Growth and Differentiation Factor-5 Contributes to the Structural and Functional Maintenance of the Intervertebral Disc

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Key Words
Growth and differentiation factor-5 • Intervertebral disc degeneration • Biological theraphy • Tissue regeneration

Abstract
Intervertebral disc degeneration (IDD) is a widely recognized contributor to low back pain (LBP). The Prevention or reversal of IDD is a potential treatment for LBP. Unfortunately, current treatments for IDD are aimed at relieving symptoms rather than regenerating disc structure or function. Recently, the injection of growth factors and mesenchymal stem cell (MSC) transplantation have been shown to be promising biological therapies for IDD. Growth factors stimulate the proliferation of and matrix synthesis by intervertebral disc (IVD) cells, leading to the regeneration of degenerative discs. Growth factors, hypoxia and co-culture with nucleus pulposus (NP) cells induce MSCs to differentiate toward an NP-like phenotype, which can increase the number of functional cells in the IVD or enhance the function of endogenous disc cells to facilitate IVD regeneration. Therefore, the emerging roles of growth factors in IVD regeneration have piqued the interest of researchers. Growth factors including transforming growth factor-β (TGF-β), fibroblast growth factor (FGF), insulin-like growth factor-1 (IGF-1) and growth and differentiation factor-5 (GDF-5), among others, have been demonstrated to enhance anabolism in IVD cells and to induce NP-like differentiation of MSCs. However, the injection of TGF, IGF and FGF into human IVDs may induce unwanted blood vessel ingrowth, which accelerates the process of IDD, the injection of GDF-5 may not have the same effect. This finding suggests that GDF-5 is a preferable growth factor for use in IDD treatment compared with TGF, IGF and FGF. The GDF-5 gene is one of the few growth factor genes that have been
found to be associated with IDD thus far; moreover, the GDF-5 gene defects lead to collagen
and proteoglycan abnormalities in discs in mice, suggesting that GDF-5 contributes to the
structural and functional maintenance of the IVD. This review is focused on the functions
of GDF-5 in the IVD and on the association between GDF-5 and a genetic predisposition to IDD.
The effects of GDF-5 on IVD regeneration and on MSC differentiation are also discussed. GDF-
5 plays a crucial role in the pathogenesis of IDD and is a promising therapeutic agent for IDD.
Additionally, stem cell transplantation has been shown to be a promising biological therapy
for IDD.

**Introduction**

LBP is one of the most prevalent musculoskeletal diseases worldwide. Approximately
70% of adults suffer from LBP at one time in their lives, and many of them are disabled
[1]. The socio-economic burdens related to LBP are massive. In the USA, approximately
25% of the population suffers from LBP and neck pain, and the associated costs reached
approximately $85 billion in 2008 [2]. Thus, LBP represents a significant threat to human
health and is a major drain on limited medical resources [2-4].

Intervertebral disc degeneration (IDD) is widely accepted as a main cause of LBP [5, 6].
IDD is defined as an aberrant cell-mediated response to progressive structural failure [7]
and is characterized by a loss of water signal intensity detected by T2-weighted MRI in the
nucleus pulposus (NP) combined with a loss of disc height, annular tears, inflammation and
bulging or herniation of the NP (Fig. 1B). Prevention or reversal of IDD is a potential treatment
for LBP. However, current treatment methods for IDD, including surgery and conservative
measures such as medications, steroid injection, and physical therapy, are aimed at treating
symptoms rather than at regenerating disc structure or function.

Because IVD tissue homeostasis is maintained by a balance between anabolism
and catabolism of disc cells, one of the potential therapeutic strategies to regenerate a
degenerative disc is to up-regulate the anabolism and to down-regulate the catabolism
induced by cytokines in the IVD [8]. Guided by this strategy, two advanced biological therapies
are being widely investigated: injection of anabolic growth factors into degenerative IVDs [9,
10] and mesenchymal stem cell (MSC) transplantation [11, 12] (Fig. 2). Growth factors shift
the metabolic status of IVD cells from the catabolic state to the anabolic state to regenerate
degenerative discs [10]. Various growth factors have been demonstrated to stimulate the
proliferation of and matrix synthesis by IVD cells *in vitro*, including transforming growth
factor-β (TGF-β), epidermal growth factor (EGF) [13, 14], insulin-like growth factor-1 (IGF-
1) [15], growth and differentiation factor-5 (GDF-5) [16, 17], osteogenic protein-1 (OP-1)
[18, 19] and bone morphogenetic protein-2 (BMP-2) [20, 21]. Furthermore, *in vivo*, OP-1
and GDF-5 have been determined to induce the restoration of disc height and to increase the
proteoglycan (PG) content in NP [22-24]. The results of these studies suggest the feasibility
of including growth factor injections in biological therapies for IDD. MSC transplantation is
also known as MSC-based therapy. The differentiation of MSCs toward an NP-like phenotype
has been shown to be induced by growth factors, co-culture with disc cells, and hypoxia [25-
27], TGF-β [25], IGF-1, fibroblast growth factor-2 (FGF-2), platelet-derived growth factor-BB
[28] and GDF-5 [29, 30] possessed the ability to induce NP-like differentiation of MSCs. The
gene expression profiles of these induced MSCs resembled those of native IVD tissue more
closely than those of joint cartilage [31]. Thus, these NP-like cells might be transplanted
into degenerative IVDs to increase the number of functional cells in IVDs or to enhance the
function of endogenous disc cells to assist IVD regeneration [12, 32].

As mentioned above, growth factors are necessary and essential in the two advanced
biological therapies for IDD. To date, growth factors that have been widely investigated
include TGF, IGF, BMP and FGF. Among these, GDF-5, a member of the BMP family, piqued
our interest. Receptors for TGF, IGF and FGF (TGFRI, IGFRI and FGFR3, respectively) were
demonstrated to be expressed on the ingrowing blood vessels in human degenerative IVDs. The angiogenic potential of TGF-β, FGF and IGF suggests that the injection of these factors into the human IVD may induce blood vessel ingrowth to enhance the degree of IDD. However, BMP receptor II, a type of GDF-5 receptor, was not observed in the infiltrated blood vessels, suggesting that GDF-5 may not induce unwanted blood vessel ingrowth. GDF-5 appears to be a preferable growth factor for use in biological therapies for IDD compared with TGF, IGF and FGF [33]. Moreover, the GDF-5 gene was shown to be a susceptibility gene for IDD [34, 35]. Recently, various genes have been analyzed in association with the genetic

Fig. 1. The molecular basis of IDD (A) and the T2 MRI image of IDD (B). A. The imbalance between anabolism and catabolism in IVD cells causes structural deficits of IVD and accelerates the process of IDD. The autophagy along with senescence or apoptosis of IVD cells as well as decreased ECM production and increased production of ECM degradative enzymes enhance catabolism in IVD cells. B. The T2-weighted MRI image showing the loss of water signal in the NP of L5-S1 along with loss of disc height as well as bulging or herniation of the NP.

Fig. 2. Two advanced biological therapies for IDD. The widely investigated therapeutic strategy for IDD is to up-regulate anabolism and down-regulate catabolism in IVD cells. Under this strategy, growth factor injection and MSC transplantation are proposed as the potential biological therapies for IDD. Grow factors shift the metabolic status of IVD cells to regenerate degenerative discs. MSCs differentiate toward an NP-like phenotype, which aids in the disc regeneration.
The pathogenesis of IDD

IDD is believed to be caused by aging, smoking, infection, excessive mechanical loading, decreased nutrient supplies and genetic predisposition [37-43]. These etiologic factors initiate the process of IDD mediated by the aberrant production of pro-inflammatory cytokines secreted by NP cells, annulus fibrosus (AF) cells, and infiltrated immune cells [44-46]. Pro-inflammatory mediators, including TNF-α, IL-1α, IL-1β, IL-6, IL-17, and various chemokines [47-52], induce autophagy, senescence or apoptosis of IVD cells [37, 53-58]; decreased extracellular matrix (ECM) production [59, 60]; and increased production of ECM degradative enzymes [61, 62]. As a result, the balance between anabolism and catabolism is disrupted in IVD (Fig. 1A), causing structural deficits of the NP and the AF as well as disc herniation under excessive mechanical loading. Concurrently, blood vessels and nociceptive nerve fibers from the dorsal root ganglion (DRG) invade into the herniated disc tissues to cause LBP [63-65]. Notably, genetic polymorphisms in various genes have been investigated in association with IDD, including the vitamin D receptor [66, 67]; aggrecan [68, 69]; GDF-5 [34, 35]; TIMP [66]; cartilage intermediate layer protein (CILP) [70, 71]; MMP 1, 2, and 3 [72-74]; and others. Each of these mutant genes encodes a protein that has a role in the pathophysiology of disc degeneration. Interestingly, although the GDF-5 gene is the one of the few growth factor genes that has been found to be associated with IDD thus far, the role of genetic polymorphisms in GDF-5 in disc degeneration remains unknown. Elucidating the functions of GDF-5 should benefit our understanding of IDD pathogenesis.

GDF-5: a member of the BMP family

GDF-5, also known as cartilage-derived morphogenetic protein-1 (CDMP-1), was identified as a new member of the TGF-β superfamily in 1994 [75]. That same year, human GDF-5 was cloned by Chang et al. [76] and by Hotten et al. [77]. GDF-5 is synthesized as a large precursor protein containing an N-terminal signal sequence, a prodomain with 358 amino acids and an active domain with 124 amino acids in the carboxyl terminus. The precursor protein then undergoes an endopeptidase cleavage at a characteristic R-X-X-R site to release a C-terminal mature peptide. This peptide includes 7 conserved cysteine residues that regulate disulfide-linked dimer formation at the C-terminus. X-ray crystallography was used to determine the 3D structure of recombinant human GDF-5. The results revealed that cysteine knots were characteristic 3D structures found within each subunit. A disulfide bridge was formed between the two subunits, allowing the formation of an active homodimer [78-80].
GDF-5 binds to the transmembrane serine/threonine kinase type I and II receptors to activate its signaling pathway [81, 82]. BMPR-1B (BMP receptor IB), BMPR-II, and activin receptor (ActR) type IIB have higher affinities for the GDF-5 ligand [83-85]. Upon GDF-5 binding, the receptors are phosphorylated to activate the downstream Smad pathway. The Smad proteins then translocate into the nucleus to regulate the transcription of various genes [86, 87].

**Functions of GDF-5 in IVD**

GDF-5 plays crucial roles in musculoskeletal development. During early limb development, GDF-5 expression is detected in precartilage condensations [75]. As the embryo develops, GDF-5 is expressed in the cartilaginous core of long bones, in articular surfaces and in osteoblast-like cells from the primary ossification centers of long bones [76], suggesting that GDF-5 is critical for the development of bone and joints. Additionally, GDF-5 has been demonstrated to play important roles in a variety of musculoskeletal physiological processes, such as endochondral ossification, the formation of ligaments and tendons and ligament maintenance and repair [88-94]. Considering the pleiotropic effects of GDF-5 in the musculoskeletal system, it is expected to play roles in IVD. In a loss-of-function study, GDF-5-deficient mice showed lumbar disc defects characterized by lower T2-weighted signal intensity in the NP accompanied by structural (histological) damage in the NP and AF [16]. However, the mRNA of GDF-5 was localized to the annulus fibrosus rather than to NP tissues in mouse embryos. It was found that notochord cells formed normal NP tissues in GDF-5-deficient mice [95]. Thus, the disc defects of GDF-5-deficient mice were likely caused by progressive postnatal degeneration of NP rather than by abnormal formation of the NP from the notochord during embryogenesis. This finding suggests that GDF-5 does not participate in the formation of the NP in embryonic mice; however, it plays a crucial role in postnatal IVD maintenance. Moreover, in the GDF-5-deficient mice, the expression of aggrecan and collagen type II in IVD cells was significantly down-regulated, and the PG content in discs was decreased. GDF-5 treatment up-regulated the expression of aggrecan and collagen type II in disc cells from GDF-5-deficient mice in a dose-dependent manner [16]. Notably, GDF-5 was shown to enhance the proliferation of bovine NP cells and AF cells in vitro. Concurrently, GDF-5 also significantly enhanced PG and collagen synthesis in both cell types [17]. Furthermore, GDF-5 was demonstrated to down-regulate MMP-3 gene expression in mouse disc cells, suggesting that GDF-5 suppresses ECM catabolism in IVD [96]. The results of these studies suggest that GDF-5 is effective in suppressing ECM degradation and in enhancing the proliferation and matrix anabolism of IVD cells (Fig. 3).

In humans, GDF-5 was shown to be expressed in both normal and degenerative IVDs, particularly in NP cells. However, the number of cells expressing GDF-5 was decreased in degenerative human IVDs. GDF-5 treatment up-regulated expression of aggrecan and collagen type II in NP cells isolated from degenerative IVDs and induced greater production of PG [97]. These findings indicate that GDF-5 is produced by human IVD cells and that it promotes ECM anabolism in IVD. Thus, GDF-5 aids in maintaining the structural integrity of the IVD. However, GDF-5 expression in IVD cells was shown to be suppressed by pro-inflammatory cytokines such as TNF-α and IL-1β (Fig. 3) [98]. Therefore, it is possible that the suppression of GDF-5 expression down-regulates ECM anabolism in the IVD to accelerate the process of IDD.

**GDF-5 gene polymorphisms associated with IDD**

Mutations in GDF-5 have been shown to be associated with several skeletal disorders such as brachydactylies (BDs), multiple synostoses syndrome [99-102], Du Pan type chondrodysplasia (DPC), Grebe-type chondrodysplasia (GTC) [103-107], angel-shaped
phalangeal dysplasia (ASPED), proximal symphalangism, and congenital vertical talus [108-110], which are consistent with the pleiotropic effects of GDF-5 on the musculoskeletal system. GDF-5 is also a susceptibility gene for osteoarthritis (OA), which is a polygenic degenerative skeletal disorder. The GDF5 single-nucleotide polymorphism (SNP) rs143383 has been demonstrated to be a susceptibility allele for OA [111-113]. The SNP rs143383, a T-to-C transition, is also associated with congenital hip dysplasia in Han Chinese and French Caucasian populations [114, 115]; it is located within the 5’ untranslated region (UTR) of the GDF-5 gene and within the GDF-5 promoter. The T-allele frequency of the gene was found to be elevated in patients with OA [111]. The expression of the OA-associated T allele was lower than that of the C allele in synovial joint tissues from OA patients, suggesting an imbalance between the expression of the C and T alleles of this SNP [116, 117]. This allelic expression imbalance (AEI) causes a joint-wide reduction in GDF-5 expression, which is assumed to trigger individual susceptibility to OA [116]. This hypothesis is supported by a study in mouse arthritis models. Mice with GDF-5 deficiency presented more severe osteoarthritic changes than wild type mice [118]. Recently, the transcription of the two alleles of this SNP was reported to be suppressed by the binding of the trans-activating factors Sp1, Sp3, P15, and DEAF1, leading to the AEI that underlies the OA susceptibility mediated by this SNP [119]. CpG methylation was demonstrated to regulate GDF-5 expression by modulating the binding of the SP1, SP3 and DEAF1 transcriptional repressors [120].

IDD is also one of the degenerative skeletal disorders that is influenced by both genetic and environmental factors [121]. Identification of susceptibility genes is crucial for elucidating the etiology and pathogenesis of IDD and for the development of new therapies for IDD. Approximately 20 genes have been investigated in association with IDD [36]. Interestingly, GDF5 rs143383 was demonstrated to be associated with IDD in northern European women and a Chinese military cohort. The T-allele frequency was also elevated in patients with IDD, suggesting that the GDF-5 gene is a susceptibility gene for IDD [34, 35]. The effect of rs143383 on GDF-5 allelic expression may be similar to the effect on OA. However, the AEI identified in OA tissues has not been investigated in degenerative disc tissues. No studies thus far have investigated whether the transcription of the two alleles of the SNP in IDD patients is also regulated by the trans-activating factors Sp1, Sp3, P15 and DEAF1 or by CpG methylation. Thus, further studies will be required to elucidate how the rs143383 SNP regulates GDF-5 allelic expression to mediate IDD susceptibility. Because IDD shares a common susceptibility allele with OA, this finding suggests that both diseases have a common molecular pathology that may involve a cellular growth and differentiation pathway, which might serve as a possible route to further understanding the pathogenesis of IDD.

**Fig. 3.** Functions of GDF-5 in IVD. GDF-5 is produced by IVD cells, which are suppressed by IL-1β and TNF-α. It down-regulates the expression of MMP to inhibit the ECM catabolism, and up-regulates the expression of aggrecan and collagen type II to enhance the ECM anabolism. Additionally, GDF-5 also stimulates the proliferation of IVD cells, which increases the number of functional cells in IVD. The pleiotropic effects of GDF-5 contribute to the functional and structural maintenance of IVD.
In vivo studies of GDF-5 injection

GDF-5 was shown to promote the proliferation of disc cells and to regulate ECM metabolism in disc cells in vitro (Table 1), suggesting a potential application of GDF-5 in IVD regeneration [17, 96]. However, the regenerative effects of GDF-5 on degenerative discs should be verified in vivo. A single injection of GDF-5 was administered to degenerative murine discs induced by static compression [24]. At 4 weeks after treatment, the disc height was significantly increased. An increase in isogenic groups of fibrochondrocytes within the inner AF and NP was observed. In response to exogenous GDF-5, the annulus fibrochondrocytes expanded into the degenerated, hypocellular NP. These cells expressed aggrecan and collagen type II genes, suggesting increased ECM synthesis within the NP [24]. These results suggest that GDF-5 is a mitogen for annulus fibrochondrocytes. GDF-5 promotes the expansion of and ECM synthesis by annulus fibrochondrocytes, which increases cellularity and the ECM content within the NP. As a result, the height and the biomechanical stability of the degenerative disc are restored. In a rabbit model of disc degeneration induced by annular puncture, a single injection of recombinant human GDF-5 was also shown to restore disc height with improvement in both histologic and MRI findings. MRI of the NP of GDF-5-treated discs showed stronger T2 signal intensity, suggesting that the hydrophilic properties of the NP were maintained after GDF-5 injection. Moreover, in the discs injected with GDF-5, the number of chondrocytic cells in the NP and rounded chondrocytes in the AF increased significantly [17]. The results of these studies suggest that GDF-5 injection can retard or reverse IDD. According to functional studies of GDF-5 and in vivo studies of GDF-5 injection, GDF-5 may arrest or reverse the process of IDD through two principal pathways. First, it is possible that GDF-5 promotes the proliferation of and ECM synthesis by disc cells to enhance anabolic metabolism in IVD. Alternatively, it is possible that GDF-5 down-regulates the expression of catabolic genes such as MMP in disc cells to suppress catabolic metabolism in IVD [96]. However, further details about these pathways are not currently available. Additional studies will be needed to elucidate the mechanism by which GDF-5 injection triggers IVD regeneration. Concomitantly, the effects of GDF-5 injection on human degenerative discs should be investigated in the future.

Alternative approaches to GDF-5 administration

GDF-5 injection has been shown to be an effective method of administering GDF-5 into degenerative IVD. However, the effects of a single injection of GDF-5 are not sustained over a
long period. Multiple GDF-5 injections can cause an inflammatory reaction in the discs [24], which limits the clinical applications of GDF-5 in biological therapy for IDD. Thus, alternative approaches of GDF-5 administration have been proposed that can ensure that the effects of GDF-5 are sustained. Delivery of the GDF-5 gene was demonstrated to be an alternative method [122]. The GDF-5 gene was transferred into IVD cells using adenovirus or plasmid vectors, and GDF-5 protein production in the transfected IVD cells was confirmed. Expressed GDF-5 protein was shown to be bioactive: it promoted the growth and proliferation of disc cells as well as ECM production by these cells [96, 122]. Furthermore, in a mouse disc degeneration model induced by annulus needle puncture, an adenoviral vector carrying the GDF-5 gene was injected into lumbar discs to evaluate the effects of GDF-5 gene therapy for IDD. The results showed that the GDF-5 gene was successfully expressed. GDF-5 induced significant restoration of T2-weighted MRI signals and disc height. Disc histology was also improved after GDF-5 gene therapy [123]. These findings indicate that delivery of the GDF-5 gene is an effective method for GDF-5 administration. The newly introduced GDF-5 gene will be expressed and will retard or reverse IDD, similar to GDF-5 injection. However, the effects of GDF-5 gene therapy on human discs have not been investigated thus far. Importantly, the safety of GDF-5 gene therapy has not been determined.

Another alternative approach to GDF-5 administration is the injection of poly (lactic-co-glycolic acid) (PLGA) microspheres loaded with recombinant human GDF-5. These PLGA microspheres loaded with GDF-5 were injected into a rat caudal disc degeneration model induced by needle puncture, and the microspheres guaranteed sustained release of active GDF-5 protein for more than 42 days [124]. As a result, the disc height was restored significantly. Histological changes were improved by the PLGA microsphere treatment. Moreover, increases in glycosaminoglycan (GAG) and DNA content with an increase in collagen type II mRNA levels and an improvement in the differentiation index (the ratio of collagen type II to collagen type I) were also observed [124]. These findings suggest that the injection of GDF-5 loaded in PLGA microspheres is also an effective method of GDF-5 administration. Encapsulation of GDF-5 in PLGA microspheres guarantees that the therapeutic effects of GDF-5 will be sustained over a long period and is a better method of GDF-5 administration compared with GDF-5 injection. However, more studies will be needed to evaluate the effects of PLGA microspheres on human discs. To summarize, GDF-5 should be administered using a safe and convenient approach, which not only guarantees sustained therapeutic effects of GDF-5 but also guarantees safety.

The Effect of GDF-5 on the Differentiation of MSCs Toward an NP-Like Phenotype

MSCs are promising graft cells for cell-based therapy of IDD [125, 126]. Transplanted MSCs are expected to differentiate into cells with an NP-like phenotype, and these NP-like cells could repair, maintain, and enhance the function of existing NP cells to arrest or reverse the process of IDD. However, the differentiation of MSCs depends on various biological microenvironmental factors. Growth factors including TGF-β, IGF-1, FGF-2 and PDGF have been shown to induce the differentiation of MSCs into NP-like cells [25, 28]. MSCs cultured under hypoxic conditions (2-3% oxygen) showed enhanced NP-like and chondrogenic differentiation [25, 127, 128]. Furthermore, MSCs co-cultured with human NP cells showed increases in chondrogenic gene expression and ECM production [26, 129]. However, the NP-like differentiation of MSCs in these studies was monitored using standard chondrogenic genes including aggrecan, collagen type II, and the transcription factor SOX-9. Thus, the differences between NP-like differentiation and chondrogenic differentiation were not considered. Recently, several potential markers were identified that can be used to distinguish between chondrogenic and NP-like differentiation, including the aggrecan/collagen type II ratio, cytokeratin 19 (KRT19), forkhead box F1 (FOXF1), and carbonic anhydrase 12 (CA12). The ratio of aggrecan to collagen is distinctly higher in the NP than in cartilage [130]. The expression of KRT19, FOXF1 and CA12 was shown to be up-regulated in
the NP compared with articular chondrocytes and AF cells [70, 131, 132]. It is hypothesized that these potential markers will be up-regulated during the process of NP-like differentiation when compared with chondrogenic differentiation [29, 30]. Interestingly, GDF-5 was shown to up-regulate the expression of aggrecan, collagen type II, and SOX-9 in MSCs [133, 134]. Moreover, a combination of GDF-5 and hypoxia or co-culture with NP cells had a synergistic effect on NP-like differentiation of MSCs. Such interventions increased the aggrecan/collagen type II ratio and up-regulated the expression of KRT-19, FOXF1 and CA12 in MSCs [29, 30]. These findings suggest that GDF-5 is suitable for inducing NP-like differentiation of MSCs, particularly when they are synergized by hypoxia and co-culture with NP cells.

In a recent study, the GDF-5 gene was transfected into human MSCs [135]. The transfected cells were grown in 3D cultures using alginate beads and were shown to express GDF-5 efficiently for up to 21 days. GDF-5 gene transfer along with 3D culture caused the up-regulation of SOX9, aggrecan and KRT19 expression in MSCs. Furthermore, the injection of GDF-5-transfected MSCs into an IVD organ culture model induced partial restoration of the GAG/DNA ratio. These results suggest that transfected MSCs could differentiate toward an NP-like phenotype and thus may serve as potential graft cells for MSC-based therapy for IDD [135]. However, another study showed that the carrier of MSCs might determine the fate of these cells without the need for GDF-5. For example, human MSCs cultured in a thermoreversible hyaluronan-based hydrogel, hyaluronan-poly (N-isopropylacrylamide) (HA-pNIPAM), under hypoxia differentiated toward an NP-like phenotype, regardless of whether GDF-5 was added [136]. Furthermore, in a bovine caudal disc organ culture model, human MSCs suspended in HA-pNIPAM without GDF-5 showed stronger NP-like differentiation than MSCs predifferentiated with GDF-5 in HA-pNIPAM [136]. These findings suggest that HA-pNIPAM induces the differentiation of MSCs toward an NP-like phenotype without the need for GDF-5. In conclusion, the differentiation of MSCs is influenced by various microenvironmental factors. The microenvironment in degenerative IVDs is highly complex, with many positive and negative factors influencing the fate of MSCs [12]. Thus, the manner in which MSCs are induced to differentiate toward an NP-like phenotype in harsh microenvironments should be explored in the future.

**Future perspectives**

GDF-5 has been demonstrated to suppress ECM degradation and to enhance the proliferation and matrix anabolism of IVD cells, suggesting that it contributes to the structural and functional maintenance of the IVD. However, GDF-5 has an extensive role in the musculoskeletal system, suggesting that it may have more functions in IVD beyond those cited. Thus, more studies are required to investigate the biological functions of GDF-5 in IVD. Although GDF-5 gene polymorphisms were shown to be associated with IDD in northern European women and a Chinese military cohort [34, 35], these previous studies used small sample sizes and non-stringent significance levels. Therefore, this association should be further investigated in broader populations. Furthermore, the mechanism by which rs143383 regulates GDF-5 allelic expression to mediate IDD susceptibility is not well understood. Exploration of these issues will help to elucidate the pathogenesis of IDD and will contribute to the development of new therapeutic targets. GDF-5 injection was shown to restore disc height and histologic changes in animal models of IDD, suggesting the feasibility of applying GDF-5 for the prevention or reversal of IDD at an early stage. However, the therapeutic effects of GDF-5 may be overestimated due to the lack of “repair” cells in human IVD. Therefore, further studies will be required to investigate whether GDF-5 injection prevents IDD effectively. Additionally, to guarantee that the therapeutic effects of GDF-5 are sustained, more safe and convenient approaches to GDF-5 administration should be investigated. GDF-5 was confirmed to induce NP-like differentiation of MSCs, and MSCs with an NP-like phenotype are promising graft cells for use in MSC-based therapy for IDD. Thus, preclinical studies and clinical trials will be required in the future. In summary, the
functions of GDF-5 in IVD and the association between GDF-5 gene polymorphisms and IDD should be explored extensively. Such knowledge will help to uncover the pathogenesis of IDD and will aid the development of feasible, effective biological therapies for IDD that are based on GDF-5.

**Abbreviations**

GDF-5 (growth and differentiation factor-5); IVD ((intervertebral disc); IDD (intervertebral disc degeneration); LBP (low back pain); MSC (mesenchymal stem cell); PG (proteoglycan); NP (nucleus pulposus); AF (annulus fibrosus); TGF (transforming growth factor); EGF (epidermal growth factor); IGF (insulin-like growth factor); OP (osteogenic protein); BMP (bone morphogenetic protein); FGF (fibroblast growth factor); MMP (matrix metalloproteinase); TIMP (tissue inhibitor of metalloproteinase); ECM (extracellular matrix); DRG (dorsal root ganglion); BMPR (BMP receptor); OA (osteoarthritis); SNP (single-nucleotide polymorphism); AEI (allelic expression imbalance); GAG (glycosaminoglycan); KRT19 (cytokeratin 19); FOXF1 (forkhead box F1); CA12 (carbonic anhydrase 12); PDGF (platelet derived growth factor).

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