation procedures. For these scaffolds, most of the literature reports on hydroxy apatite, b-tricalcium phosphate or a mixture of the two as mineral component interacting with MSC[80,81]. These scaffolds for bone engineering should possess key characteristic specifications including: osteo-conductivity, biocompatibility (adequate biological response), biodegradability, easily manufactured and sterilized, easily handled in the surgery room, and cost effective[82-85]. Moreover, the scaffold should have an architecture that resembles the structure of bone.

Thus, with their vast appealing functional roles, including immunosuppression, CB-MSCs are ideal cells for cellular therapy in bone tissue engineering. Several researchers have proposed using CB-MSCs and three-dimensional scaffolds and implanting this combination into donor patients. To date, however, very few studies have looked into the use of CB-MSCs and scaffolds for compact bone regeneration. Perhaps with future research, CB-MSCs will be also considered as promising candidates for use in development of bioengineered bone to potentially impact clinical therapy and possibly beneficial to in bone engineering and regeneration[86-100].

**CONCLUSION**

MSCs hold great promise for regenerative therapies in osteogenic surgery. While there is still debate on the ideal source of MSCs to use in tissue regeneration, the field is still moving in the right direction for clinical applications. Previous work from our lab shows that compared with BM-MSCs and AD-MSCs, CB-MSCs have superior ability to survive in hypoxic conditions while remaining biosynthetically active[27]. CB-MSCs have been demonstrated to have excellent immunomodulatory efficacy in various animal models. More work needs to be continued both *in vitro* and *in vivo* to properly characterize these cells and make them functional for tissue engineering and regeneration.

**REFERENCES**

1 **Hernigou P**, Poignard A, Manicom O, Mathieu G, Rouard H. The use of percutaneous autologous bone marrow transplantation in nonunion and avascular necrosis of bone. *J Bone Joint Surg Br* 2005; **87**: 896-902 [PMID: 15972899 DOI: 10.1302/0301-620X.87B7.16289]

2 **Jones E**, Yang X. Mesenchymal stem cells and bone regeneration: current status. *Injury* 2011; **42**: 562-568 [PMID: 21489533 DOI: 10.1016/j.injury.2011.03.030]

3 **Nöth U**, Rackwitz L, Steinert AF, Tuan RS. Cell delivery therapeutics for musculoskeletal regeneration. *Adv Drug Deliv Rev* 2010; **62**: 765-783 [PMID: 20398712 DOI: 10.1016/j.addr.2010.04.004]

4 **Steinert AF**, Rackwitz L, Gilbert F, Nöth U, Tuan RS. Concise review: the clinical application of mesenchymal stem cells for musculoskeletal regeneration: current status and perspectives. *Stem Cells Transl Med* 2012; **1**: 237-247 [PMID: 23197783 DOI: 10.5966/sctm.2011-0036]

5 **Fathi E**, Farahzadi R, Sheikhzadeh N. Immunophenotypic characterization, multi-lineage differentiation and aging of zebrafish heart and liver tissue-derived mesenchymal stem cells as a novel approach in stem cell-based therapy. *Tissue Cell* 2019; **57**: 15-21 [PMID: 30947959 DOI: 10.1016/j.tice.2019.01.006]

6 **Ren G**, Zhang L, Zhao X, Xu G, Zhang Y, Roberts AI, Zhao RC, Shi Y. Mesenchymal stem cell-mediated immunosuppression occurs via concerted action of chemokines and nitric oxide. *Cell Stem Cell* 2008; **2**: 141-150 [PMID: 18371435 DOI: 10.1016/j.stem.2007.11.014]

7 **Sherman LS**, Shaker M, Mariotti V, Rameshwar P. Mesenchymal stromal/stem cells in drug therapy: New perspective. *Cytotherapy* 2017; **19**: 19-27 [PMID: 27765601 DOI: 10.1016/j.jcyt.2016.09.007]

8 **Laschke MW**, Schank TE, Scheuer C, Kleer S, Shadmanov T, Eglin D, Alini M, Menger MD. In vitro osteogenic differentiation of adipose-derived mesenchymal stem cell spheroids impairs their *in vivo* vascularization capacity inside implanted porous polyurethane scaffolds. *Acta Biomater* 2014; **10**: 4226-4235 [PMID: 24998773 DOI: 10.1016/j.actbio.2014.06.035]

9 **Corradetti B**, Taraballi F, Powell S, Sung D, Minardi S, Ferrari M, Weiner BK, Tasciotti E. Osteoprogenitor cells from bone marrow and cortical bone: understanding how the environment affects their fate. *Stem Cells Dev* 2015; **24**: 1112-1123 [PMID: 25517215 DOI: 10.1089/scd.2014.0351]

10 **McDaniel JS**, Antebi B, Pilia M, Hurtgen BJ, Belenkiy S, Necsoiu C, Cancio LC, Rathbone CR, Batchinsky AI. Quantitative Assessment of Optimal Bone Marrow Site for the Isolation of Porcine Mesenchymal Stem Cells. *Stem Cells Int* 2017; **2017**: 1836960 [PMID: 28539939 DOI: 10.1155/2017/1836960]

11 **Hernigou P**, Homma Y, Flouzat Lachaniette CH, Poignard A, Allain J, Chevallier N, Rouard H. Benefits of small volume and small syringe for bone marrow aspirations of mesenchymal stem cells. *Int Orthop* 2013; **37**: 2279-2287 [PMID: 23881064 DOI: 10.1007/s00264-013-2017-z]

12 **Zhu M**, Heydarkhan-Hagvall S, Hedrick M, Benhaim P, Zuk P. Manual isolation of adipose-derived stem cells from human lipoaspirates. *J Vis Exp* 2013; e50585 [PMID: 24121366 DOI: 10.3791/50585]

13 **Mahmoudifar N**, Doran PM. Mesenchymal Stem Cells Derived from Human Adipose Tissue. *Methods Mol Biol* 2015; **1340**: 53-64 [PMID: 26445830 DOI: 10.1007/978-1-4939-2938-2\_4]

14 **Odabas S**, Elçin AE, Elçin YM. Isolation and characterization of mesenchymal stem cells. *Methods Mol Biol* 2014; **1109**: 47-63 [PMID: 24473777 DOI: 10.1007/978-1-4614-9437-9\_3]

15 **Rajabzadeh N**, Fathi E, Farahzadi R. Stem cell-based regenerative medicine. *Stem Cell Investig* 2019; **6**: 19 [PMID: 31463312 DOI: 10.21037/sci.2019.06.04]

16 **Caplan AI**. Review: mesenchymal stem cells: cell-based reconstructive therapy in orthopedics. *Tissue Eng* 2005; **11**: 1198-1211 [PMID: 16144456 DOI: 10.1089/ten.2005.11.1198]

17 **Osdoby P**, Caplan AI. Osteogenesis in cultures of limb mesenchymal cells. *Dev Biol* 1979; **73**: 84-102 [PMID: 527770 DOI: 10.1016/0012-1606(79)90140-4]

18 **Adesida AB**, Mulet-Sierra A, Jomha NM. Hypoxia mediated isolation and expansion enhances the chondrogenic capacity of bone marrow mesenchymal stromal cells. *Stem Cell Res Ther* 2012; **3**: 9 [PMID: 22385573 DOI: 10.1186/scrt100]

19 **Pountos I**, Corscadden D, Emery P, Giannoudis PV. Mesenchymal stem cell tissue engineering: techniques for isolation, expansion and application. *Injury* 2007; **38 Suppl 4**: S23-S33 [PMID: 18224734 DOI: 10.1016/s0020-1383(08)70006-8]

20 **Osiecki MJ**, Michl TD, Kul Babur B, Kabiri M, Atkinson K, Lott WB, Griesser HJ, Doran MR. Packed Bed Bioreactor for the Isolation and Expansion of Placental-Derived Mesenchymal Stromal Cells. *PLoS One* 2015; **10**: e0144941 [PMID: 26660475 DOI: 10.1371/journal.pone.0144941]

21 **Sivanathan KN**, Gronthos S, Grey ST, Rojas-Canales D, Coates PT. Immunodepletion and Hypoxia Preconditioning of Mouse Compact Bone Cells as a Novel Protocol to Isolate Highly Immunosuppressive Mesenchymal Stem Cells. *Stem Cells Dev* 2017; **26**: 512-527 [PMID: 27998209 DOI: 10.1089/scd.2016.0180]

22 **Lin M**, Liu X, Zheng H, Huang X, Wu Y, Huang A, Zhu H, Hu Y, Mai W, Huang Y. IGF-1 enhances BMSC viability, migration, and anti-apoptosis in myocardial infarction via secreted frizzled-related protein 2 pathway. *Stem Cell Res Ther* 2020; **11**: 22 [PMID: 31918758 DOI: 10.1186/s13287-019-1544-y]

23 **Nöth U**, Osyczka AM, Tuli R, Hickok NJ, Danielson KG, Tuan RS. Multilineage mesenchymal differentiation potential of human trabecular bone-derived cells. *J Orthop Res* 2002; **20**: 1060-1069 [PMID: 12382974 DOI: 10.1016/S0736-0266(02)00018-9]

24 **Guo Z**, Li H, Li X, Yu X, Wang H, Tang P, Mao N. In vitro characteristics and *in vivo* immunosuppressive activity of compact bone-derived murine mesenchymal progenitor cells. *Stem Cells* 2006; **24**: 992-1000 [PMID: 16644925 DOI: 10.1634/stemcells.2005-0224]

25 **Zhu H**, Guo ZK, Jiang XX, Li H, Wang XY, Yao HY, Zhang Y, Mao N. A protocol for isolation and culture of mesenchymal stem cells from mouse compact bone. *Nat Protoc* 2010; **5**: 550-560 [PMID: 20203670 DOI: 10.1038/nprot.2009.238]

26 **Nagamura-Inoue T**, He H. Umbilical cord-derived mesenchymal stem cells: Their advantages and potential clinical utility. *World J Stem Cells* 2014; **6**: 195-202 [PMID: 24772246 DOI: 10.4252/wjsc.v6.i2.195]

27 **Fernandez-Moure JS**, Corradetti B, Chan P, Van Eps JL, Janecek T, Rameshwar P, Weiner BK, Tasciotti E. Enhanced osteogenic potential of mesenchymal stem cells from cortical bone: a comparative analysis. *Stem Cell Res Ther* 2015; **6**: 203 [PMID: 26503337 DOI: 10.1186/s13287-015-0193-z]

28 **Fernandez-Moure JS,** *et al* (2016) Characterization of Mesenchymal Stem Cells from Human Cortical Bone. International Journal of Translational Science **1**:71-86

29 **Robey PG**, Termine JD. Human bone cellsin vitro. *Calcif Tissue Int* 1985; **37**: 453-460 [PMID: 29372293 DOI: 10.1007/BF02557826]

30 **Tuli R**, Seghatoleslami MR, Tuli S, Wang ML, Hozack WJ, Manner PA, Danielson KG, Tuan RS. A simple, high-yield method for obtaining multipotential mesenchymal progenitor cells from trabecular bone. *Mol Biotechnol* 2003; **23**: 37-49 [PMID: 12611268 DOI: 10.1385/MB:23:1:37]

31 **Salamanna F**, Sartori M, Brodano GB, Griffoni C, Martini L, Boriani S, Fini M. Mesenchymal Stem Cells for the Treatment of Spinal Arthrodesis: From Preclinical Research to Clinical Scenario. *Stem Cells Int* 2017; **2017**: 3537094 [PMID: 28286524 DOI: 10.1155/2017/3537094]

32 **Connolly JF**. Clinical use of marrow osteoprogenitor cells to stimulate osteogenesis. *Clin Orthop Relat Res* 1998: S257-S266 [PMID: 9917645 DOI: 10.1097/00003086-199810001-00026]

33 **Gangji V**, Hauzeur JP, Matos C, De Maertelaer V, Toungouz M, Lambermont M. Treatment of osteonecrosis of the femoral head with implantation of autologous bone-marrow cells. A pilot study. *J Bone Joint Surg Am* 2004; **86**: 1153-1160 [PMID: 15173287 DOI: 10.2106/00004623-200406000-00006]

34 **Baghaei K**, Hashemi SM, Tokhanbigli S, Asadi Rad A, Assadzadeh-Aghdaei H, Sharifian A, Zali MR. Isolation, differentiation, and characterization of mesenchymal stem cells from human bone marrow. *Gastroenterol Hepatol Bed Bench* 2017; **10**: 208-213 [PMID: 29118937]

35 **Soleimani M**, Nadri S. A protocol for isolation and culture of mesenchymal stem cells from mouse bone marrow. *Nat Protoc* 2009; **4**: 102-106 [PMID: 19131962 DOI: 10.1038/nprot.2008.221]

36 **Sun S**, Guo Z, Xiao X, Liu B, Liu X, Tang PH, Mao N. Isolation of mouse marrow mesenchymal progenitors by a novel and reliable method. *Stem Cells* 2003; **21**: 527-535 [PMID: 12968107 DOI: 10.1634/stemcells.21-5-527]

37 **da Silva Meirelles L**, Chagastelles PC, Nardi NB. Mesenchymal stem cells reside in virtually all post-natal organs and tissues. *J Cell Sci* 2006; **119**: 2204-2213 [PMID: 16684817 DOI: 10.1242/jcs.02932]

38 **Hare JM**, Traverse JH, Henry TD, Dib N, Strumpf RK, Schulman SP, Gerstenblith G, DeMaria AN, Denktas AE, Gammon RS, Hermiller JB Jr, Reisman MA, Schaer GL, Sherman W. A randomized, double-blind, placebo-controlled, dose-escalation study of intravenous adult human mesenchymal stem cells (prochymal) after acute myocardial infarction. *J Am Coll Cardiol* 2009; **54**: 2277-2286 [PMID: 19958962 DOI: 10.1016/j.jacc.2009.06.055]

39 **Kawamoto A**, Katayama M, Handa N, Kinoshita M, Takano H, Horii M, Sadamoto K, Yokoyama A, Yamanaka T, Onodera R, Kuroda A, Baba R, Kaneko Y, Tsukie T, Kurimoto Y, Okada Y, Kihara Y, Morioka S, Fukushima M, Asahara T. Intramuscular transplantation of G-CSF-mobilized CD34(+) cells in patients with critical limb ischemia: a phase I/IIa, multicenter, single-blinded, dose-escalation clinical trial. *Stem Cells* 2009; **27**: 2857-2864 [PMID: 19711453 DOI: 10.1002/stem.207]

40 **Tateishi-Yuyama E,** Matsubara H, Murohara T, Ikeda U, Shintani S, Masaki H, Amano K, Kishimoto Y, Yoshimoto K, Akashi H, Shimada K, Iwasaka T, Imaizumi T, Therapeutic Angiogenesis using Cell Transplantation Study. Therapeutic angiogenesis for patients with limb ischaemia by autologous transplantation of bone-marrow cells: a pilot study and a randomised controlled trial. *Lancet* 2002; 360: 427-435 [PMID: 12241713 DOI: 10.1016/S0140-6736(02)09670-8]

41 **Cobellis G**, Maione C, Botti C, Coppola A, Silvestroni A, Lillo S, Schiavone V, Molinari AM, Sica V. Beneficial effects of VEGF secreted from stromal cells in supporting endothelial cell functions: therapeutic implications for critical limb ischemia. *Cell Transplant* 2010; **19**: 1425-1437 [PMID: 20587143 DOI: 10.3727/096368910X509068]

42 **Au P**, Tam J, Fukumura D, Jain RK. Bone marrow-derived mesenchymal stem cells facilitate engineering of long-lasting functional vasculature. *Blood* 2008; **111**: 4551-4558 [PMID: 18256324 DOI: 10.1182/blood-2007-10-118273]

43 **Cai Y**, Liu T, Fang F, Xiong C, Shen S. Comparisons of mouse mesenchymal stem cells in primary adherent culture of compact bone fragments and whole bone marrow. *Stem Cells Int* 2015; **2015**: 708906 [PMID: 25821472 DOI: 10.1155/2015/708906]

44 **Dominici M**, Le Blanc K, Mueller I, Slaper-Cortenbach I, Marini F, Krause D, Deans R, Keating A, Prockop Dj, Horwitz E. Minimal criteria for defining multipotent mesenchymal stromal cells. The International Society for Cellular Therapy position statement. *Cytotherapy* 2006; **8**: 315-317 [PMID: 16923606 DOI: 10.1080/14653240600855905]

45 **Raposio E**, Caruana G, Bonomini S, Libondi G. A novel and effective strategy for the isolation of adipose-derived stem cells: minimally manipulated adipose-derived stem cells for more rapid and safe stem cell therapy. *Plast Reconstr Surg* 2014; **133**: 1406-1409 [PMID: 24867723 DOI: 10.1097/PRS.0000000000000170]

46 **Zull JE**, Youngman K, Caplan AI. The development of hormonal responses of cultured embryonic chick limb mesenchymal cells. *Dev Biol* 1981; **86**: 61-68 [PMID: 6269927 DOI: 10.1016/0012-1606(81)90315-8]

47 **Beaver R**, Brinker MR, Barrack RL. An analysis of the actual cost of tibial nonunions. *J La State Med Soc* 1997; **149**: 200-206 [PMID: 9188244]

48 **Earley M**, Butts SC. Update on mandibular distraction osteogenesis. *Curr Opin Otolaryngol Head Neck Surg* 2014; **22**: 276-283 [PMID: 24979370 DOI: 10.1097/MOO.0000000000000067]

49 **Liu Y**, Liu Y, Wang P, Tian H, Ai J, Liu Y, Zhou Y, Liu Z, Guo W, Yang S. Autologous bone marrow stem cell transplantation for the treatment of postoperative hand infection with a skin defect in diabetes mellitus: A case report. *Oncol Lett* 2014; **7:** 1857-1862 [PMID: 24932248 DOI: 10.3892/ol.2014.1998]

50 **Tano N**, Narita T, Kaneko M, Ikebe C, Coppen SR, Campbell NG, Shiraishi M, Shintani Y, Suzuki K. Epicardial placement of mesenchymal stromal cell-sheets for the treatment of ischemic cardiomyopathy; *in vivo* proof-of-concept study. *Mol Ther* 2014; **22**: 1864-1871 [PMID: 24930600 DOI: 10.1038/mt.2014.110]

51 **Holley RJ**, Tai G, Williamson AJ, Taylor S, Cain SA, Richardson SM, Merry CL, Whetton AD, Kielty CM, Canfield AE. Comparative quantification of the surfaceome of human multipotent mesenchymal progenitor cells. *Stem Cell Reports* 2015; **4**: 473-488 [PMID: 25684225 DOI: 10.1016/j.stemcr.2015.01.007]

52 **Talele NP**, Fradette J, Davies JE, Kapus A, Hinz B. Expression of α-Smooth Muscle Actin Determines the Fate of Mesenchymal Stromal Cells. *Stem Cell Reports* 2015; **4**: 1016-1030 [PMID: 26028530 DOI: 10.1016/j.stemcr.2015.05.004]

53 **Bar-Nur O**, Gerli MFM, Di Stefano B, Almada AE, Galvin A, Coffey A, Huebner AJ, Feige P, Verheul C, Cheung P, Payzin-Dogru D, Paisant S, Anselmo A, Sadreyev RI, Ott HC, Tajbakhsh S, Rudnicki MA, Wagers AJ, Hochedlinger K. Direct Reprogramming of Mouse Fibroblasts into Functional Skeletal Muscle Progenitors. *Stem Cell Reports* 2018; **10**: 1505-1521 [PMID: 29742392 DOI: 10.1016/j.stemcr.2018.04.009]

54 **Lin H**, Qiu X, Du Q, Li Q, Wang O, Akert L, Wang Z, Anderson D, Liu K, Gu L, Zhang C, Lei Y. Engineered Microenvironment for Manufacturing Human Pluripotent Stem Cell-Derived Vascular Smooth Muscle Cells. *Stem Cell Reports* 2019; **12**: 84-97 [PMID: 30527760 DOI: 10.1016/j.stemcr.2018.11.009]

55 **Thambiah MD**, Tan MKL, Hui JHP. Role of High Tibial Osteotomy in Cartilage Regeneration - Is Correction of Malalignment Mandatory for Success? *Indian J Orthop* 2017; **51**: 588-599 [PMID: 28966382 DOI: 10.4103/ortho.IJOrtho\_260\_17]

56 **Hernigou P**, Poignard A, Beaujean F, Rouard H. Percutaneous autologous bone-marrow grafting for nonunions. Influence of the number and concentration of progenitor cells. *J Bone Joint Surg Am* 2005; **87**: 1430-1437 [PMID: 15995108 DOI: 10.2106/JBJS.D.02215]

57 **Tee BC**, Sun Z. Mandibular distraction osteogenesis assisted by cell-based tissue engineering: a systematic review. *Orthod Craniofac Res* 2015; **18 Suppl 1**: 39-49 [PMID: 25865532 DOI: 10.1111/ocr.12087]

58 **Lau RL**, Perruccio AV, Evans HM, Mahomed SR, Mahomed NN, Gandhi R. Stem cell therapy for the treatment of early stage avascular necrosis of the femoral head: a systematic review. *BMC Musculoskelet Disord* 2014; **15**: 156 [PMID: 24886648 DOI: 10.1186/1471-2474-15-156]

59 **Jäger M**, Emami R, Thorey F, Krauspe R. Saving Implants BMP-2 Application in Revision Total Hip Surgery. *Int J Biomed Sci* 2006; **2**: 187-195 [PMID: 23674982]

60 **Goldberg A**, Mitchell K, Soans J, Kim L, Zaidi R. The use of mesenchymal stem cells for cartilage repair and regeneration: a systematic review. *J Orthop Surg Res* 2017; **12**: 39 [PMID: 28279182 DOI: 10.1186/s13018-017-0534-y]

61 **Walker ND**, Patel J, Munoz JL, Hu M, Guiro K, Sinha G, Rameshwar P. The bone marrow niche in support of breast cancer dormancy. *Cancer Lett* 2016; **380**: 263-271 [PMID: 26546045 DOI: 10.1016/j.canlet.2015.10.033]

62 **Castillo M**, Liu K, Bonilla L, Rameshwar P. The immune properties of mesenchymal stem cells. *Int J Biomed Sci* 2007; **3**: 76-80 [PMID: 23675026]

63 **Munoz JL**, Bliss SA, Greco SJ, Ramkissoon SH, Ligon KL, Rameshwar P. Delivery of Functional Anti-miR-9 by Mesenchymal Stem Cell-derived Exosomes to Glioblastoma Multiforme Cells Conferred Chemosensitivity. *Mol Ther Nucleic Acids* 2013; **2**: e126 [PMID: 24084846 DOI: 10.1038/mtna.2013.60]

64 **Li G**, Yuan L, Ren X, Nian H, Zhang L, Han ZC, Li X, Zhang X. The effect of mesenchymal stem cells on dynamic changes of T cell subsets in experimental autoimmune uveoretinitis. *Clin Exp Immunol* 2013; **173**: 28-37 [PMID: 23607419 DOI: 10.1111/cei.12080]

65 **Aggarwal S**, Pittenger MF. Human mesenchymal stem cells modulate allogeneic immune cell responses. *Blood* 2005; **105**: 1815-1822 [PMID: 15494428 DOI: 10.1182/blood-2004-04-1559]

66 **Valencic E**, Loganes C, Cesana S, Piscianz E, Gaipa G, Biagi E, Tommasini A. Inhibition of mesenchymal stromal cells by pre-activated lymphocytes and their culture media. *Stem Cell Res Ther* 2014; **5**: 3 [PMID: 24405828 DOI: 10.1186/scrt392]

67 **Blashki D**, Murphy MB, Ferrari M, Simmons PJ, Tasciotti E. Mesenchymal stem cells from cortical bone demonstrate increased clonal incidence, potency, and developmental capacity compared to their bone marrow-derived counterparts. *J Tissue Eng* 2016; **7**: 2041731416661196 [PMID: 27579159 DOI: 10.1177/2041731416661196]

68 **Murphy MB**, Blashki D, Buchanan RM, Fan D, De Rosa E, Shah RN, Stupp SI, Weiner BK, Simmons PJ, Ferrari M, Tasciotti E. Multi-composite bioactive osteogenic sponges featuring mesenchymal stem cells, platelet-rich plasma, nanoporous silicon enclosures, and Peptide amphiphiles for rapid bone regeneration. *J Funct Biomater* 2011; **2**: 39-66 [PMID: 24956163 DOI: 10.3390/jfb2020039]

69 **Shi HZ**, Qin XJ. CD4CD25 regulatory T lymphocytes in allergy and asthma. *Allergy* 2005; **60**: 986-995 [PMID: 15969678 DOI: 10.1111/j.1398-9995.2005.00844.x]

70 **Short B**, Wagey R. Isolation and culture of mesenchymal stem cells from mouse compact bone. *Methods Mol Biol* 2013; **946**: 335-347 [PMID: 23179842 DOI: 10.1007/978-1-62703-128-8\_21]

71 **Short BJ**, Brouard N, Simmons PJ. Prospective isolation of mesenchymal stem cells from mouse compact bone. *Methods Mol Biol* 2009; **482**: 259-268 [PMID: 19089361 DOI: 10.1007/978-1-59745-060-7\_16]

72 **Majumdar MK**, Thiede MA, Haynesworth SE, Bruder SP, Gerson SL. Human marrow-derived mesenchymal stem cells (MSCs) express hematopoietic cytokines and support long-term hematopoiesis when differentiated toward stromal and osteogenic lineages. *J Hematother Stem Cell Res* 2000; **9**: 841-848 [PMID: 11177595 DOI: 10.1089/152581600750062264]

73 **Zhang Y**, Li C, Jiang X, Zhang S, Wu Y, Liu B, Tang P, Mao N. Human placenta-derived mesenchymal progenitor cells support culture expansion of long-term culture-initiating cells from cord blood CD34+ cells. *Exp Hematol* 2004; **32**: 657-664 [PMID: 15246162 DOI: 10.1016/j.exphem.2004.04.001]

74 **Li H,** Guo ZK, Li XS, Hou CM, Tang PH, Mao N (2007) Functional and phenotypic alteration of intrasplenic lymphocytes affected by mesenchymal stem cells in a murine allosplenocyte transfusion model. Cell Transplant 16 (1):85-95

75 **Li H**, Guo Z, Jiang X, Zhu H, Li X, Mao N. Mesenchymal stem cells alter migratory property of T and dendritic cells to delay the development of murine lethal acute graft-versus-host disease. *Stem Cells* 2008; **26**: 2531-2541 [PMID: 18635870 DOI: 10.1634/stemcells.2008-0146]

76 **Qiao S**, Ren H, Shi Y, Liu W. Allogeneic compact bone-derived mesenchymal stem cell transplantation increases survival of mice exposed to lethal total body irradiation: a potential immunological mechanism. *Chin Med J (Engl)* 2014; **127**: 475-482 [PMID: 24451953]

77 **Cho KS**, Roh HJ. Immunomodulatory effects of adipose-derived stem cells in airway allergic diseases. *Curr Stem Cell Res Ther* 2010; **5**: 111-115 [PMID: 19941459 DOI: 10.2174/157488810791268681]

78 **Shan Z**, Hirai Y, Nakayama M, Hayashi R, Yamasaki T, Hasebe R, Song CH, Horiuchi M. Therapeutic effect of autologous compact bone-derived mesenchymal stem cell transplantation on prion disease. *J Gen Virol* 2017; **98**: 2615-2627 [PMID: 28874230 DOI: 10.1099/jgv.0.000907]

79 **Fiorentini E**, Granchi D, Leonardi E, Baldini N, Ciapetti G. Effects of osteogenic differentiation inducers on *in vitro* expanded adult mesenchymal stromal cells. *Int J Artif Organs* 2011; **34**: 998-1011 [PMID: 22161283 DOI: 10.5301/ijao.5000001]

80 **Khojasteh A**, Eslaminejad MB, Nazarian H. Mesenchymal stem cells enhance bone regeneration in rat calvarial critical size defects more than platelete-rich plasma. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2008; **106**: 356-62; discussion 363 [PMID: 18424120 DOI: 10.1016/j.tripleo.2007.10.017]

81 **Jafarian M**, Eslaminejad MB, Khojasteh A, Mashhadi Abbas F, Dehghan MM, Hassanizadeh R, Houshmand B. Marrow-derived mesenchymal stem cells-directed bone regeneration in the dog mandible: a comparison between biphasic calcium phosphate and natural bone mineral. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2008; **105**: e14-e24 [PMID: 18442730 DOI: 10.1016/j.tripleo.2008.01.010]

82 **Ayatollahi M**, Geramizadeh B, Zakerinia M, Ramzi M, Yaghobi R, Hadadi P, Rezvani AR, Aghdai M, Azarpira N, Karimi H. Human Bone Marrow-derived Mesenchymal Stem Cell: A Source for Cell-Based Therapy. *Int J Organ Transplant Med* 2012; **3**: 32-41 [PMID: 25013621]

83 **Kastrinaki MC**, Andreakou I, Charbord P, Papadaki HA. Isolation of human bone marrow mesenchymal stem cells using different membrane markers: comparison of colony/cloning efficiency, differentiation potential, and molecular profile. *Tissue Eng Part C Methods* 2008; **14**: 333-339 [PMID: 18800875 DOI: 10.1089/ten.tec.2008.0173]

84 **Keller LH**. Bone marrow-derived aldehyde dehydrogenase-bright stem and progenitor cells for ischemic repair. *Congest Heart Fail* 2009; **15**: 202-206 [PMID: 19627297 DOI: 10.1111/j.1751-7133.2009.00101.x]

85 **Boxall S**, Jones E. The use of multiparameter flow cytometry and cell sorting to characterize native human bone marrow mesenchymal stem cells (MSC). *Methods Mol Biol* 2015; **1235**: 121-130 [PMID: 25388391 DOI: 10.1007/978-1-4939-1785-3\_11]

86 **Lee JS**, Kim SK, Cha JK, Jung BJ, Choi SB, Choi EY, Kim CS. Novel Technique for Isolating Human Bone Marrow Stem Cells Using Hyaluronic Acid Hydrogel. *Tissue Eng Part C Methods* 2016; **22**: 941-951 [PMID: 27609497 DOI: 10.1089/ten.TEC.2016.0214]

87 **Sakaguchi Y**, Sekiya I, Yagishita K, Ichinose S, Shinomiya K, Muneta T. Suspended cells from trabecular bone by collagenase digestion become virtually identical to mesenchymal stem cells obtained from marrow aspirates. *Blood* 2004; **104**: 2728-2735 [PMID: 15242873 DOI: 10.1182/blood-2003-12-4452]

88 **Gao X**, Usas A, Tang Y, Lu A, Tan J, Schneppendahl J, Kozemchak AM, Wang B, Cummins JH, Tuan RS, Huard J. A comparison of bone regeneration with human mesenchymal stem cells and muscle-derived stem cells and the critical role of BMP. *Biomaterials* 2014; **35**: 6859-6870 [PMID: 24856105 DOI: 10.1016/j.biomaterials.2014.04.113]

89 **Sottile V**, Halleux C, Bassilana F, Keller H, Seuwen K. Stem cell characteristics of human trabecular bone-derived cells. *Bone* 2002; **30**: 699-704 [PMID: 11996907 DOI: 10.1016/s8756-3282(02)00674-9]

90 **Tuli R**, Tuli S, Nandi S, Wang ML, Alexander PG, Haleem-Smith H, Hozack WJ, Manner PA, Danielson KG, Tuan RS. Characterization of multipotential mesenchymal progenitor cells derived from human trabecular bone. *Stem Cells* 2003; **21**: 681-693 [PMID: 14595128 DOI: 10.1634/stemcells.21-6-681]

91 **Ogulur I**, Gurhan G, Aksoy A, Duruksu G, Inci C, Filinte D, Kombak FE, Karaoz E, Akkoc T. Suppressive effect of compact bone-derived mesenchymal stem cells on chronic airway remodeling in murine model of asthma. *Int Immunopharmacol* 2014; **20**: 101-109 [PMID: 24613203 DOI: 10.1016/j.intimp.2014.02.028]

92 **Duran JM**, Makarewich CA, Sharp TE, Starosta T, Zhu F, Hoffman NE, Chiba Y, Madesh M, Berretta RM, Kubo H, Houser SR. Bone-derived stem cells repair the heart after myocardial infarction through transdifferentiation and paracrine signaling mechanisms. *Circ Res* 2013; **113**: 539-552 [PMID: 23801066 DOI: 10.1161/CIRCRESAHA.113.301202]

93 **Cheng K**, Rai P, Lan X, Plagov A, Malhotra A, Gupta S, Singhal PC. Bone-derived mesenchymal stromal cells from HIV transgenic mice exhibit altered proliferation, differentiation capacity and paracrine functions along with impaired therapeutic potential in kidney injury. *Exp Cell Res* 2013; **319**: 2266-2274 [PMID: 23806280 DOI: 10.1016/j.yexcr.2013.06.008]

94 **Yamachika E**, Tsujigiwa H, Matsubara M, Hirata Y, Kita K, Takabatake K, Mizukawa N, Kaneda Y, Nagatsuka H, Iida S. Basic fibroblast growth factor supports expansion of mouse compact bone-derived mesenchymal stem cells (MSCs) and regeneration of bone from MSC in vivo. *J Mol Histol* 2012; **43**: 223-233 [PMID: 22203245 DOI: 10.1007/s10735-011-9385-8]

95 **Bakker AD**, Kroeze RJ, Korstjens C, de Kleine RH, Frölke JP, Klein-Nulend J. Reaming debris as a novel source of autologous bone to enhance healing of bone defects. *J Biomed Mater Res A* 2011; **97**: 457-465 [PMID: 21491583 DOI: 10.1002/jbm.a.33080]

96 **Lim K**, Hexiu J, Kim J, Seonwoo H, Cho WJ, Choung PH, Chung JH. Effects of electromagnetic fields on osteogenesis of human alveolar bone-derived mesenchymal stem cells. *Biomed Res Int* 2013; **2013**: 296019 [PMID: 23862141 DOI: 10.1155/2013/296019]

97 **Lim K**, Kim J, Seonwoo H, Park SH, Choung PH, Chung JH. In vitro effects of low-intensity pulsed ultrasound stimulation on the osteogenic differentiation of human alveolar bone-derived mesenchymal stem cells for tooth tissue engineering. *Biomed Res Int* 2013; **2013**: 269724 [PMID: 24195067 DOI: 10.1155/2013/269724]

98 **Lim KT,** Kim J, Seonwoo H, Chang JU, Choi H, Hexiu J, Cho WJ, Choung PH, Chung JH. Enhanced osteogenesis of human alveolar bone-derived mesenchymal stem cells for tooth tissue engineering using fluid shear stress in a rocking culture method. *Tissue Eng Part C Methods* 2013; **19**: 128-145 [doi: 10.1089/ten.tec.2012.0017]

99 **Wenisch S**, Trinkaus K, Hild A, Hose D, Heiss C, Alt V, Klisch C, Meissl H, Schnettler R. Immunochemical, ultrastructural and electrophysiological investigations of bone-derived stem cells in the course of neuronal differentiation. *Bone* 2006; **38**: 911-921 [PMID: 16418015 DOI: 10.1016/j.bone.2005.10.021]

100 **Wenisch S**, Trinkaus K, Hild A, Hose D, Herde K, Heiss C, Kilian O, Alt V, Schnettler R. Human reaming debris: a source of multipotent stem cells. *Bone* 2005; **36**: 74-83 [PMID: 15664005 DOI: 10.1016/j.bone.2004.09.019]

**Footnotes**

**Conflict-of-interest statement:** The authors declare that they have no conflict of interest.

**Open-Access:** This article is an open-access article that was selected by an in-house editor and fully peer-reviewed by external reviewers. It is distributed in accordance with the Creative Commons Attribution NonCommercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited and the use is non-commercial. See: http://creativecommons.org/Licenses/by-nc/4.0/

**Manuscript source:** Unsolicited manuscript

**Peer-review started:** April 14, 2020

**First decision:** September 18, 2020

**Article in press:**

**Specialty type:** Orthopedics

**Country/Territory of origin:** United States

**Peer-review report’s scientific quality classification**

Grade A (Excellent): 0

Grade B (Very good): B, B

Grade C (Good): 0

Grade D (Fair): D

Grade E (Poor): 0

**P-Reviewer:** Farahzadi R, Huang Y, Valente S **S-Editor:** Zhang L **L-Editor: P-Editor:**

**Table 1 Source and isolation methods of mesenchymal stromal cells**

|  |  |  |
| --- | --- | --- |
| **Source** | **Isolation method** | **Ref.** |
| Bone marrow | Aspirates cultured and media changed every 3-4 d to select for MSCs | [34] |
|  | Aspirates layered over Ficoll-Paque density-gradient and plates in tissue culture dish. Adherent cells maintained with periodic passaging | [82] |
|  | Bone marrow mononuclear cells seeded from single colony-forming unit fibroblasts and selected for by CD105(+)/CD45(-) | [83] |
|  | Sort bone mononuclear cells based on aldehyde deydrogenase expression (ALDHhighCD45-) | [84] |
|  | Sort based on CD45−/lowCD271+ phenotype following a microbead-based pre-enrichement | [85] |
|  | Layer bone marrow over hyluronic acid followed by centrifugation, collect most superficial layer containing the mononuclear cells | [86] |
| Compact bone | Trabecular bone fragments rinsed and placed in complete α-MEM/Ham’s F12, confluent monolayers were obtained within 10-20 d | [87-89] |
|  | Bone cell cultures established by treating bone fragments with collagenase in low Ca2+ medium  | [9,90,30] |
|  | Compact bone fragments obtained, cultured, and isolated. CB-MSCs then undergo trypsinization to reveal enhanced osteogenic capacity | [43] |
| Adipose  | Place 10-20 mL of washed adipose tissue in 100 mm Petri dish; dissect out yellow tissue; mince tissue finely and place in enzymatic digestion solution; centrifuge and collect pellet for wash; resuspend in complete culture medium | [14,13] |
|  | Wash lipoaspirate with PBS; enzymatically digest using collagenase 1A solution; spin down cells, wash and plate in complete medium | [12] |
| Bone marrow | Aspirates cultured and media changed every 3-4 d to select for MSCs | [34] |
|  | Aspirates layered over Ficoll-Paque density-gradient and plates in tissue culture dish. Adherent cells maintained with periodic passaging | [82] |
|  | Bone marrow mononuclear cells seeded from single colony-forming unit fibroblasts and selected for by CD105(+)/CD45(-) | [83] |
|  | Sort bone mononuclear cells based on aldehyde deydrogenase expression (ALDHhighCD45-) | [84] |
|  | Sort based on CD45−/lowCD271+ phenotype following a microbead-based pre-enrichement | [85] |

MSC: Mesenchymal stromal cell; CB: Compact bone; PBS: Phosphate buffer saline.

**Table 2 Potential clinical scenarios for use of mesenchymal stromal cell therapy**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Ref.** | **Animal model/methods** | **Findings** | **Conclusion** | ***In vitro/in vivo*** |
| Ogulur *et al*[91] | mCB-MSCs isolated from 6–8 wk old BALB/c mice | mCB-MSCs significantly reduced cellular immune infiltration and presence of goblet cells as well as the thickness of epithelium, smooth muscle layers, and basement membrane in ovalbumin induced chronic asthmatic mice | Inflammation in distal and proximal airways of ovalbumin induced asthmatic mice can be suppressed by use of IV mCB-MSCs | *In vivo* |
| Qiao *et al*[76]  | CB-MSCs isolated from C57BL/6 mice administered to 8–10 wk old BALB/c mice | BALB/c mice exposed to 8 Gy TBI and treated with CB-MSCs showed improved survival, body weight, and CFU-GM counts of bone marrow cells coupled with suppressed Th1 immunity with increased Treg percentages and decreased IFN-γ, CXCR3 and CCR5 | CB-MSC transplantation post total body irradiation attenuates radiation-induced hematopoietic toxicity and provides immunoprotection | *In vivo* |
| Duran *et al*[92] | Cortical bone–derived stem cells from 12-wk-old EGFP+ transgenic mice | Improved 6 wk survival post MI procedure (50.4% to 76.5%) from saline to CB-MSC therapy. Increased expression of proangiogenic paracrine factors (bFGF and VEGF) and differentiation into infarct zone | Treatment with CB-MSCs post MI leads to enhanced survival, cardiac function, and remodeling | *In vivo* |
| Cheng *et al*[93] | MSCs isolated from compact bone of Tg26 HIV-1 transgenic mice | Transplanted Tg26 HIV-1 MSCs were less effective in protecting renal tubular cells compared to healthy mice MSCs in a cisplatin-induced AKI model due to inferior proliferation and decrease in secretion of protective cytokines | Compact bone MSCs infected with HIV-1 had impaired proliferation, differentiation, and function resulting in less therapeutic potential | *In vivo* |
| Yamachika *et al*[94] | MSCs from compact bone of 5-week-old C57-GFP male mice | Cells cultured in bFGF-conditioned medium demonstrated trilineage differentiation potential even at passage 24 in contrast to leukemia inhibitory factor-conditioned medium  | Compact bone MSCs cultured in bFGF-conditioned medium demonstrated bone formation ability *in vivo* | *In vivo* |
| Bakker *et al*[95] | Tibial reaming debris from adult female sheep | Treatment with reaming debris, similar to iliac crest, revealed larger callus volume with decreased cartilage in the fracture gap, increased bone volume, and improved toughness at 3 wk with greater torsional stiffness at 6 wk | Reaming debris has characteristics similar to iliac crest bone that allow it to be an excellent replacement for enhancing healing of bone defects fixed with an intramedullary nail | *In vivo* |
| Guo *et al*[24]  | Murine mesenchymal progenitor cells (muMPCs) isolated from 2-3 wk old C57BL/6 female mice tibia/femur compact bone | Collagenase‐digested bone fragments produced muMPCs that inhibited Con A‐stimulated splenocyte proliferation and suppressed lymphocyte activation by allogeneic cellular stimuli *in vitro*. In addition, muMPCs improved survival of allogeneic skin grafts *in vivo* | Using this protocol allows acquiring of muMPCs with similar properties to marrow counterparts, which allows them to be used in future investigations with mouse models | *In vivo* |
| Lim *et al*[96] | hABMSCs | hABMSCs exposed to low-intensity pulsed ultrasound revealed increased ALP, expression levels of CD29, CD44, COL1, and OCN, and calcium deposition | Treatment with LIPUS could improve the cell viability and osteogenic differentiation of hABMSCs | *In vitro* |
| Lim *et al*[97] | hABMSCs | hABSMSCs treated with extremely low frequency pulsed electromagnetic fields (ELF-PEMFs) revealed 15% increased proliferation at day 5, increased ALP, vinculin, vimentin, and CaM expressions, and enhanced mineralization during osteogenesis | Exposing hABMSCs with ELF-PEMFs could improve and accelerate the process of early cell proliferation mediated osteogenesis | *In vitro* |
| Lim *et al*[98] | hABMSCs harvested from human mandibular alveolar bone | hABSMSCs exposed to LFDSS for 10–60 min/d demonstrated improved viability, proliferation, and mineralization in culture with osteoblasts. ALP activity and gene expression of IBSP, COL-I, OCN, and OPN increased | Proper intensity and exposure time of LFDSS to hABMSCs can improve their differentiation and maturation | *In vitro* |
| Soleimani *et al*[35] | MSCs isolated from 6-8 wk old BALB/c mouse tibial and femoral bone marrow | The protocol states MSCs should be cultured in Dulbecco's modified Eagle's medium (DMEM) and fetal bovine serum (FBS) in a 37 °C–5% CO2 incubator with passage at 2 wk of culture | This protocol allows development of a purified population of MSCs 3 wk after the initiation of culture | *In vitro* |
| Dominici *et al*[44] | Human multipotent MSC | In standard culture, MSC must be plastic-adherent, express CD105, CD73 and CD90, and lack expression of CD45, CD34, CD14 or CD11b, CD79alpha or CD19 and HLA-DR and demonstrate tridifferentiation *in vitro* | Standard criteria for MSC characterization, will allow for exchange of more uniform data between researchers | *In vitro* |
| Wenisch *et al*[99] | Mesenchymal stem cells harvested from HRD of 12 adult patients with closed diaphyseal femoral fractures | With neuronal induction, MSCs assumed neuronal morphologies and expressed neuron-specific enolase, beta-III-tubulin, neurofilament-H and HNK-1. Similar to immature neurons, MSCs had features of neuritogenesis and synaptogenesis and lacked electrical signaling | Neuronal induction allowed initiation of the early neuronal differentiation, but exposure to non-neurological stressors led to necrotic alterations | *In vitro* |
| Wenisch *et al*[100] | Mesenchymal stem cells harvested from HRD of 12 adult patients with closed diaphyseal femoral fractures | After multiple passages, HRD-derived cells and MSCs maintained a nondifferentiated phenotype and showed osteogenic and neuronal pathway differentiation ability after induction | Human reaming debris provides a multipotent stem cells which have the ability to grow and proliferate *in vitro* | *In vitro* |
| Tuli *et al*[90] | Collagenase‐treated human trabecular bone chips | Collagenase‐treated trabecular bone fragments contain cells that stain positive for CD73, STRO‐1, and CD105, and negative for CD34, CD45, and CD144 with tridifferentiation potential | Trabecular bone‐derived cells maintain a nondifferentiated phenotype and display tridifferentiation potential with long‐term *in vitro* culture | *In vitro* |

AKI: Acute kidney injury; bFGF: Basic fibroblast growth factor; CBSC: Cortical bone stem cell; CB-MSCs: Compact bone mesenchymal stem cells; CFU-GMC: Colony-forming unit granulocyte/macrophage; LIPUS: Low intensity pulsed ultrasound; MI: Myocardial infarction; TBI: Total body irradiation; VEGF: Vascular endothelial growth factor; HRD: Human reaming debris; hABMSC: Human alveolar bone-derived mesenchymal stem cell; LFDSS: Low fluid dynamic shear stress; ALP: A lkaline phosphatase; HLA: Human leukocyte antigen; HIV: Human immunodeficiency virus.