



REVIEW ARTICLE

Cell therapy for intervertebral disc repair: Clinical perspective



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KEYWORDS

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Summary Low back pain is the main cause of disability and is associated with intervertebral disc degeneration. Contemporary treatments are limited to palliative therapeutics or aggressive surgical interventions; however, current advancements in cell therapy offer to fill this breach. Clinical data suggest that cell transplantation can accomplish pain relief without any observed adverse effects. Despite a large variety of preclinical studies and preliminary clinical investigations, controversy remains on the optimal cell type and transplantation strategies. The translational potential of this article lies in the aim to update on the current state of intervertebral disc cell therapy and to identify current obstacles.

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Introduction

Low back and neck pain are the most common musculoskeletal conditions worldwide and pose a major global health issue. An approximate 632 million people are affected by low back pain, of which an estimated 5–10% will progress toward a chronic condition [1,2]. Consequently, low back pain engenders an immense economic burden on society. Annual socioeconomic costs in the

United States are estimated to exceed \$100 billion [3,4]. Similar trends are observed in other developed countries [5–7]. A small reduction in low back pain related health usage or disability could consequently result in a large economic impact [8].

Low back pain is generally associated with intervertebral disc (IVD) degeneration. The IVDs are the fibrocartilage tissue bodies situated between the bony vertebrae, absorbing and distributing complex and substantial loads along the spine [9]. The IVD is composed of a hydrophilic gelatinous core, the nucleus pulposus (NP), which is encompassed by thick layers of tightly radially aligned collagen fibres, forming the annulus fibrosus (AF). Additionally, a thin layer of hyaline cartilage borders the vertebrae and the IVD. This cartilage layer functions as the

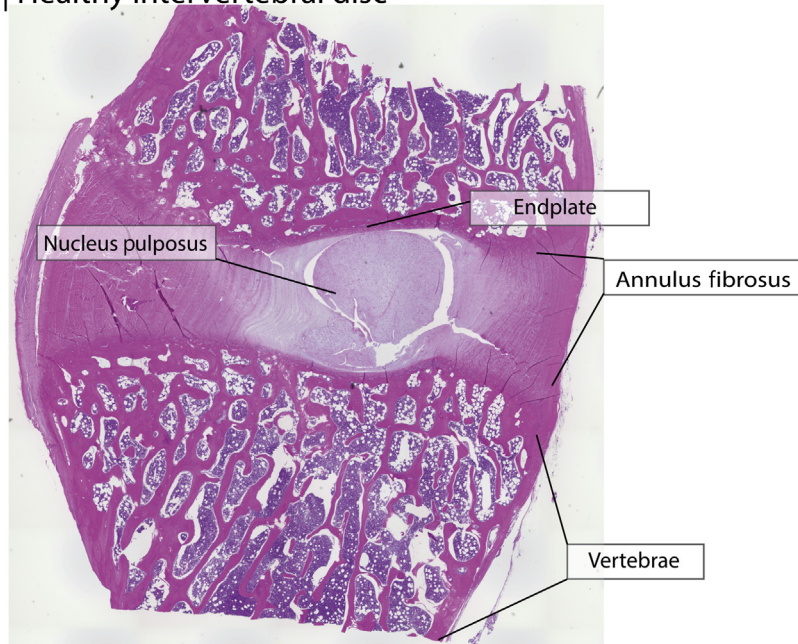
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waste and nutrient exchange for the interior of the IVD [10]. The proteoglycan-rich extracellular matrix (ECM) induces the NP to swell. However, the AF and vertebrae spatially contain the NP, establishing a high hydrostatic pressure. This enables the IVD to absorb extraordinary compressive forces, yet permitting flexible motility [11]. Region-specific cells provide a continuous turnover of ECM that accomplishes these tissue-specific biomechanical features (Figure 1A). AF cells are morphologically similar to collagen-producing fibroblast cells. Endplate cells resemble

hyaline chondrocytes. The NP cell population gradually changes up to adulthood, progressively differentiating from large vacuolated notochordal cells to small chondrocyte-like NP cells. The notochord-derived cells are postulated to possess a more potent regenerative capacity compared to the chondrocyte-like NP cells [12].

The exact origin of IVD degeneration remains to be identified; however, the NP is believed to be the place of onset, as this tissue displays the severest change during the early stages of IVD degeneration [13,14]. The progressive

A | Healthy intervertebral disc



B | Degenerative intervertebral disc

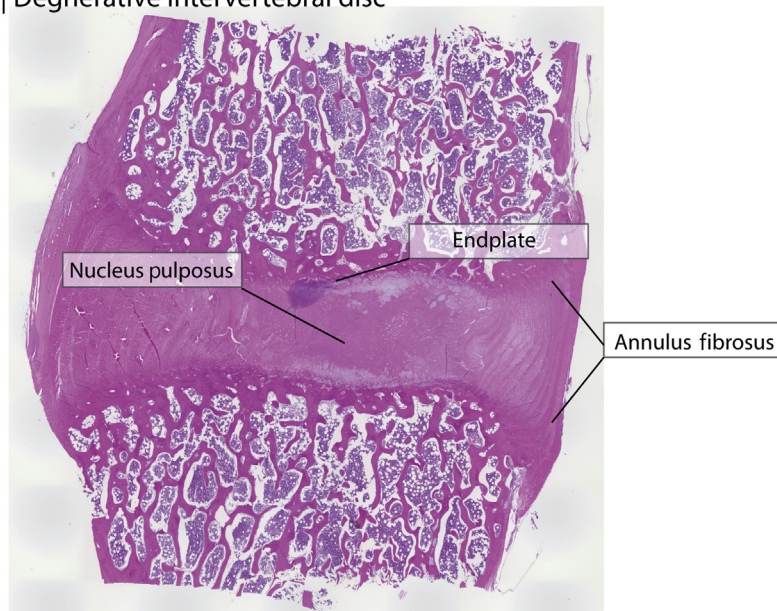


Figure 1 Canine intervertebral disc and vertebrae sections stained by hematoxylin/eosin staining. (A) A section of a healthy intervertebral disc with a healthy gelatinous nucleus pulposus core. (B) An artificially degenerated disc section with a fibrous nucleus pulposus core. Degeneration was induced by aspirating approximately 25 mg of nucleus pulposus tissue by methods from previously published work [74]. Fourteen weeks after aspiration, the tissue was explanted and stained.

degeneration is defined by a decrease in production of proteoglycans and an increase in matrix degrading proteins [15,16]. Moreover, a larger portion of NP cells become senescent, and cell viability declines [17]. The overall loss of proteoglycans is followed by a decrease in IVD water content and a disorganisation of collagen fibres. Consequently, the disc loses its hydrostatic features and shrinks in size [18]. Morphologically, the NP changes from a soft fibrocartilage tissue towards a stiffer fibrotic structure [19] (Figure 1B). These structural changes alter the biomechanical features along the spine, affecting adjacent vertebrae and potentially inducing facet joints arthritis, bone spur formation, and promoting spine diseases such as canal stenosis, spondylolisthesis, and kyphoscoliosis.

Despite the well-known ensuing pathologies of IVD degeneration, preventative and therapeutic approaches remain primarily palliative. Conservative treatment modalities, such as physical therapy and pain medication are used, whereas for more severe cases surgical resection or immobilisation of the disc is applied. The effects of these treatment options are limited in reversing and restoring the IVD homeostasis [20]. In fact, the surgical procedures often further disrupt the biomechanical disbalance, resulting in accelerated degeneration in adjacent segments [21]. Therefore, a great interest has developed for the application of cell transplantation to restore IVD homeostasis and reverse the degeneration process. In this narrative review, we will discuss the rationale for cell transplantation-mediated therapies. Finally, we will review published and ongoing clinical trials to elucidate current obstacles and potential solutions.

Innate regeneration

Disc degeneration is characterised as a disease of ageing, hallmarked by a loss of viable cells and an increase in cell senescence [17,22]. Moreover, reports have demonstrated that IVD progenitor populations diminish with age [23]. For most tissues, new and active cells can be attracted to damaged or distressed sites to promote repair and regain homeostasis. Studies have explored the potential of *in situ* cell recruitment into the IVD. In a bovine whole IVD *ex vivo* culture, exogenous human mesenchymal stem cells (MSCs) were able to infiltrate the disc via the endplates. This study found that infiltration increases for IVDs in a degenerated state [24]. Additionally, an *in vivo* rabbit study revealed a possible migratory pathway into the outer AF layers from a stem cell niche seen in the AF adjoining the perichondrium- and outer ligament zone [25]. Both studies indicate that cell recruitment into the IVD is possible; however, it remains limited to the vascularised tissues, such as the endplate and most outer AF. Because of the avascular nature of the IVD, cell migration into the NP and inner AF appears limited [26,27].

A second innate regeneration source is endemic progenitor cell populations. A previous study identified an MSC-like CD105⁺CD73⁺CD90⁺CD45⁻CD34⁻CD14⁻CD11b⁻CD79⁻CD19⁻HLADR⁻ plastic-adherent cell population from a complete IVD extract to possess *in vitro* self-renewal and multilineage differentiation potential [28]. However, their *in vivo* characteristics and localisation remain

undetermined. A later study identified a NP-specific Tie2⁺ and GD2⁺ progenitor cell population [23]. This particular population had a superior ECM production and proliferation, and showed multipotent differentiation capacity both *in vivo* and *in vitro*. The identified progenitor cell population might pose a promising target to stimulate and induce tissue repair. In an *in vitro* assessment, Tie2⁺ cells were stimulated by ANG-1, which resulted in an increased colony formation and decreased apoptosis rate [23]. The same group showed that Tie2⁺ GD2⁺ populations decrease with age. This could pose an obstacle in using these progenitor cell populations as a target for endemic cell-mediated repair, in particular, for older patients.

Clinical reports

Owing to the lack of active cell populations in the IVD and limited cell recruiting potential, a large variety of investigations have aimed to introduce cell populations into the IVD. These introduced cells can thereafter be incorporated *in situ* and contribute to *de novo* matrix production or stimulate endemic cells through trophic factors. In total, eight published and 12 unpublished clinical trials assessing cellular transplantations for IVD regeneration were identified as of November 2016 (Table 1). The first-in-human trial was a prospective study of 10 discogenic low back pain patients treated with autologous hematopoietic stem cells followed by 2 weeks of hyperbaric oxygen therapy [29]. One year after transplantation, no improvement in visual analog scores were observed. No additional radiographic or magnetic resonance imaging (MRI)-established hydration values were reported.

On the contrary, a German- and Austrian-based prospective controlled randomised multicentre trial assessed transplantation of IVD cells combined with discectomy. This resulted in a clinically significant decrease in pain score compared to a discectomy only group [30,31]. Additionally, improved hydration was observed in both treated and adjacent discs at 2 years follow-up. No significant difference in disc height index was observed between the groups.

A Japanese group investigated the potential of autologous bone marrow derived MSC in two female patients suffering from lumbar spinal stenosis with insatiability and presence of air in the IVD space [32]. The MSCs were infused into a dermal-derived collagen sponge. The stenosed spinal cord was fenestrated and via percutaneous procedure, the grafted collagen sponge was inserted into the afflicted disc. Radiographic imaging revealed enhancement in stability and reduction of air in the IVD 2 years after the operation. Moreover, improved hydration was confirmed in both patients. Finally, self-reported low back pain and leg numbness improved.

Subsequently, an autologous bone marrow-derived MSC pilot study was performed in Spain [33]. Ten patients who had chronic low back pain with disc degeneration in the lumbar area received MSC suspension directly injected into the NP. Three months after transplantation, a clinical and significant reduction was observed in lumbar pain scores. Rapid improvement was also observed in decreasing disability score. One-year follow-up MRI evaluations

Table 1 Reported clinical trial overview.

Study	Year	Location	Mode	Cell type	Concentration	Volume	Carrier	Indication	n	Period (y)	Outcome
Haufe and Mork [29]	2006	USA	Autologous	Haematopoietic stem cells	Unspecified	Unspecified	Suspension	Discogenic low back pain	10	1	No improvement
Meisel et al [30,31]	2007	Germany/Austria	Autologous	Intervertebral disc cells	Unspecified	Unspecified	Suspension	Single level lumbar disc herniation discectomy	112	4	Reduced low back pain, improved hydration in treated adjacent IVDs, no change in disc height
Yoshikawa et al [32]	2010	Japan	Autologous	Bone marrow mesenchymal stem cells	Unclear	540 mm ³	Pelnac Collagen sponge	Lumbar spinal canal stenosis	2	2	Improvement hydration and reduced low back pain
Orozco et al [33]	2011	Spain	Autologous	Bone marrow mesenchymal stem cells	$10(\pm 5) \times 10^6$	1 mL	Suspension	Lumbar disc degeneration and chronic low back pain	10	1	No adverse effects, reduced pain and disability, improved hydration, no enhanced disc height
Coric et al [35]	2013	USA	Allogenic	Juvenile articular chondrocytes	$1-2 \times 10^7$	1-2 mL	Fibrin	Single level degeneration disc disease with low back pain	15	1	Improvement in low back pain and on MRI
Pettine et al [34]	2014	USA	Autologous	Bone marrow concentrate	$121(\pm 11) \times 10^6$	2-3 mL	<i>Not applicable</i>	Discogenic low back pain	26	1	Reduced low back pain, sporadic hydration increase
Mochida et al [38]	2015	Japan	Autologous	Reactivated nucleus pulposus cells	1×10^6	702 μ L	Suspension	Disc degeneration adjacent to fused disc	9	3	No adverse effects, no progression of degeneration detected
Elabd et al [39]	2016	USA	Autologous	Bone marrow mesenchymal stem cells	$31(\pm 14) \times 10^6$	0.25-1 mL	Suspension	Chronic low back pain	5	4-6	No adverse effects, reduced IVD protrusion, improved mobility & strength

IVD = intervertebral disc; MRI = magnetic resonance imaging.

showed a significant increase in water content; however, no improvement was observed in disc height index.

An open-label nonrandomised pilot study reported the effects of bone marrow concentrate therapy [34]. Twenty-six patients received autologous bone marrow concentrate, treated bone marrow aspirate containing a variety of MSCs and unspecified growth factors, anti-inflammatory factors, and chemoattractants. Patients were included with discogenic low back pain. After 3 months, 6 months, and 12 months, a continuous significant reduction in 21 of 26 patients was observed by reported pain and disability scores. Eight of the 20 evaluated patients showed a one-level improvement in Pfirrmann grading after 1 year. Additionally, the data suggest that the effectiveness of the transplantation is dependent on implanted cell concentration. Patient age was an indicator for *in vitro* MSC expansion capacity and therefore the effectiveness of the treatment.

In a prospective study, 15 patients diagnosed with single-level lumbar spondylosis paired with mechanical low back pain were treated via a single percutaneous transplantation of allogenic juvenile chondrocytes encapsulated in a fibrin matrix [35]. Six months follow-up revealed that 10 of the 13 evaluated patients had enhanced MRI hydration values. No immunological, neurological deterioration, or other severe adverse effects were reported. Pain and disability as surveyed via the Oswestry disability index improved for all recipients during the 12 months follow-up. Disc height index status was not reported. A new clinical trial [36] has been submitted; however, this has been terminated because of a change in clinical strategy [37].

Subsequently, a Japanese group has reported a prospective clinical study of nine patients with Pfirrmann Grade III disc degeneration in levels adjacent to discs scheduled for lumbar intervertebral fusion [38]. Extruded discs were recovered, and viable NP cells were isolated via enzymatic digestion. NP cells were thereafter cocultured with autologous bone marrow derived MSC for 3 days. The reactivated autologous NP cells were transplanted into the IVDs adjacent to the fused IVD 7 days after the first fusion surgery. MRI revealed a slight improvement in one patient. All patients reported being relieved of low back pain 3 years after transplantation. Finally, disc height index did not deteriorate during the 3-year follow-up. No adverse effects were reported.

The final published clinical report describes a feasibility study of autologous bone marrow derived MSC transplantation in five patients with degenerative disc disease [39]. The MSC cells were preconditioned by expanding them under 5% O₂ hypoxic conditions prior to transplantation. After a 4- to 6-year follow-up, all patients reported improvement in pain, and four out of five reported improvement in mobility. Four patients showed a reduction in posterior protrusion, and for one patient the protrusion increased. Nevertheless, MRI assessment revealed a mild reduction of disc height in four out of five patients. No neoplasms or other abnormalities were observed. Hydration changes of the discs were not reported.

Twelve additional unpublished clinical trials were registered at the United States (US) National Health Institutes or the European Union Clinical Trials Register (Table 2). Two registered trials from Spain have been altered from an autologous transplantation study to a new

allogenic bone marrow derived MSC clinical trial [40–42]. This, prospective, randomised, blinded, and Phase I–II controlled clinical trial aims to compare allogenic MSC to 1% mepivacaine treatment. Another study from Australia and the US finished a mesenchymal precursor cell transplantation trial in 2015 [43]. Within this study, they applied a specific STRO-3 positive bone marrow derived MSC population that has been suggested to possess a higher proliferation capacity and potency [44,45]. A continuation in the form of a prospective, multicentre, randomised, double-blind, placebo-controlled Phase III trial has been accepted and aims to enrol 360 patients, making it the largest human IVD cell therapy study [46]. A pilot Phase I/II study, from Austria and Germany, aims to assess the safety and efficacy of autologous disc chondrocyte transplantation for nucleotomised and degenerative lumbar discs. The study set out to compare a placebo group of transplantation IVD chondrocytes suspension and a control group treated with only surgery to the transplantation of nucleotomised disc cells in a modified albumin hyaluronic acid gel (NOVOCART® Basic; TETEC, Reutlingen, Germany) [47–49]. The study aims to follow patients for a period of 5 years, making it the longest follow-up study on human IVD cell transplantation registered. Next, a clinical trial assessed juvenile chondrocyte transplantation in a fibrin gel [36]. However, the trial has been terminated because of a change in clinical strategies [37]. A US study aims to assess bone marrow derived MSC in either a hyaluronic acid gel or in decellularised bone matrix in 100 lumbar disc degeneration patients [50]. A study from Denmark aims to assess the clinical benefit from bone marrow derived MSC in 34 lumbosacral spondylosis without myelopathy patients [51]. A small study from South Korea aims to assess adipose tissue-derived MSC transplantation encapsulated in a hyaluronic acid derived gel [52]. It appears to be a redesigned trial from the 2012 study proposal [53]. Finally, a study within the US aims to assess adipose derived MSC [54]. This study, however, will transplant the MSCs in suspension, with a follow-up of 6 months.

Notably, 10 out of the 12 unpublished study proposals aim to assess MSCs, either derived from bone marrow [40–43,46,50,51] or adipose tissue [52–54]. One terminated study aimed to assess juvenile chondrocytes transplantation [36]. Additionally, disc-derived chondrocyte transplantations are ongoing with a finalisation date of 2021 [48,49].

Cell sources

The selection of a proper cell type and source is crucial for successful regeneration of the IVD, as indicated by Haufe and Mork [29]. The choice of cell types is dependent on practical issues such as accessibility, abundance, and safety concerns, such as tumorigenesis and immunogenicity. The capacity to differentiate and contribute to IVD homeostasis and ECM production under stringent biomechanical forces should be considered. The avascular nature establishes a hypertonic, acidic, hypoglycemic, and hypoxic microenvironment, forming an obstacle for exogenous cell to survive and thrive. Furthermore, introducing a new population of cells increases nutrient demand and might, therefore, promote further imbalance, resulting in additional cell death and tissue

Table 2 Ongoing clinical trial overview.

Sponsor	Start	Completion	Location	Mode	Cell type	Concentration	Volume (mL)	Carrier	Indication	n	Period	Status	GOV ID	EudraCT
Red de Terapia Celular [40]	2010	Unspecified	Spain	Autologous	Bone marrow mesenchymal stem cells	$0.5\text{--}1.5 \times 10^6/\text{kg}$ bodyweight	Unspecified	Suspension	Lumbar degenerative disc disease	15	6 mo	Unknown	NCT01513694	—
Mesoblast, Ltd. [43]	2011	2015	United States/ Australia	Allogenic	Mesenchymal precursor cells	6×10^6 or 18×10^6	Unspecified	Hyaluronic acid	Lumbar disc degeneration and chronic low back pain	100	6 mo	Completed	NCT01290367	—
Red de Terapia Celular [41]	2011	2012	Spain	Autologous	Bone marrow mesenchymal stem cells	Unspecified	Unspecified	Unspecified	Lumbar disc degeneration and chronic low back pain	0	1 y	Withdrawn	NCT02440074	—
Biostar [53]	2012	2014	South Korea	Autologous	Adipose derived mesenchymal stem cells	4×10^7	1	Unspecified	Lumbar disc degeneration and chronic low back pain	8	6 mo	Unknown	NCT01643681	—
Tetec AG [48,49]	2012	2021	Austria/ Germany	Autologous	Disc chondrocytes	Unclear	0.5–2	NOVOCART Disc plus (modified albumin hyaluronic acid gel)	Nucleotomised and degenerative lumbar disc	120	5 y	Ongoing (not recruiting)	NCT01640457	2010-023830-22
ISTO Technologies, Inc. [36]	2012	2016	United States	Allogenic	Juvenile chondrocytes	Unspecified	Unspecified	Fibrin	Lumbar disc degeneration and chronic low back pain	44	2 y	Terminated	NCT01771471	—
The Foundation for Spinal Research, Education and Humanitarian Care, Inc. [50]	2013	2018	United States	Autologous or Allogenic	Bone marrow mesenchymal stem cells	Unspecified	Unspecified	Hyaluronic acid/ decellularised bone matrix	Lumbar disc degeneration and chronic low back pain	100	2 y	Enrolling	NCT02529566	—
Århus University Hospital [51]	2013	Unspecified	Denmark	Autologous	Bone marrow mesenchymal stem cells	Unspecified	Unspecified	Unspecified	Lumbar disc degeneration and chronic low back pain	34	2 y	Ongoing	—	2012-003160-44
Red de Terapia Celular [42]	2013	2016	Spain	Allogenic	Bone marrow mesenchymal stem cells	$10 (\pm 5) \times 10^6$	1	Suspension	Lumbar disc degeneration and chronic low back pain	24	1 y	Ongoing (not recruiting)	NCT01860417	—
Bioheart, Inc. [54]	2014	2017	United States	Autologous	Adipose derived stem cells	Patient-specific	Patient-specific	Suspension	Lumbar disc degeneration and chronic low back pain	100	6 mo	Recruiting	NCT02097862	—

(continued on next page)

Table 2 (continued)

Sponsor	Start	Completion	Location	Mode	Cell type	Concentration	Volume (mL)	Carrier	Indication	n	Period	Status	GOV ID	EudraCT
Inbo Han [52]	2015	2017	South Korea	Autologous	Adipose derived stem cells	$2 \text{ or } 4 \times 10^7$	2	Tissuefill Hyaluronic acid derivatives	Lumbar disc degeneration and chronic low back pain	10	1 y	Recruiting	NCT02338271	—
Mesoblast, Ltd. [46]	2015	2020	United States/ Australia	Allogenic	Mesenchymal precursor cells	6×10^6	2	Hyaluronic acid	Lumbar disc degeneration and chronic low back pain	360	2 y	Recruiting	NCT02412735	—

IVD = intervertebral disc.

degeneration [55], especially considering that end-plate perfusion is also negatively affected by disc degeneration [56]. Despite these harsh conditions, innate NP cells have the unique ability to survive within this avascular niche. Unlike most other cells, NP cells express hypoxia-inducible factor 1- α (HIF1 α) continuously, regardless of oxygen concentrations, advocating the NP cells regulation system to adapt towards glycolysis, making NP cells well equipped to manage with limited nutrient accessibility [57,58]. Additionally, HIF1 α enhances NP-specific ECM matrix production [59]. It remains unclear if transplanted cells are able to acquire the functional properties similar to NP cells to survive within this unique niche.

A variety of cells has been explored preclinically as a cell source for disc regeneration. Roughly, these cell types can be divided into five categories: (1) IVD-derived cells, (2) chondrocyte-like cells; (3) MSCs; (4) induced pluripotent stem cells (iPSCs), and (5) embryonic stem (ES) cells. No published human studies explored ES or iPSC cell transplantation. Recent investigations have revealed that iPSCs can be successfully induced to chondrocyte-like cell [60,61]. ES cell and iPSC application hold great potential; nevertheless, their inherent risk of tumourigenesis and ethical concerns demand cautiousness.

IVD-derived cells and chondrocytes are inherently pre-disposed to create NP-like ECM and survive under hypoxic conditions. However, their accessibility and low cell yield are considered a disadvantage. Additionally, the available tissue sources are commonly compromised or diseased. For this reason, Mochida et al [38] assessed an MSC coculture system to reactivate the NP cell derived from the degenerated discs. The reactivation resulted in a significant increase in cell proliferation compared to the cells cultured without coculture. NP cells without coculture did not show an increase in cell number after 7 days of culture. Reactivation presents a promising option to circumvent the cell senesce obstacle from degenerated IVD tissue. The study of Meisel et al [30] did not implement a reactivation method to their IVD-derived chondrocytes. However, their patient pool was limited to herniated discs and therefore the senescence concern might not pose an issue. Therefore, excised herniated IVD tissue might offer a promising source for IVD-derived cells. In both cases, improvements in pain and MRI assessments were observed. Similarly, the transplantation of juvenile articular chondrocytes obtained relatively young and healthy cells as a cell source for their treatment [35]. Therefore, it appears that IVD-derived cells or chondrocyte are able to improve IVD conditions. It will be interesting to see the result from the large multicentre NOVOCART clinical trial, which is set to finish in 2021. This long-term follow-up study will most likely reveal new insights into the potential of using IVD as a cell source for safe and effective cell therapy.

The most commonly clinically evaluated cell types are MSCs. MSCs are multipotent cells and have the advantage of being efficiently expandable and easily accessible from a variety of tissue source (e.g., umbilical cord, bone marrow, and adipose tissue). MSCs from different sources are, however, predisposed to certain differentiation pathways. The most potent source for NP differentiation remains to be determined. Hematopoietic stem cells, however, might not be the optimal cell source, as was suggested by the first IVD

cell therapy clinical trial [29]. Other studies evaluating bone marrow derived MSC were able to decrease pain scores, and three out of the four trials reported improvement in hydration values. No adverse effects were reported in any of the studies; however, preclinical studies have shown that leakage of MSCs from degenerated discs can result in osteophyte formation [62]. It remains to be elucidated if preconditioning MSCs towards a chondrogenic state would be beneficial.

Additionally, the mode of transplantation should be taken into account. Autologous cell transplantation presents the lowest risk of immunogenic responses; however, this approach commonly requires timely and costly cell expansion, differentiation, and selection procedures. Moreover, *ex vivo* culturing increases the chance of infectious agents to be introduced. On the contrary, allogenic or xenogenic transplantation support an off-the-shelf product. Nevertheless, the introduction of xenogenic and allogenic agents pose a risk of triggering an immunogenic reaction. The immunogenicity of allogenic or xenogenic cells in the IVD space has not been well documented; however, the interior of the IVD is considered an immune-protected tissue, owing to its avascular nature [63]. The clinical trials cited support this notion as none reported any immunogenicity-related effects in their allogenic cell transplantations.

Transplantation methodology

Because of the avascular characteristics of the IVD, transplantation via injection currently remains the only option of administration. Nevertheless, injection into the IVD requires puncturing of the AF, which has been shown to accelerate degeneration [64]. Another essential consideration of cell transplantation is the carrier or medium in which cells are implanted. The majority of studies focused on transplanted cells in suspension; however, a selection of trials encapsulated their cell products. Carriers used within these clinic trials are atelocollagen [32], fibrin [35], hyaluronic acid [43,46,50], and hyaluronic acid derivative gel [48,49,52]. Gels and scaffold can enhance *in situ* incorporation and guide differentiation [65]. Encapsulation is also a potential method to limit cell leakage. Cell leakage might occur either during the transplantation procedure or *in situ* through AF fissures, which could lead to osteophyte formation [62]. Finally, the carriers can be modified and loaded with bioactive factors or drugs to enhance the desired regeneration process. Another issue to consider is the number of cells implanted and the volume of the transplantation. Work from Serigano et al [66] demonstrated in a canine disc degeneration model that the efficacy of a cell therapy is dependent on the number of transplanted cells. All studies mentioned here seem to consistently administer 10^6 or 10^7 cells per disc. One exception is the bone marrow concentrate study, which implanted 1.2×10^8 cells on average [34]. In effect, it appears that current cell dosages can promote restoration of low back pain; nevertheless, current work does not reveal an optimal cell dose.

Outcome parameters

All identified studies limited their outcome parameters to radiography and MRI combined with self-reported pain and

disability scores. Although reduction in pain and disability scores is the primary intention, they do not directly present improvements in IVD features. Moreover, none of the identified studies have corrected for a placebo effect, and therefore results should be interpreted with caution (Table 1). MRI modalities remain the primary outcome to evaluate repair of IVD structures by assessing the disc height index, Pfirrmann classification, and intensity values. However, reports have indicated the lack of relationship between MRI classification and histological features [67]. Hydration loss is not a unique aspect of disc degeneration, and features such as cell clustering and AF fissures are not observable by MRI. New advancements in and clinical standardisation of imaging techniques are impending [68]. In particular, we would like to highlight MR spectroscopy, a developing technique that would allow direct assessment of *in situ* matrix composition [69,70]. In addition, progress in the field of biomarkers, such as the discovery of CCL5 and CXCL6 [71], might also offer new, easy, and reliable outcome parameters to assess cell therapy efficacy.

Identifying the right patient

The clinical trials presented in this review have mainly focused their efforts on alleviating IVD degeneration associated pain and disability. However, the role of disc degeneration in the presentation of pain remains controversial. Moreover, disc degeneration is promoted by a multitude of factors, such as genetics, lifestyle, mechanical factors, and ageing. Additionally, cell therapy might provide a more preventive opportunity for patients with mild degeneration, to impede progression towards secondary spinal diseases. Therefore, selection criteria to identify which patient population that will benefit from IVD cell therapy remain to be determined [70,72]. This might be hindered, however, by an inadequacy of imaging modalities to detect small alteration in IVD matrix on a clinical scale. Furthermore, new insights in the genetic predispositions of disc degeneration are emerging as an encouraging method to select the right patients for cell transplantation [73]. Finally, identifying and normalising biomarkers will provide new opportunities to subdivide patient populations.

Conclusion

Preclinical and clinical results demonstrate the potential of IVD cell therapies. In the presented overview, all studies implementing bone marrow derived MSC or chondrocyte-like cells resulted in reported pain relief, disability reduction, and improved imaging features. Nevertheless, it remains uncertain if the transplanted cells are able to induce or contribute to *de novo* matrix production. At present, diagnostic methods are limited in detecting potential matrix regeneration. New innovations and standardisation are therefore highly needed. Moreover, a placebo-controlled study is necessary to confirm the effectiveness of pain and disability reduction. Still, the absence of adverse side effects, in particular immunogenic reactions, indicates that cell transplantations (including allogenic transplantation) are a safe approach, supporting the notion that the IVD is an immune privileged tissue. The questions of optimal cell

source and optimal administration method remain to be determined. In addition, current investigations have focused predominantly on repairing the NP. Investigations on repairing AF and endplate could offer new opportunities and insights. Cell therapies pose a novel opportunity to bridge the gap between contemporary palliative therapies and aggressive surgical treatment. Well-designed clinical trials will determine the potential of cell therapies as a novel tool against IVD degeneration and low back pain.

Conflicts of interest

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