EVOLVING CONCEPTS OF CHONDROGENIC DIFFERENTIATION: HISTORY, STATE-OF-THE-ART AND FUTURE PERSPECTIVES

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Abstract

As a cell source, multipotent mesenchymal stromal cells or mesenchymal stem cells (MSCs) are promising candidates for chondrogenic differentiation and subsequent cartilage regeneration. From previous literature, it is known that chondrogenic differentiation of MSCs inevitably leads to hypertrophy and subsequent endochondral ossification. In this review, we examine the history of currently established protocols of chondrogenic differentiation and elaborate on the roles of individual components of chondrogenic differentiation medium. We also summarise the effects of physical, chemical and biological factors involved, and propose potential strategies to differentiate MSCs into articular chondrocytes with homogenous mature phenotypes through spatial-temporal incorporation of cell differentiation and chondrogenesis.

Keywords: Chondrogenic differentiation, chondrogenesis, mesenchymal stem cells, chondrocytes, chondrogenic differentiation factors.

Introduction

Articular cartilage is an avascular connective tissue with limited capacity for self-regeneration. Injury and degeneration of cartilage have far-reaching impacts on personal life, healthcare expenses and reduced productivity in the work force (Ge et al., 2006). Current clinical treatment strategies, such as autologous chondrocyte implantation, bone marrow stimulation and mosaicplasty, have varying success rates, but their long-term results are far from satisfactory due to the lack of structural organisation of articular cartilage, as well as inferior mechanical properties of the newly formed tissue (Hunziker, 2009). Cartilage tissue engineering has the potential to create a more durable and functional replacement for the degenerated tissue; chondrocytes and stem cells are two promising cell source candidates for this replacement tissue. Chondrocytes are potentially the ideal seed cells with mature and stable phenotype as well as lineage stability. However, they are limited by scarcity during harvest and dedifferentiation during in vitro proliferation (Kock et al., 2012). Establishment of embryonic stem cells (ESCs) requires embryos, which leads to ethical issues for clinical applications. Induced pluripotent stem cell (iPSC) technology can provide patient-specific cells, but uncontrolled and unexpected differentiation limits their application (Blin et al., 2010; Yoshida and Yamanaka, 2010). Multipotent mesenchymal stromal cells or mesenchymal stem cells (MSCs) are a broadly adopted cell source for cartilage regeneration due to ample availability from multiple tissues, high proliferation capacity and the ability to differentiate into chondrocytes (Derfoul et al., 2006; Kassis et al., 2006). However, concomitant premature phenotypes of the differentiated chondrocytes, undesirable hypertrophic differentiation (Studer et al., 2012), lack of subtype phenotypes and subsequent immature extracellular matrix (ECM) under current chondrogenic differentiation protocols have hindered the clinical application of stem cell-differentiated chondrocytes (Huey et al., 2012; Mueller and Tuan, 2008).

Weighing the advantages and disadvantages of candidate cell sources, apart from using chondrocytes, MSCs may be the most adaptive cell source for current clinical use and for cartilage tissue engineering applications. Therefore, finding ways to improve in vitro chondrogenic differentiation of MSCs may be the next primary focus of tissue engineering research, which is somewhat different with the well-
orchestrated embryonic chondrogenic differentiation process of MSCs. Embryonic chondrogenesis have been reviewed extensively with the focus on mesenchymal cell condensation, chondroprogenitor cells, chondrocytes as well as related mediators (Goldring et al., 2006). Apart from embryonic chondrogenesis, joint specification and postnatal development have also been reviewed, though many questions remain unexplored (Onyekwelu et al., 2009). MSCs have been well studied, regarding their definition, tissue origins, chemokines and receptors, as well as their in vivo microenvironments (Augello et al., 2010); key factors like cell metabolic activity and transcript levels important for functional MSC-derived cartilage regeneration are summarised elsewhere (Chen et al., 2012). Based on all these progresses, we summarise the history and challenges faced by current broadly used chondrogenic differentiation protocols with an aim to shed valuable light on the potential novel strategies to circumvent the challenges faced, which may benefit bioengineers and researchers in the field of tissue engineering and regenerative medicine.

Chondrogenic differentiation into articular chondrocytes

Chondrogenesis is initiated by cell condensation during embryonic development, before the mesenchymal stem cells differentiate into multiple lineages, such as articular, growth plate, intervertebral disc chondrocytes or endochondral ossification [some of the cells survive and transform into osteoblasts (Zhang et al., 2014)]. For years, mesoderm was thought to be the origin of MSCs; however, new evidence indicates that the neuroepithelium, including the neural crest, may also be an early origin of MSCs (Morikawa et al., 2009; Takashima et al., 2007). MSCs from the somatopleure of the lateral plate mesoderm, neural crest cells in the neural ectoderm and sclerotome compartment of the paraxial mesoderm or somite differentiate into chondrogenic lineages and then yield the limbs, craniofacial bones and axial skeleton separately (Goldring et al., 2006; Olsen et al., 2000). Chondrogenesis may occur in one of two directions in the developing bone. One leads to the formation of bone via endochondral ossification, (at the primary and secondary centres of ossification, and in the growth plate) and the other leads to stable hyaline articular cartilage. The growth plate is composed of the resting zone, proliferative zone and hypertrophic zone (Abad et al., 2002). Growth plate cartilage progresses to form the bone (Mackie et al., 2008), whereas the articular cartilage does not (Pacifici et al., 2005). Chondrocytes of the presumptive articular surface arise directly from a subpopulation of early chondroprogenitor cells, expressing doublecortin and growth/differentiation factor-5 (GDF-5) (Koyama et al., 2008; Zhang et al., 2007), but not matrilin-1 (Hyde et al., 2007). Articular chondrocytes maintain the phenotype instead of resorting to hypertrophy by maintaining high expression of ACAN and PRG4 (lubricin gene) and low expression of COL2A1 with low proliferation (Lefebvre and Smits, 2005).

While articular cartilage at birth undergoes ossification and mineralisation, appositional growth from the surface forms an adult articular cartilage until puberty (Hunziker et al., 2007; Onyekwelu et al., 2009). These slowly dividing stem cells have bidirectional mitotic activity. In the horizontal direction, they furnish new stem cells that replenish the pool and contribute to the lateral expansion of the articular cartilage layer. In the vertical direction, the superficial zone supplies the rapidly dividing, transiting-amplifying daughter-cell pool that feeds the transitional and upper radial zones and gradually forms the layered structure (Hunziker et al., 2007). This growth activity of the articular surface ceases at puberty, whereas expansion of the metaphyseal growth plate continues until the time of skeletal maturity (Clark et al., 1997; Hunziker et al., 2007). Knowledge derived from endochondral ossification has been largely used to establish current chondrogenic differentiation protocols, while growth plate chondrocytes that are easily accessible sources are often compared to articular chondrocytes (Iwamoto et al., 2013; Leijten et al., 2012) (Fig. 1).

A history of the understanding of chondrogenic differentiation

Studies of the embryonic development of cartilage or cartilaginous tissues started as early as the 1960s. Ectopic implantation was a major research model during this period. The somites, which are embryonic cartilaginous progenitor cells, differentiated into chondrocytes in vitro when co-cultured with notochords (Lash et al., 1960). Holtzer observed chondrogenesis of somites occurring in the presence of neural tubes (Holtzer, 1952; Holtzer and Detwiler, 1953). A fraction obtained from a cold perchloric acid extract of spinal cord and notochord was able to induce chondrogenesis (Lash et al., 1962), which contained chondrogenic factors consisting of polypeptides, nucleotides and sugars (Holtzer, 1964; Hommes et al., 1962). De-differentiation of chondrocytes was reported with morphological changes from spherical to stellate coupled with decreased synthesis of chondroitin sulphate and enhanced cell proliferation (Abbott and Holtzer, 1966). These findings led to the establishment of the pellet culture system, now broadly used in chondrogenic differentiation (Hattori and Ide, 1984).

In the 1970s and 1980s, laboratory studies evaluating the effect of cell shape, cell-cell and cell-matrix interactions on chondrogenesis were undertaken. Chondrocytes with spherical morphologies synthesised higher levels of chondroitin sulphate in comparison to those with spindle-like morphologies (Archer et al., 1982). Cell-cell interactions, including both interactions amongst limb bud mesenchymal cells (Owens and Solursh, 1982) and epithelial-mesenchymal cells (Sanders, 1988), are essential for the differentiation of prechondrogenic limb mesenchyme into cartilage. Gene expression of both COL I and fibronectin increased at the onset of condensation, reached the highest point of chondrogenic differentiation and then subsided and were replaced with elevated COL2A1 expression (Dessau et al., 1980; Kulyk et al., 1982).
In the late 1990s, the role of integrins in mediating cell attachment to extracellular matrix proteins was highlighted. These interactions regulated morphogenesis and cell differentiation. Treatment with integrin β1 antibodies inhibited early chondrogenesis of limb bud cells from mouse embryos \textit{in vitro} (Shakibaei, 1998). Additionally, \textit{SOX9} was found to be a master gene which regulated downstream \textit{COL2A1} expression directly (Healy \textit{et al.}, 1999).

Understanding of chondrogenic differentiation has accelerated since the year 2000, attributed to the application of a variety of genetic modification techniques. Epigenetics then emerged as an important field. MicroRNAs (miRNAs) proved effective mediators of key pathways during MSC differentiation through regulating transcription factors (Hong and Reddi, 2012). DNA methylation and histone modification (including histone acetylation and deacetylation) are involved in chondrogenesis through modulating chromatin structures, which directly influence the activity of DNA in transcription, replication and

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**Fig. 1.** A schematic representation of different stages of chondrogenesis and endochondral ossification. The development of cartilage starts with MSC condensation. After committing to chondrogenesis, cells follow one of two different directions in the developing bone. One leads to the formation of bone \textit{via} endochondral ossification (at the primary ossification centre (POC), secondary ossification centre (SOC), and in the growth plate) (the process marked in black) and the other that leads to stable hyaline articular cartilage. All committed hyaline chondrocytes start expressing \textit{COL2A1}; matrilin-1 expression by cells arising from the interzones that are destined to become growth plate chondrocytes distinguishes them from articular chondrocytes. Doublecortin and GDF-5 only express in the articular cartilage. Most embryonic articular cartilage present at the ends of the bone at birth is replaced by bone and new cartilage formed by stem cells in the superficial zone. Articular cartilage becomes fully mature in adulthood. With the disappearance of growth plate cartilage, the SOC connects with the POC and gradually disappears in mature mammals. Stem-like cells exist in the cell condensation stage, keep stemness in the superficial zone of AC from birth until puberty, and exist in the form of resting stem-like cell after adulthood.
recombination (Furumatsu and Ozaki, 2010; Roth et al., 2011). Recently, several groups found an important relationship between epigenetic marking and gene expression in chondrogenesis. Herlofsen et al. found that modifications can provide primary epigenetic control of the early differentiation of MSCs toward the chondrogenic lineage (Herlofsen et al., 2013).

Biophysical, chemical and mechanical factors were found to be heavily involved in chondrogenesis (Leijten et al., 2014). Small chemical molecules (Benoit et al., 2008), matrix elasticity (Engler et al., 2006; Park et al., 2011), cell material property (cell softness) (Chowdhury et al., 2010) and many more factors, are now known to guide MSCs to differentiate into specific cell lineages. A breakthrough in the regeneration of articular cartilage illustrated that an entire articular surface can be regenerated using adult stem/progenitor cells recruited from the host with the help of biomaterial-based scaffold and growth factors (Lee et al., 2010).

**Table 1. Chondrogenic differentiation medium and effects of individual components on chondrogenesis**

<table>
<thead>
<tr>
<th>Factors</th>
<th>Function</th>
<th>Signalling</th>
<th>Dose</th>
<th>Synergy</th>
<th>Subtypes</th>
</tr>
</thead>
<tbody>
<tr>
<td>TGF-β1-3 (Zuscik et al., 2004; Lutz and Knaus, 2002; Park et al., 2011; Schmierer and Hill, 2007)</td>
<td>Promotes chondrogenesis, enhances extracellular matrix production and downregulates collagen I expression</td>
<td>MAPK, Wnt, β-catenin, Smad</td>
<td>10 ng/mL</td>
<td>TGF-I, BMPs, PTHrP</td>
<td>TGF-β1, β2 and β3, have similar functions</td>
</tr>
<tr>
<td>Insulin (Mueller et al., 2013; Quarto et al., 1992)</td>
<td>Stimulates collagen synthesis, inhibits hypertrophy</td>
<td>Enhances tyrosine kinase activity of the insulin receptor</td>
<td>1-10 μg/mL</td>
<td>Insulin, selenium</td>
<td>TGF-β</td>
</tr>
<tr>
<td>Transferrin (Cigan, 2013; Kisiday et al., 2005)</td>
<td>Iron-binding</td>
<td></td>
<td>1-30 μg/mL</td>
<td>Insulin, selenium</td>
<td>TGF-β</td>
</tr>
<tr>
<td>Selenium (Yan et al., 2012)</td>
<td>Anti-oxidant and enhances proliferation</td>
<td></td>
<td>5 μg/mL</td>
<td>Insulin, transferrin</td>
<td>TGF-β</td>
</tr>
<tr>
<td>Dex (M.Flörine et al., 2013; Thomas M.Randua, 2013)</td>
<td>Supports cell viability and delays the appearance of type X collagen</td>
<td>GRSs, Scapie Responsive Gene</td>
<td>10^4 M</td>
<td>TGF-β</td>
<td>TGF-β</td>
</tr>
<tr>
<td>Glucose (Cigan, 2013; Han et al., 2004; Tsui, 2013)</td>
<td>Major energy source, precursor for the synthesis of glycosaminoglycans</td>
<td>PKCα, p38MAPK, ERK</td>
<td>4.5 g/L</td>
<td>Proline</td>
<td>L-ascorbate, sodium L-ascorbate, and L-ascorbate-2-phosphate</td>
</tr>
<tr>
<td>Ascorbic acid (Choi et al., 2008; Franceschi, 1992; Peterkofsky, 1972; Stone and Meister, 1962)</td>
<td>Proliferation, DNA synthesis, collagen biosynthesis and reductant</td>
<td>Reduction of iron to its ferrous state</td>
<td>50 mg/mL</td>
<td>Proline</td>
<td>L-ascorbate, sodium L-ascorbate, and L-ascorbate-2-phosphate</td>
</tr>
<tr>
<td>Pyruvate (Andrae et al., 1985; Gushi et al., 2000)</td>
<td>Energy source, against hydrogen peroxide-induced cytotoxicity</td>
<td></td>
<td>1 mM</td>
<td>Proline</td>
<td>L-ascorbate, sodium L-ascorbate, and L-ascorbate-2-phosphate</td>
</tr>
<tr>
<td>Proline (Peterkofsky, 1972; Washington et al., 2010)</td>
<td>Stabilisation of the collagen triple helix, promotes ES cell differentiation</td>
<td>mTOR signalling pathway</td>
<td>40 μg/mL</td>
<td>Ascorbic acid</td>
<td>TGF-β</td>
</tr>
<tr>
<td>BMPs (Cao and Chen, 2005; Hassel et al., 2003; Hankeyama et al., 2004; Jin et al., 2006; Sekiya et al., 2005; Shen et al., 2010)</td>
<td>Enhances cartilage formation</td>
<td>MAPK, Wnt, Smad</td>
<td>10-500 ng/mL</td>
<td>TGF-β</td>
<td>BMP-2, enhances proliferation and ECM, and downregulates Col I expression</td>
</tr>
<tr>
<td>GDF-5(BMP-14) (Coleman and Tuan, 2003; Hankeyama et al., 2004)</td>
<td>Enhances cell condensation, chondrogenesis, and ECM production</td>
<td>Gap junction intercellular communication, p38MAPK</td>
<td>150 ng/mL</td>
<td>TGF-β, BMP</td>
<td>BMP-2, enhances proliferation and ECM, and downregulates Col I expression</td>
</tr>
<tr>
<td>PTHrP (Barbara Zerega, 1999; Kim et al., 2008; Mau et al., 2007)</td>
<td>Inhibits the TGF-β1-induced hypertrophic differentiation</td>
<td>PTHrP and IHH feedback loop</td>
<td>10 μM</td>
<td>TGF-β</td>
<td>PTHrP-1-34</td>
</tr>
<tr>
<td>FGF (Ng et al., 2008; Solchaga et al., 2005; Tsutsui et al., 2001)</td>
<td>Regulates proliferation, and increases cartilaginous ECM production</td>
<td>ERK</td>
<td>10 ng/mL, FGF-2</td>
<td>TGF-β</td>
<td>FGF-2, increases proliferation, and proteoglycan production</td>
</tr>
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</table>

Key elements in current chondrogenic differentiation medium

At present, MSCs cultured in pellet and micromass systems in the presence of chondrogenic differentiation medium are the two major methods for initiating chondrogenic differentiation in vitro. The following sections will describe...
the in-depth role of the ingredients potentially used in chondrogenic differentiation medium.

TGF-β is the core component in most chondrogenic differentiation protocols used currently. TGF-βs exist in three homologous homodimeric forms (β1, β2 and β3) and all of them signal through the same receptors [TGF-β receptor I (TGF-β RI) and II (TGF-β RII)]. After activation of the TGF-β receptors, TGF-β induces chondrogenesis mainly through TGF-β/drosophila mothers against decapentaplegic protein (Smad) and mitogen-activated protein kinase (MAPK) signalling pathways, that cross-talk with each other (Li et al., 2010; Lutz and Knaus, 2002; Schmierer and Hill, 2007) (Fig. 2). Before phosphorylation by TGF-β RII, TGF-β RI is catalytically inactive due to a wedge-shaped GS region (a highly conserved 30-amino acid region with a characteristic SGSGSG sequence) inserted into the kinase domain (Massagué, 1998). In Smad signalling, TGF-β RII phosphorylates the GS region after forming a ligand-receptor complex with TGF-β, which results in the activation of TGF-β RI (Huse et al., 1999). The activated TGF-β RI phosphorylates Smad2/3, which recruits Smad4, and the complex translocates into the nucleus (Massagüé and Wotton, 2000). The translocated Smad2/3 associates with Sox9 and CBP/p300 (cAMP-response element-binding protein, which has an intrinsic histone acetyltransferase activity and acts as an important co-activator for the expression of the COL2A1) on the COL II enhancer region containing the Sox9-binding site that is important for the initiation of chondrogenic differentiation (Furumatsu et al., 2005). As for MAPK signalling, the major subtypes of MAPK include p38, extracellular signal-regulated kinase-1 (ERK-1) and c-jun N-terminal kinase (JNK). In addition, p38 is an enhancer of chondrogenesis, whereas ERK-1 is a repressor of chondrogenesis; JNK plays a minor role in chondrogenesis. Activation of MAPK involves indirect modulation of cell adhesion molecules, including N-cadherin and integrin α5β1, during precartilage condensation and progression to chondrogenic differentiation (Tuli et al., 2003). TGF-β induces the expression of the chondrogenic factor SOX9 and the function of the main chondrogenic trio (SOX5, SOX6 and SOX9) (Lefebvre et al., 1998; Lefebvre and Smits, 2005) that further regulates chondrogenic differentiation and ECM formation. It is known that the genes for many ECM components, such as ACAN, COL2A1 and Matrilin-1, are only expressed when the three Sox proteins bind to the high-mobility group (HMG)-domain sites in their enhancers (Akiyama and Lefebvre, 2011). On the contrary, TGF-β also plays an inhibitory role in chondrocyte maturation (Bullock et al., 1993; Kato et al., 1988; Serra et al., 1997).

ITS premix is a substitute for foetal bovine serum that maintains cellular activity in biosynthesis and cell division. Serum has some disadvantages including poor characterisation and inconsistency in batch-to-batch composition and quality (Barnes and Sato, 1980; Cigan, 2013). Insulin is a primary factor involved in the onset and progression of chondrogenesis (Quarto et al., 1992) and can facilitate chondrogenesis in a dose-dependent manner (1-10 μg/mL) with added TGF-β (Mueller et al.,...
Furthermore, insulin can facilitate glucose uptake (Kono et al., 1982) and enhance DNA synthesis and proteoglycan production in cartilage cultures (Maor et al., 1993; Rosen, 1987). Transferrin promotes cell proliferation and differentiation through detoxifying oxygen radicals and peroxides (Ned et al., 2003; Schäfer et al., 2007). Selenite, a co-factor for glutathione peroxidase and other proteins, enhances proliferation of chondrocytes through acceleration of G1-phase cell cycle progression and the induction of cyclin D1 (Wei et al., 1986). This effect is mediated by the enhancement of intracellular adenosine triphosphate (ATP) content (Yan et al., 2012).

Dex, a synthetic glucocorticoid, promotes chondrogenic differentiation through enhancing related gene expression (Florine et al., 2013; Jakobsen et al., 2014; Randua et al., 2013). The chondrogenic effects of glucocorticoids are predominantly mediated via the glucocorticoid receptors (GRs). GRα constitutes the main active GR form while GRβ constitutes a negative isoform of GRs (Oakley et al., 1999). Dex promotes chondrogenic differentiation by down-regulating GRβ levels and maintaining GRα levels (Derfoul et al., 2006). Dex enhances the gene expression of COL XI under chondrogenic conditions (collagen XI acts as both the template for collagen II fibrillogenesis and a regulator for maintaining fibril diameters in cartilage) (Chen et al., 2005; Derfoul et al., 2006). Previous studies have shown that Dex enhanced the TGF-β1 induced expression of ACAN, COL2A1 and cartilage oligomeric matrix protein (COMP) and supported cell viability, as well as delayed the expression of COL X when used in conjunction with TGF-β (Derfoul et al., 2006; Quarto et al., 1992). The tissue origin of MSCs determines the effect of Dex on chondrogenic differentiation. Dex enhanced TGF-β1-induced chondrogenesis in bone marrow-derived MSCs (BMSCs) but had no significant impact on the TGF-β1 or BMP2-induced response in synovial derived MSCs (Kurth et al., 2007; Park et al., 2005; Shintani and Hunziker, 2011; Shintani et al., 2007). This may be due to the different cell survival rates and microenvironment which could be tissue-source dependent (Buxton et al., 2011).

Glucose, a major energy source and precursor of ECM for most mammalian cells, promotes chondrogenic differentiation and inhibits apoptosis at high levels (4.5 g/L or 25 mM) (Mackay et al., 1998; Shikhman et al., 2001; Tsai et al., 2013). Glucose participates in multiple metabolic cycles of MSCs during chondrogenic differentiation, including oxygen consumption, glucose consumption and lactate production. High levels of glucose in the medium enhance cell differentiation by changing the metabolic patterns and modulating subsequent cell signalling pathways. The synthesis of proteoglycans increases through progressively inhibiting the respiration of chondrocytes cultured in vitro, as the glucose concentrations (1-10 mM) increase (Derfoul et al., 2006; Otte, 1991). High doses of glucose enhance the differentiation of stem cells into chondrocytic lineages through the down-regulation of ERK and protein kinase Cα (PKCα) activities, up-regulation of p38, as well as through modulating the expression of adhesion molecules such as fibronectin, integrin β1 and N-cadherin (Han et al., 2004).

Both ascorbic acid and proline are essential for the production of collagen in cartilage. Ascorbic acid enhances cell proliferation, synthesis and extracellular deposition of collagenous matrix, in particular collagen I and II (Choi et al., 2008; Franceschi, 1992; Potdar and D’Souza, 2010; Stone and Meister, 1962). Ascorbic acid stabilises the collagen triple helical structure through reduction of iron to its ferrous state, which is important for the hydroxylation of proline residues in procollagen and hydroxyproline and the maturation of procollagen to collagen (Padh, 1991; Peterkofsky, 1991). Proline has been shown to regulate ESC differentiation into early primitive ectoderm-like (EPL) cells, through mammalian targeting of the rapamycin (mTOR) signalling pathway (Washington et al., 2010).

Sodium pyruvate is essential for enhancing the energy metabolism in the Krebs cycle (Geshi et al., 2000). Mammalian cells secrete pyruvate and α-ketoacids in culture to protect them against hydrogen peroxide-induced cytotoxicity (Andrae et al., 1985; O’Donnell-Tormey et al., 1987). Pyruvate up-regulates the expression of genes involved in free radical scavenging which, in turn, enhances the antioxidative machinery and is essential for maintaining mitochondrial activity. Super-physiological concentrations of pyruvate (50 mM, 50 folds of physiological concentrations) enhance mitochondrial mass and functionality (Wilson et al., 2007).

Phenol red, a commonly used pH indicator in tissue culture medium can inhibit the chondrogenic differentiation of MSCs (Lydahl et al., 2013). During chondrogenic differentiation, phenol red in Dulbecco’s Modified Eagle Medium (DMEM) has been shown to decrease SOX9, COL2A1 and ACAN on days 14 and 21 and proteoglycan synthesis on days 21 and 28 in culture (Lydahl et al., 2013). This phenomenon may have occurred due to phenol red’s structural resemblance to certain nonsteroidal oestrogens and weak oestrogen agonist activity (Berthois et al., 1986).

BMPs are morphogens in the TGF-β superfamily and regulate chondrogenesis and skeletogenesis during normal embryonic development (Hogan, 1996). They are involved in various stages of chondrogenic differentiation, from initiation of chondrogenic differentiation, to regulation of chondrocyte maturation and terminal differentiation (Pizette and Niswander, 2000). BMP2, BMP4, BMP6 and BMP7 are the most commonly used BMPs for chondrogenic differentiation (Kramer et al., 2000; Sekiya et al., 2005; Shen et al., 2010). BMPs signal through Smad or non-Smad signalling pathways. The Smad1/5/8 route is an important Smad-dependent pathway that induces hypertrophy and bone formation (Cao and Chen, 2005). The alternative Smad-independent pathway in BMP regulates chondrogenesis, mediated by activating several MAPKs including ERKs and p38 kinases (Hassel et al., 2003). p38 enhances chondrogenesis by up-regulating SOX9 expression directly or by inhibiting the Wnt7a/beta catenin pathway indirectly (Jin et al., 2006). MSCs from different species and tissue sources vary in their responsiveness to BMPs, partly due to their distinct cell receptor repertoires (Hennig et al., 2007; Osyczka et al., 2004).

GDF5, also known as BMP14 in humans, is a member of the TGF-β superfamily and plays an important role in the differentiation of stem cells into chondrocytic lineages. GDF5 positively regulates chondrogenesis, mediated by activating the Smad1/5/8 pathway (Pizette and Niswander, 2000). GDF5 is a member of the TGF-β superfamily and plays an important role in the differentiation of stem cells into chondrocytic lineages. GDF5 positively regulates chondrogenesis, mediated by activating the Smad1/5/8 pathway (Pizette and Niswander, 2000).
role in limb bud mesenchymal cell condensation and chondrogenesis during embryogenesis (Coleman and Tuan, 2003; Storm et al., 1994). GDF5 stimulates the recruitment and differentiation of chondrogenic cells at early stages and increases chondroprogenitor cell condensation and cartilaginous nodules without altering the overall pattern of differentiation. It causes a more sustained elevated expression level of SOX9 than BMP4 (Hatakeyama et al., 2004). GDF5 increases mesenchymal cell condensation independent of cell density or N-cadherin-mediated adhesion and signalling; however, it is dependent on gap junction-mediated cellular communication (Coleman and Tuan, 2003; Sun et al., 2012). GDF5 can promote chondrogenesis via signalling cross-talk, when used together with TGF-β3 and BMP2 in vitro (Murphy et al., 2015). GDF5 has also been shown to increase the expression of COL2A1 and hypertrophic marker, alkaline phosphatase (ALP) by enhancing the phosphorylation of Smad1/5/8 (Coleman et al., 2013), which is activated by BMPs. GDF5’s effect on the enhancement of ACAN and the inhibition of MMP13 expression occurs by up-regulating the canonical Wnt inhibitors DKK1 (Enochson et al., 2014).

PThrP inhibits TGF-β-induced hypertrophic differentiation by up-regulating the chondrogenic markers COL2A1 and SOX9 and down-regulating the hypertrophic markers COL10A1 and RUNX2 during in vitro chondrogenesis of MSCs (Kim et al., 2008; Weiss et al., 2010). PThrP exerts its effects in vivo via the PThrP and Ihh feedback loop by binding to its receptor (PTHR1) and activating a range of signalling molecules, e.g. protein kinase A (PKA), PKC and inositol 1, 4, 5-tris-phosphate (IP3). Some signalling molecules act as negative regulators for Ihh. Hence, PThrP inhibits the terminal differentiation of chondrocytes driven by Ihh (Kim et al., 2008; Mau et al., 2007; Rabie et al., 2003). The chondrogenic effects of PThrP vary amongst different PThrP isoforms. PThrP 1-34, added in chondrogenic medium containing TGF-β3, significantly increases chondrogenic differentiation with less hypertrophic differentiation, while other isoforms (PThrP 1-86, 7-34 and 107-139) show inconsistent effects (Lee and Im, 2012). When culturing MSC pellets under hypertrophy-enhancing conditions [hypertrophy-enhancing medium consisting of DMEM, 1 % ITS, 50 μg/ mL ascorbate-2-phosphate, 40 μg/mL L-proline and 1 nM triiodothyronine (T3)], adding PThrP (1-40) does not diminish the induced enhancement of hypertrophy (Mueller et al., 2013b).

The FGF family, especially FGF [basic FGF (bFGF); also known as FGF2], can maintain MSCs in an immature state during in vitro expansion and enhance MSC proliferation and differentiation potential (Mastrogiacomo et al., 2001; Solchaga et al., 2005; Tsutsumi et al., 2001). Literature suggests that aggregates of human MSCs that were expanded in culture in the presence of bFGF lacked the collagen I-positive and collagen II-negative outer layer characteristics of aggregates (Ng et al., 2008; Solchaga et al., 2005). However, in pellet cultures, the prolonged exposure of MSCs to bFGF caused the reduction of glycosaminoglycan (GAG) production (Hellingman et al., 2010). Therefore, bFGFs can be added into the medium to culture MSCs, but in differentiation medium, it may not be necessary.

Physical, chemical and biological factors

In addition to biochemical molecules used in current chondrogenic differentiation medium, many other factors are involved in chondrogenic differentiation. These factors include physical (oxygen tension, mechanical, topography, etc.), chemical (small molecules, chemical properties, etc.) and biological factors (gene modification, bioactivity, epigenetics, etc.). Apart from biochemical factors (growth factors), biophysical factors (co-culture) and biophysicochemical factors (biomaterials) are equally important (Fig. 3). The influence of biophysical factors on chondrogenesis in vivo and in vitro have been reviewed (Huang et al., 2010a; Studer et al., 2012; Tate et al., 2008).

In this section, we focus on the use of biophysical and biochemical cues for chondrogenesis and recent advances in the field of tissue engineering.

Hypoxia can facilitate chondrogenic differentiation of MSCs, in addition to maintaining an undifferentiated state and inducing apoptosis. The microenvironment or the niche of MSCs in the bone marrow has low oxygen tension (< 32 mm Hg, 4.2 % oxygen) (Oze et al., 2012; Spencer et al., 2014). Therefore, chondrogenic differentiation is enhanced when MSCs are cultured in hypoxia (5 % oxygen) in comparison to normoxia (20 % oxygen) (Lee et al., 2013). Hypoxia has a positive influence on chondrogenic differentiation of MSCs, mainly through phosphorylation of AKT (known as protein kinase B) and p38 MAPK, thereby down-regulating hypoxia-inducible factor (HIF-1) (Kanchai et al., 2008).

Mechanical stimulation can directly influence the fate of undifferentiated stem cells (Estes et al., 2004) via cellular and nuclear deformation and indirect biophysical factors, including osmotic and hydrostatic pressure and fluid flow (O’Conor et al., 2013). Matrix elasticity directs the differentiation of stem cells; soft matrix (~ 1 kPa) has been shown to promote MSC differentiation into a chondrogenic lineage (Engler et al., 2006; Park et al., 2011), while activation and internalisation of integrin are actively involved in the regulation of stem cell differentiation (Du et al., 2011). Cell-material properties, such as cell stiffness, dictate cell spreading and alter differentiation in response to physical stimuli (Chowdhury et al., 2010). Surface topography can trigger changes in MSC morphology, gene expression and cytoskeletal structure (Huang et al., 2010b).

Compared to non-patterned surfaces, nano-pillar and nano-hole topographies enhanced MSC chondrogenesis and facilitated hyaline cartilage formation, whereas nanogrid topography delayed chondrogenesis and induced the formation of fibro/superficial zone cartilage (Wu et al., 2014).

Small chemical molecules are also known to guide MSC differentiation (Benoit et al., 2008) by binding to specific receptors that promote chondrogenic differentiation (Cho et al., 2012; Johnson et al., 2012; Kafienah et al., 2007; Schugar et al., 2008). As an illustrative example, kartogenin (KGN) has been shown to encourage
chondrogenic differentiation of human MSCs, by significantly enhancing the expression of COL2A1, SOX9 and ACAN. However, KGN had no significant effect on the gene products associated with chondrocyte calcification, such as osteocalcin (OCN), ALP and COL10A1, in human MSCs or chondrocytes (Johnson et al., 2012). KGN functions by binding to filamin A, an actin-binding protein that cross-links actin filaments. Thereby, by regulating the cytoskeletal network organisation and dynamics (Gorlin et al., 1990) and disrupting its interaction with core binding factor β (CBFβ), it modulates the activity of the RUNX family of transcription factors (Johnson et al., 2012).

Small molecule inhibitors can regulate chondrogenesis by blocking key receptors or signalling pathways. As a nuclear receptor, retinoic acid receptor β (RARβ) is down-regulated significantly during chondrogenesis. The synthetic inhibitor (LE135) enhances chondrogenesis while inhibiting hypertrophic differentiation (Kafienah et al., 2007). Another small molecule inhibitor, dorsomorphin, can block Smad1/5/8 signalling, enhance chondrogenesis, elevate the production of collagen II and prevent mineralisation (Hellingman et al., 2011; Retting et al., 2009). Inhibition of inflammatory factors can boost the chondrogenic differentiation capacity of MSCs obtained from osteoarthrits patients through inhibiting inflammatory stimuli-induced damage, hypertrophy and apoptosis (Murphy et al., 2002; Rainbow et al., 2013).

Using a gene transfer/silencing strategy on MSCs can facilitate change in the complex regulatory networks of stem cell biology and regulate chondrogenic differentiation processes (Feng et al., 2008; Paik et al., 2012). For example, knockdown of HIF-1α by HIF-1α small interfering RNA (siRNA) leads to an increase in chondrogenesis (Kanichai et al., 2008).

Biomaterials can facilitate chondrogenesis in multiple ways, including mechanical support, surface topography and stiffness, chemical modification and bioactivity (Bian et al., 2013; Lutolf et al., 2009; Wise et al., 2009; Zhang et al., 2014). Co-cultures of chondrocytes and MSCs enhance chondrogenesis due to the trophic role of MSCs (MSCs secrete a variety of cytokines and growth factors that have both paracrine and autocrine activities), which stimulate chondrocyte proliferation and matrix production. However, MSCs in co-culture conditions do not actively undergo chondrogenic differentiation themselves (Caplan and Dennis, 2006; Meretoja et al., 2012; Wu et al., 2012).

**Future Perspectives**

Heterogeneous differentiation of differentiated MSCs is one of the main challenges faced in *in vitro* chondrogenic induction and is seldom discussed. Multiple factors are involved in these processes, such as variance in cell-cell and cell-matrix adhesions, autocrine or paracrine activities, different subpopulations of MSCs used, individual cells encapsulated in biomaterials that induces different cellular microenvironments (such as exchange of nutrient and waste, oxygen gradients), etc.. High-throughput technologies, such as microfluidics or microfabrication, may be able to set up large scale production of homogeneous microtissues or microenvironments to circumvent this issue.
Senescence and apoptosis inherently occur during both embryonic development and in vitro chondrogenic differentiation, so regulation of these two processes could potentially regulate chondrogenic differentiation. Senescence and apoptosis synergistically prevent the over-growth of chondrocytes and shapes the articular cartilage during embryonic development (Ito and Kida, 2000; Loeser, 2009). Senescence of bone marrow MSCs is associated with low proliferation activity and decline of stemness (Squillaro et al., 2015), which may lead to inferior chondrogenic differentiation efficiency (Vacanti et al., 2005). Efforts in hampering cell senescence during chondrogenic differentiation with growth factors, anti-inflammatory drugs, antioxidants, nutrients as well as appropriate microenvironments such as hypoxia and stem cell matrices effectively improve the efficiency and quality of tissue-engineered cartilage in vitro and in vivo (Li and Pei, 2012; Rainbow et al., 2013). It is known that the majority of cells in pellet cultures undergo apoptosis (Wang et al., 2010). Apoptosis may occur due to low nutrient supply to cells in the centre of the pellet, hypoxia and subsequent cell fate. Some preconditioning steps, such as use of medium with high glucose, and hypoxia preconditioning, may be able to protect MSCs from undergoing the process of apoptosis (Mackay et al., 1998; Wang et al., 2008).

In addition, biophysical signals are indispensable for successful chondrogenic differentiation. Mechanical properties influence phenotypes of differentiated chondrocytes and affect respective progenies (Yang et al., 2014). Oxygen tension or hypoxia can facilitate differentiation. MSCs can differentiate into hyaline cartilage chondrocytes instead of hypertrophic chondrocytes which is more likely to happen under current chondrogenic differentiation protocols (Leijten et al., 2014). Premature and unstable phenotypes of differentiated chondrocytes pose challenges for potential clinical use and lead to inferior quality of regenerated cartilage (Pelttari et al., 2006). Mimicking embryonic articular cartilage formation instead of embryonic chondrogenesis can assist bioengineers in overcoming this challenge, which means that temporal regulation of multiple factors may be required. For example, decreased Wnt, Hedgehog and BMP signalling and specification of GDF-5 expression are of great importance for the homeostasis of articular chondrocytes (Bobacz et al., 2008; Leijten et al., 2012). Previous studies have shown that over expression of GDF-5 led to the unsuccessful differentiation of articular chondrocytes (Feng et al., 2008). However, the role of GDF-5 in embryonic arthrogenesis and postnatal development is not entirely clear. From our viewpoint, hypertrophy will not pose challenges to chondrogenic differentiation if optimised protocols can further differentiate stem cells into articular chondrocytes and maintain their classic phenotypes.

Temporally fine-tuning chondrogenic differentiation medium can profoundly enhance differentiation efficiency. Chondrogenic differentiation medium is involved in administering TGF-β and other factors throughout the entire culture period (Johnstone et al., 1998). Previously, multiple factors induced step-wise mesoderm differentiation and subsequent chondrogenesis through mimicking embryonic chondrogenesis (Oldershaw et al., 2010). The sequential addition of growth factors may be able to improve chondrogenesis based on gene expression of cell surface receptors and effectiveness of growth factors; withdrawal of the growth factors after nine days improves chondrogenesis (Handorf and Li, 2014). Apart from the addition of growth factors, inhibition of specific cell signalling pathways may also enhance chondrogenesis, such as the Smad1/5/8 signalling inhibitor dorsomorphin (Hellingman et al., 2011; Retting et al., 2009) or Wnt inhibitors [Gremlin 1, frizzled-related protein (FRP) or dickkopf (Dkk-1)] (Leijten et al., 2012).

Use of mathematical models can assist researchers in regulating chondrogenic differentiation. A “seesaw model” describes a balance between mesendodermal and ectodermal specification of pluripotency (Shu and Deng, 2013) and the cross-talk between genetics and epigenetics (Leijten et al., 2014). The lineage specifiers of mesendodermal and ectodermal are considered as pluripotency rivals. However, these lineage specifiers have shown to facilitate reprogramming of differentiated cells to the pluripotent state when a balance is achieved.

**Summary**

MSCs are a promising source of precursor cells, which are widely used in cartilage tissue engineering. By reviewing the process of cartilage development and the constituents of existing medium formulations for promoting chondrogenic differentiation, we have identified potential factors to generate a more stable and reliable hyaline cartilage in vitro. Cellular metabolic status, especially glucose metabolism and inhibition of inflammatory factors, need to be considered when trying to inhibit cell senescence and apoptosis. The combination and concentration of growth factors, the timing of the application of biochemical components and proper biophysical stimuli during cell culture needs further optimisation to achieve desirable differentiation outcomes.

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