Effect of lentivirus-mediated survivin transfection on the morphology and apoptosis of nucleus pulposus cells derived from degenerative human disc in vitro

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Abstract. Lower back pain is a common concern, and 40% of all cases involve the degeneration of the intervertebral disc (IVD). However, the excessive apoptosis of disc cells plays an important role in IVD degeneration, particularly in the nucleus pulposus (NP). Thus, anti-apoptotic gene therapy to attenuate or reverse the degenerative process within the NP is being developed. Survivin is a unique inhibitor of apoptosis (IAP) and has been extensively investigated in cancer cells. However, little is known of the effects of survivin transfection on NP cells derived from degenerative human disc. In this study, we aimed to investigate the effects of lentivirus (LV)-mediated survivin transfection on the morphology and apoptosis of NP cells derived from degenerative human disc in vitro. NP cells were transfected with LV-mediated survivin. Subsequently, cell morphology was observed and the survivin mRNA expression levels were measured by RT-qPCR. Apoptosis was analyzed by flow cytometry and by measuring caspase-3 activity. The results revealed that the morphology of the NP cells derived from degenerative human disc transfected with LV-mediated survivin was significantly altered as evidenced by cytomorphosis, the reduction of the cytoplasm and cell shrinkage. Following transfection, survivin gene expression significantly increased in the transfected cells and subsequent generation cells; however, no significant differences in the cell apoptotic rate and caspase-3 activity were observed. We found that transfection of the survivin gene into NP cells led to the stable expression of survivin and induced marked changes in cell morphology. Furthermore, no significant anti-apoptotic effects were observed following LV-mediated survivin transfection.

Overall, our findings demonstrate that LV carrying surviving may be used to successfully enforce the expression of survivin in NP cells. However, cell morphology was evidently altered, whereas the apoptotic rate did not decrease. Comprehensive studies on the feasibility of using survivin in gene therapy in an aim to attenuate disc degeneration are warranted. Further research on the mechanisms responsible for the changes in cell morphology and cell function are also required.

Introduction

Lower back pain is an endemic problem that causes substantial disability (1-3). It is estimated that 60-80% of individuals are affected by lower back pain at some point in their lives (4-7). The causes of lower back pain are multifactorial, although 40% of all cases involve the degeneration of the intervertebral disc (IVD) (8). However, conservative and surgical treatments only target the alleviation of the symptoms rather than the repair or deceleration of the underlying degenerative process. Therapies, such as gene therapy, to attenuate or reverse the degenerative process within the IVD are being developed (9).

The IVD consists of two regions: the inner nucleus pulposus (NP) and the outer anulus fibrosus (AF). The normal NP is mainly composed of aggrecan and collagen type II, whereas the normal AF contains significant amounts of collagen type I (10-12). Previous studies have demonstrated that the number of NP cells decreases and the composition of the extracellular matrix associated with these cells is altered in degenerative discs (13-15). In vitro and in vivo studies have suggested that the cellular loss attributed to the excessive apoptosis of disc cells plays an important role in IVD degeneration (16,17).

Among the apoptotic signaling pathways, two main caspase-dependent pathways have been observed: the intrinsic and extrinsic pathways, which are mediated by the mitochondria and death receptor, respectively (18). Several studies have demonstrated that the mechanism of apoptosis involves two pathways in NP cells derived from degenerative human disc which vary among patients. However, these two pathways ultimately induce caspase-3 to initiate apoptosis (19-22).

Survivin is a unique inhibitor of apoptosis (IAP) that deters the activation of intrinsic and extrinsic pathways, with
a focus on the former. Survivin inhibits apoptosis by binding to caspase-9 or by blocking second mitochondria-derived activator of caspases (SMAC; a pro-apoptotic protein that binds IAPs and thus prevents them from inhibiting caspases) and thus prevents the pro-apoptotic protein from blocking IAP proteins (Fig. 1) (23). The expression of survivin is strictly controlled in embryonic tissues and in the majority of tumors, but not during tissue differentiation and maturation (23,24). Thus, survivin presents an attractive target for cancer therapy (25), and has been extensively studied in cell cycle and apoptotic assays for cancer cells (26,27). Studies have demonstrated that the oncofetal gene, survivin, is re-expressed in osteoarthritis and rheumatoid arthritis (28-30). Moreover, preliminary studies have indicated that survivin is expressed in fetal disc tissue and have noted the differential expression of survivin between NP tissue derived from degenerative disc and that derived from a relatively normal disc (31,32). However, to our knowledge, limited research has been conducted on the effects of lentivirus (LV)-mediated survivin transfection on NP cells derived from degenerative human disc in vitro.

The present study was conducted to determine the effects of the LV-mediated survivin transfection on the morphology and apoptosis of NP cells in vitro. Our results provide fundamental information on the effectiveness of gene therapy aimed at the attenuation of disc degeneration in vitro.

Materials and methods

Experimental materials. NP samples from herniated IVDs of the lumbar spine were collected from 10 patients, including 6 males and 4 females, with an average age of 51 years (46-62 years) (Table 1). All patients were diagnosed with IVD degeneration (lumbar disc herniation) by magnetic resonance imaging and had undergone spinal fusion to relieve chronic lower back pain. This study was approved by the Ethics Committee of the Affiliated Hospital of Qingdao University Medical College (Shandong, China). Written informed consent was obtained from all patients prior to enrollment; all patients agreed to the publication of their clinical data.

The tissue material was harvested and collected under sterile conditions. A phosphate-buffered saline (PBS) solution at 4˚C was used as a transport medium. All biopsies were delivered under controlled conditions. A phosphate-buffered saline (PBS) solution at 4˚C was used for all procedures on the day of harvest.

LV with survivin and an empty LV were purchased from Shanghai Genechem Co. Ltd. (Shanghai, China) and used at 37°C for approximately 4 h, after which the tissues were centrifuged at 1,000 rpm for 5 min and washed twice with DMEM/F12 medium containing 15% fetal calf serum.

The cells were transferred to a 12.5-cm² culture flask at a density of 10⁶ cells/cm². The cells were then cultured in a CO₂ incubator (Sanyo Electric Co., Ltd., Osaka, Japan) at 37°C with 10% fetal calf serum containing 1% penicillin/streptomycin (Invitrogen Life Technologies, Tokyo, Japan). The growth medium was changed every 3 days after cell adhesion. Cell samples from different patients were kept separate from one another. All experiments were carried out in duplicate and were conducted with human NP cells from passages 2 to 3.

Immunohistochemistry. NP cells from passage 2 were cultured on glass slides and were then fixed for 10 min with 4% paraformaldehyde followed by permeabilization for 5 min with 0.1% Triton X-100 in PBS. For antigen retrieval, the slides were boiled for 20 min (10 mM citrate buffer, pH 6.0) and then endogenous peroxidase was blocked using hydrogen peroxide. The cells were then incubated for 1 h in a solution of PBS containing 10% goat serum to prevent non-specific antibody binding. The NP cells were incubated for 1 h at 4°C with anti-human collagen type II antibody (1:100; Cat. no. ab3092) and anti-human aggrecan antibody (1:100; Cat. no. ab3778) (both from Abcam (Hong Kong) Ltd., Hong Kong, China). Following incubation, the cells were washed 3 times with PBS, incubated for 1 h at room temperature with rabbit anti-mouse IgG and then rinsed with PBS. This was followed by coloration with DAB and hematoxylin staining and observation under a microscope (Olympus GX51; Olympus Corp., Tokyo, Japan).

Table I. Demographic data of the patients.

<table>
<thead>
<tr>
<th>Patient no.</th>
<th>Gender</th>
<th>Age (years)</th>
<th>Location of lumbar disc herniation</th>
<th>Pfirrmann grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Male</td>
<td>46</td>
<td>L4/L5</td>
<td>IV</td>
</tr>
<tr>
<td>2</td>
<td>Female</td>
<td>50</td>
<td>L5/S1</td>
<td>V</td>
</tr>
<tr>
<td>3</td>
<td>Male</td>
<td>57</td>
<td>L4/L5</td>
<td>V</td>
</tr>
<tr>
<td>4</td>
<td>Male</td>
<td>61</td>
<td>L5/S1</td>
<td>V</td>
</tr>
<tr>
<td>5</td>
<td>Female</td>
<td>62</td>
<td>L4/L5</td>
<td>V</td>
</tr>
<tr>
<td>6</td>
<td>Female</td>
<td>55</td>
<td>L4/L5</td>
<td>IV</td>
</tr>
<tr>
<td>7</td>
<td>Male</td>
<td>48</td>
<td>L5/S1</td>
<td>IV</td>
</tr>
<tr>
<td>8</td>
<td>Male</td>
<td>53</td>
<td>L5/S1</td>
<td>V</td>
</tr>
<tr>
<td>9</td>
<td>Female</td>
<td>51</td>
<td>L4/L5</td>
<td>IV</td>
</tr>
<tr>
<td>10</td>
<td>Male</td>
<td>55</td>
<td>L4/L5</td>
<td>V</td>
</tr>
</tbody>
</table>

The intervertebral discs were classified according to the Pfirrmann grade grading system for lumbar intervertebral disc degeneration.

Gene transfection. To quantify the percentage of successfully transfected NP cells at a given multiplicity of infection (MOI), an identical procedure was performed with the LV-green fluorescent protein (GFP) (Shanghai Genechem Co., Ltd.)
for each MOI assessed. NP cells from passage 2 were plated as a monolayer in 96-well plates at 4x10⁴ cells/ml and were incubated for 24 h. Solutions of the viral particles equal to 30, 40, 60, 80 and 100 MOI were pre-mixed with DMEM/F12 medium and were added to the 96-well plates. After 48 h, the NP cells were examined under a fluorescence microscope (Olympus CKX41SF; Olympus Corp.), and the percentage of NP cells synthesizing GFP was determined.

NP cells from passage 2 were divided into 3 groups (the positive, negative control and blank control groups), which were transfected with LV with survivin, the empty LV or an equal amount of DMEM/F12 medium, respectively. The transfection procedure was performed with an MOI value of 50. The transfected NP cells were incubated in a CO₂ incubator at 37°C. After 8 h, the growth medium was changed.

**Table II.** Nucleotide sequences of sense and antisense primers and product size.

<table>
<thead>
<tr>
<th>Gene</th>
<th>Primer</th>
<th>Product size (bp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survivin</td>
<td>F: CAGATGACGACCCCCATAGAGGA</td>
<td>141</td>
</tr>
<tr>
<td></td>
<td>R: CCTTTGCAATTTTGTTCTTGCC</td>
<td></td>
</tr>
<tr>
<td>GAPDH</td>
<td>F: GGATTGTGTCGTAATGGG</td>
<td>205</td>
</tr>
<tr>
<td></td>
<td>R: GGAAGATGGTGATGGAATT</td>
<td></td>
</tr>
</tbody>
</table>

F, forward; R, reverse; GAPDH, glyceraldehyde-3-phosphate dehydrogenase.

**Observation of cell morphology.** The morphology and growth of the NP cells were observed daily under an inverted microscope (Olympus CKX41; Olympus Corp.). The cell morphological changes induced by transfection with LV carrying survivin were recorded and images were obtained using a microscope.

**RNA extraction and reverse transcription-quantitative PCR (RT-qPCR).** To measure the expression of survivin following transfection with LV in the transfected cells and subsequent generation cells, RT-qPCR was performed. mRNA was extracted from the NP cells using TRIzol reagent (Invitrogen Life Technologies, San Diego, CA, USA) according to the one-step method. A total of 1 µg mRNA was reverse transcribed into cDNA using PrimeScript RT Reagent (Takara DRR037A; Takara Bio, Inc., Shiga, Japan), and the reaction product was treated with RNase-Free DNase I. The absorbance at 260 and 280 nm was measured for quantification and quality control.

qPCR was conducted using the following cycling conditions (LightCycler 480II; Roche Diagnostics GmbH, Mannheim, Germany); 95°C for 5 min followed by 33 cycles of 94°C for 45 sec, 56°C for 45 sec and 72°C for 45 sec and a final extension at 72°C for 10 min. Primers and probes were designed using Primer Express Software (Applied Biosystems, Ltd., Warrington, UK). Total gene specificity was confirmed by BLAST searches (GenBank database sequences). Primers were purchased from Sangon Biotech Co., Ltd. (Shanghai, China) (Table II). Another specific primer pair for human glyceraldehyde-3-phosphate dehydrogenase (GAPDH) was used as an internal control. In each experiment, samples were analyzed in duplicate. The normalized target gene expression was determined through the comparative Ct (ΔΔCt) method.

**Detection of apoptosis by flow cytometry and measurement of caspase-3 activity.** Second-generation NP cells transfected with LV were placed in 6-well culture plates at 1x10⁵ cells/well and treated as above. The apoptotic rate of the NP cells was detected by Annexin V/propidium iodide (PI) (Nanjing KeyGen Biotech. Co., Ltd., Jiangsu, China) double staining according to the manufacturer’s instructions and as previously
described (17,33). Briefly, the cells of the different groups were collected by trypsinization and centrifugation, and then washed with ice-cold PBS twice and resuspended in 500 µl binding buffer. A total of 5 µl of fluorescein-conjugated Annexin V and 5 µl of PI was added followed by further incubation in the dark for 15 min at room temperature. The apoptotic rate was analyzed by flow cytometry (BD LSR II flow cytometer) using FACSDiva software (both from Becton-Dickinson, Franklin Lakes, NJ, USA). The cells stained positive for Annexin V and negative for PI were identified as early apoptotic cells and those positive for double staining were identified as late apoptotic cells in each sample. They were counted and represented as a percentage of the total cell population.

Apoptosis was evaluated by measuring caspase-3 activity using a Caspase-3 Colorimetric Assay kit (BioVision, Inc., Milpitas, CA, USA). Second-generation NP cells were counted and pelleted at 1.5x10^6 cells for 48 h following transfection with LV carrying survivin or the empty LV. The cells were then resuspended in cell lysis buffer, and 50 µl of 2X reaction buffer (containing 10 mM DTT) and 5 µl of DEVE-pNA were added. The samples were incubated for 90 min at 37°C, and the absorbance was read at 405 nm using a Microtiter Plate Reader (Sunrise™; Tecan Group, Ltd., Männedorf, Switzerland).

**Statistical analysis.** All values were presented as the means ± SEM. One-way ANOVA with Fisher's least significant difference (LSD) post hoc test were applied to reveal the statistical significance of the differences. A value of P<0.05 was considered to indicate a statistically significant difference. Statistical analyses were performed using SPSS software for Windows, version 19 (SPSS, Inc., Chicago, IL, USA).

**Results**

**Transfection efficiency of LVs.** Following transfection of the NP cells with the LVs for 48 h, all the transfected cells expressed GFP successfully. For NP cells derived from degenerative human disc, the changes in the transfection rate were demonstrated by the changes in MOI (transfection with LV-GFP): 60-70% of cells with an MOI of 30 and 40, 70-85% of cells with an MOI of 60 and 80-100% of cells with an MOI of 80 and 100 (Fig. 2).
Observation of cell morphology under a light microscope. The primary NP cells derived from degenerative human disc were round at the moment of isolation (Fig. 3A) and they had attached to the culture dish after 5-7 days of culture. The cells gradually became elongated and triangular or polygonal in shape, and the cytoplasm became plump and equally distributed. The number of attached cells exponentially increased. After 15-20 days, 90% of the cells had formed colonies. The passaged NP cells derived from degenerative human disc only required 3 h to attach to the culture dish, and 90% of the cells formed colonies after 7-10 days of culture. Cell morphology was similar to that of primary cells (Fig. 3B).

To identify the NP cell phenotype, immunohistochemistry for type II collagen and aggrecan was performed (Fig. 3C and D). The results revealed that these cells expressed both type II collagen and aggrecan, which confirmed the NP cell phenotype.

In the second-passage exponential growth phase, survivin was transfected into the cells using LV. At 3 days after transfection, the morphology of the NP cells derived from degenerative human disc, which were transfected with LV carrying survivin significantly changed compared with that of the control groups. In addition, cytomorphosis, the reduction of the cytoplasm and cell shrinkage were evident. The cell volume changed significantly, and pseudopodia became longer (Fig. 4A-C). The morphology of the third-passage cells was similar to that of the second-passage cells (Fig. 4D-F).

Expression levels of survivin. The survivin mRNA expression levels in the NP cells derived from degenerative human disc were measured in the transfected cells and subsequent generation cells. The results revealed that in the transfected cells and subsequent generation cells, the expression of survivin following transfection with LV carrying survivin was significantly higher than that in the control groups (p<0.01). No significant difference in the survivin expression levels was observed between the transfected cells and subsequent generation cells (transfected generation + LV-survivin vs. subsequent generation + LV-survivin, p=0.242; transfected generation + empty LV vs. subsequent generation + empty LV, p=0.996; transfected generation + equal DMEM/F12 medium vs. equal DMEM/F12 medium + equal DMEM/F12 medium, p=0.999). In addition, no significant differences were observed between the negative control and blank control groups (transfected cells, p=0.786; subsequent generation cells, p=0.790; Fig. 5).

Measurement of apoptotic rate and caspase-3 activity. The effect of LV-mediated survivin transfection on the apoptosis of the NP cells derived from degenerative human disc was examined by flow cytometry and by measuring caspase-3 activity. The results revealed that the transfection of survivin into the NP cells did not contribute to decreasing the apoptotic rate and caspase-3 activity. No significant differences in the apoptotic rate (Fig. 6) and in caspase-3 activity (Fig. 7) were observed between the positive (survivin-transfected cells and the control...
MA et al: MORPHOLOGY AND APOPTOSIS OF SURVIVIN-TRANSFECTED NUCLEUS PULPOSUS CELLS

Discussion

Degenerative disc disease is a serious healthcare problem. Traditional methods focus on the treatment of multiple symptoms simultaneously. Gene therapy is a developing technology with great potential. The in vitro culture of NP cells derived from degenerative human disc serves as the foundation of gene therapy and aids in the study of cell proliferation, cell morphology, gene and protein expression, as well as in cell function. Therefore, a better understanding of the in vitro culture of NP cells and the identification of NP cells are important for future research.

Disc tissue consists of NP and AF cells. No significant differences have been observed in the morphology of NP and AF cells during monolayer expansion (34). However, significant differences have been found between the matrices of NP and

Figure 4. Morphology of nucleus pulposus (NP) cells derived from degenerative human disc from passage 2 and 3 (magnification, x100). (A-C) NP cells from passage 2 following transfection for 3 days with the blank control (equal amount of DMEM/F12 medium), negative control (empty LV) and positive control (LV with survivin), respectively. Following transfection with survivin, cytomorphosis, the reduction of the cytoplasm and cell shrinkage were evident. The cell volume changed significantly, and pseudopodia became longer. (D-F) Using the cells described in (A-C, respectively), the cells were passaged for 1 more day. The morphology of the third-passage cells was similar to that of the second-passage cells.

Figure 5. RT-qPCR of survivin mRNA expression following transfection with lentivirus (LV) carrying survivin in the transfected cells and subsequent generation cells (passage 3). The expression of survivin following transfection was significantly higher than that in the control groups (p<0.01). No significant difference in the expression levels was observed between the transfected cells and subsequent generation cells, as well as between the negative and the blank control groups (p>0.05). Positive group, transfection with lentivirus carrying survivin; negative group, transfection with empty lentivirus; blank group, transfection with an equal amount of DMEM/F12 medium.

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AF cells. NP cells have a gelatinous structure that is primarily composed of aggrecan and collagen type II. The outer AF cells contain substantial amounts of collagen type I (35-37). Therefore, the current study confirmed the NP cell phenotype by using immunohistochemistry for type II collagen and aggrecan.

In our study, in primary culture the NP cells had a polygonal shape with short pseudopodia during early proliferation. However, these cells later became increasingly elongated. This change in cell morphology was even more pronounced when the cells were passaged. Compared with the primary NP cells, the passaged cells had reduced adhesiveness and mostly assumed a short spindle-shaped appearance. After the fourth passage, cells have been shown to develop slowly (34). For the negative and blank control groups, our observations were consistent with the results of a previous study (34).

However, in the positive group (survivin-transfected cells), the cell morphology was significantly altered compared with the other 2 control groups in terms of the reduction in the cytoplasm, cell shrinkage, lengthening of pseudopodia and increased intercellular space. Nevertheless, the cells did not die, but rather remained attached to the culture dish. After passage, these cells sequentially attached to the dish but did not develop. This phenomenon suggested that the cell morphology was affected by transfection.

The results obtained by RT-qPCR revealed the stable over-expression of survivin following transfection with LV carrying survivin in the transfected cells and subsequent generation cells. No significant differences were observed between the NP cells derived from degenerative human disc transfected with the empty LV and an equal amount of culture fluid (DMEM/F12). Furthermore, during our research, LV-TGFβ3, LV-TIMP1, LV-TGFβ3-TIMP1, LV-survivin-TIMP1, LV-survivin-TGFβ3, and LV-survivin-TGFβ3-TIMP1 were simultaneously transfected into NP cells derived from degenerative human disc. The results revealed that similar morphological changes occurred in the NP cells following transfection with LV-survivin-TIMP1, LV-survivin-TGFβ3, and LV-survivin-TGFβ3-TIMP1. No
changes were observed in the NP cells following transfection with LV-TGFβ3, LV-TIMP1, LV-TGFβ3-TIMP1 without survivin (data not shown). These results suggest that survivin contributes to these morphological changes.

Cell morphology is at least partly determined by the cytoskeleton. It has been demonstrated that some factors may alter actin filaments through the activation or inhibition of distinct mitogen-activated protein kinase (MAPK) pathways (38). MAPK pathways have been implicated in G2/M phase regulation and apoptosis (39-42). The regulation of survivin is closely associated with MAPK pathways (23,43). Therefore, the over-expression of survivin may reversely affect MAPK pathways, similar to the inhibition of different tyrosine kinases in the actin signal transduction pathways, which may subsequently result in alterations in cytoskeleton dynamics. To confirm this phenomenon, further studies are required to examine the structure of the actin filaments in cells, in which following transfection with LV carrying survivin, the phosphorylation state of p38 MAPK, extracellular signal-regulated kinase (ERK) and JNK in NP cells derived from degenerative human disc, as well as to elucidate the mechanisms involved in this process.

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References


