

## TGFβ<sub>1</sub> is involved in the chondrogenic differentiation of mesenchymal stem cells and is dysregulated in osteoarthritis



M. Ruiz †, M. Maumus †, G. Fonteneau †, Y.-M. Pers ‡, R. Ferreira ‡, L. Dagneaux §, C. Delfour ||, X. Houard ¶, F. Berenbaum ¶, F. Rannou #, C. Jorgensen † ‡<sup>a</sup>, D. Noël † ‡<sup>a</sup>

† IRMB, University Montpellier, INSERM, CHU Montpellier, Montpellier, France

‡ Hôpital Lapeyronie, Clinical Immunology and Osteoarticular Diseases Therapeutic Unit, Montpellier, France

§ Hôpital Lapeyronie, Department of Orthopaedic Surgery, Montpellier, France

|| CHU Montpellier, Cellular and Tissular Biopathology Department, Montpellier, France

¶ Sorbonne University, UPMC University Paris 06, INSERM, Centre de Recherche Saint-Antoine, Paris, France

# INSERM U1124, University Paris Descartes, APHP Hôpital Cochin, Paris, France

### ARTICLE INFO

#### Article history:

Received 8 May 2018

Accepted 14 November 2018

#### Keywords:

Mesenchymal stem cells

TGFβ<sub>1</sub>

Osteoarthritis

Cartilage

### SUMMARY

**Objective:** Transforming growth factor-β (TGFβ) is a major regulator of cartilage homeostasis and its deregulation has been associated with osteoarthritis (OA). Deregulation of the TGFβ pathway in mesenchymal stem cells (MSCs) has been proposed to be at the onset of OA. Using a secretome analysis, we identified a member of the TGFβ family, TGFβ-induced protein (TGFβ<sub>1</sub> or β<sub>1</sub>GH3), expressed in MSCs and we investigated its function and regulation during OA.

**Design:** Cartilage, bone, synovium, infrapatellar fat pad and bone marrow-MSCs were isolated from patients with OA or healthy subjects. Chondrogenesis of BM-MSCs was induced by TGFβ<sub>3</sub> in micropellet culture. Expression of TGFβ<sub>1</sub> was quantified by RT-qPCR, ELISA or immunohistochemistry. Role of TGFβ<sub>1</sub> was investigated in gain and loss of function experiments in BM-MSCs and chondrocytes.

**Results:** TGFβ<sub>1</sub> was up-regulated in early stages of chondrogenesis and its knock-down in BM-MSCs resulted in the down-regulation of mature and hypertrophic chondrocyte markers. It likely occurred through the modulation of adhesion molecules including integrin (ITG)β<sub>1</sub>, ITGβ<sub>5</sub> and N-cadherin. We also showed that TGFβ<sub>1</sub> was upregulated *in vitro* in a model of OA chondrocytes, and its silencing enhanced the hypertrophic marker type X collagen. In addition, TGFβ<sub>1</sub> was up-regulated in bone and cartilage from OA patients while its expression was reduced in BM-MSCs. Similar findings were observed in a murine model of OA.

**Conclusions:** Our results revealed a dual role of TGFβ<sub>1</sub> during chondrogenesis and pointed its deregulation in OA joint tissues. Modulating TGFβ<sub>1</sub> in BM-MSCs might be of interest in cartilage regenerative medicine.

© 2019 The Authors. Published by Elsevier Ltd on behalf of Osteoarthritis Research Society International. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

### Introduction

Osteoarthritis (OA) is the most common rheumatic disease affecting all joint tissues including cartilage, sub-chondral bone, synovium and fat pad<sup>1</sup>. It results in progressive destruction of articular cartilage and loss of joint function leading to morbidity

and disability in adults. This induces a societal burden that will increase in the coming years due to the aging of population and increased prevalence of obesity and metabolic disorders<sup>2</sup>. Although the aetiology of OA is still imperfectly understood, a number of environmental and genetic factors contribute to the breakdown of cartilage homeostasis and OA initiation. Evidence from genome-wide association studies has emerged that growth factors belonging to the transforming growth factor-β (TGFβ) family play a role in the development of OA<sup>3</sup>.

Members of the TGFβ superfamily can be divided into the TGFβ and activin group, the bone morphogenetic protein (BMP) group

\* Address correspondence and reprint requests to: D. Noël, Inserm U1183, IRMB, Hôpital Saint-Eloi, 80 avenue Augustin Fliche, 34295 Montpellier cedex 5, France. Tel.: 33-4 67-33-04-73; Fax: 33-4 67-33-01-13.

E-mail address: [daniele.noel@inserm.fr](mailto:daniele.noel@inserm.fr) (D. Noël).

<sup>a</sup> equally contributing authors.

and the growth and differentiation factor (GDF) group<sup>4</sup>. The TGF $\beta$  signalling is essential for articular cartilage homeostasis. It is rapidly upregulated by mechanical loading, stimulates proteoglycan synthesis and blocks the expression of chondrocyte hypertrophic genes<sup>5</sup>. Indeed, under physiological conditions, TGF $\beta$  is expressed at basal levels in articular cartilage or upregulated by loading and prevents chondrocyte terminal differentiation and cartilage degeneration<sup>6</sup>. However, TGF $\beta$  signalling is deregulated in OA and high concentrations of TGF $\beta$  can be found in the synovial fluids of patients. Soluble TGF $\beta$  is produced by activated synovial cells and released from reservoirs in the cartilage matrix upon its degradation. High levels of TGF $\beta$  result in preferential activation of the SMAD1–5–8 pathways instead of the SMAD2–3 pathways and in upregulation of genes involved in fibrogenesis and hypertrophy leading to synovial fibrosis and osteophyte formation<sup>7</sup>.

In OA, osteophytes arise from chondrocyte terminal differentiation of mesenchymal progenitors residing in the periosteum due to the increased expression of TGF $\beta$ . TGF $\beta$  expression is also increased in the subchondral bone where are located mesenchymal stem/stromal cells (MSCs). Demonstration that deregulation of TGF $\beta$  signalling in MSCs is involved in OA progression or initiation came from the study of Zhen and co-authors<sup>8</sup>. They showed that knock-down of TGF $\beta$  type II receptor in nestin-positive MSCs resulted in less severe cartilage lesions in mice whereas transgenic expression of TGF $\beta$ 1 in osteoblasts induced OA. Indeed, excessive subchondral bone formation in OA is associated with enhanced TGF $\beta$  activity in osteoblasts and MSCs. Other studies have reported cartilage resident MSC-like progenitors with senescence features, which might be related to failure of repair<sup>9</sup> and the possible involvement of synovium-derived MSCs in cartilage repair following joint injury<sup>10</sup>. Our hypothesis was that dysregulation of TGF $\beta$  signalling in MSCs is responsible for lack of cartilage repair in OA. Based on a previous secretome analysis of MSCs derived from bone marrow and adipose tissue, we identified basal secretion of several TGF $\beta$  family members, including TGF $\beta$ -induced gene product-h3 (TGF $\beta$ i/BIGH3/RGD-CAP)<sup>11</sup>. The aim of the present study was to determine the functional role of TGF $\beta$ i in MSCs and to investigate its deregulation in OA.

## Method

### Cell culture

Human tissue specimens were recovered from post-mortem or amputated healthy subjects and patients with grade IV OA, aged  $52.5 \pm 8.5$  years and  $74.4 \pm 5.1$  years, respectively. The study was approved for OA specimen recovery by the French Ministry of Research and Innovation and the Personal data Protection ethics Committee (CPP) of Languedoc-Roussillon (approval DC-2010-1185) and CPP of Paris V, Ile de France and the Consultative Committee on the Treatment of Information in Research in Health field (CCTIRS) (approval 15-623-ter). Healthy tissues were recovered after approval by the Agence de la Biomédecine (authorization #: PFS16-006) for post-mortem subjects or for amputated patients (C17-53). Cartilage, bone, synovium and infrapatellar fat pad samples were recovered from the same patients, cut in small pieces and weighted. Supernatants were produced using 1 g tissue/6 mL IMDM medium containing 1% penicillin/streptomycin and 1% glutamine incubated at 37°C for 24 h. For RNA extraction, 300 mg of each tissue were snap frozen and stored at –80°C. MSCs isolated from bone marrow (BM-MSCs) or adipose tissue (ASCs) were characterized by phenotyping and trilineage differentiation potential as described<sup>12</sup>. They were cultured in  $\alpha$ MEM containing 2 mmol/mL glutamine, 100  $\mu$ g/mL penicillin/streptomycin, 10% foetal calf serum (FCS) and 1 ng/mL basic fibroblast growth factor

(bFGF) (R&D Systems, Lille). Human chondrocytes were isolated from knee cartilage and cultured in DMEM supplemented with 2 mmol/mL glutamine, 100  $\mu$ g/mL penicillin/streptomycin, 10% FCS, 5  $\mu$ g/mL insulin, 5 ng/mL bFGF till passage 1<sup>13</sup>.

### Collagenase-induced osteoarthritis mouse model

The study was conducted in accordance with guidelines and regulations of the Ethical Committee for animal experimentation of the Languedoc-Roussillon (Approval 5349-2016050918198875). The experiment was performed after final approval given by the French Ministry for Education, Higher Education and Research. Collagenase-induced osteoarthritis (CIOA) model was performed as previously described<sup>14</sup>. They were euthanatized at day 7, 14, 42. Hind paws were collected and fixed in formaldehyde 3.7% for 2 days before histological processing.

### MSC differentiation and chondrocyte culture

BM-MSCs were differentiated towards chondrocytes by culture in micropellet for 21 days. Briefly,  $2.5 \times 10^5$  BM-MSCs were centrifuged in 15 mL conical tubes and cultured in DMEM high glucose (Lonza, Levallois) with 100  $\mu$ g/mL penicillin/streptomycin, 0.35 mM proline, 0.1  $\mu$ M dexamethasone, 0.17 mM ascorbic acid-2-phosphate, 1 mM pyruvate sodium, 1% insulin-transferrin-selenic acid (Lonza) and 10 ng/mL TGF- $\beta$ 3 or 100 ng/mL BMP-2 or IGF-1 (R&D Systems). BM-MSCs were differentiated towards osteoblasts or adipocytes by culture in inductive conditions for 21 days as described<sup>15</sup>.

For the model of late passages, chondrocytes were maintained till reaching sub-confluency and replated at 6000 cells/cm<sup>2</sup> till passage 3. Otherwise, chondrocytes were used at Passage 1. After seeding, chondrocytes were cultured for 72 h before stimulation with 10 ng/mL IL-1 $\beta$  for 72 h or 10 ng/mL TGF $\beta$ 3 for 24 h (R&D Systems). Media were replaced for 24 h before recovering supernatants and cells.

### Cell transfection

BM-MSCs and chondrocytes were transfected at 60% confluence with 50 nM of control siRNA (siCTRL) or TGF $\beta$ i siRNA (siTGF $\beta$ i) (Ambion, ThermoFisher Scientific, Illkirsch) using Oligofectamine reagent (Life Technologies, Courtaboeuf). BM-MSCs transfection was done twice: at day 3 and 1 before pellet formation. Chondrocytes were harvested 1 week after transfection for RNA extraction.

### Protein analysis

TGF $\beta$ i was quantified in culture supernatants by ELISA (CliniSciences, Nanterre). Phospho-SMAD3 and 1 were quantified in cell extracts by InstantOne ELISA assays as indicated by supplier (eBioscience, Paris). For Western blotting, cells were incubated with RIPA (Sigma Aldrich, Saint-Quentin Fallavier) containing Halt protease inhibitor cocktail (150  $\mu$ L/3 pellets) at 4°C for 30min. Cell lysates were incubated in Bolt LDS sample buffer and Bolt sample reducing agent at 70°C for 10min (ThermoFisher Scientific). Protein extracts (50  $\mu$ g) were analyzed by SDS-PAGE on Bolt 4–12% Bis-Tris Plus resolving gels, followed by transfer to nitrocellulose membranes. Membranes were blocked in Tris Buffered Saline containing 5% milk for 2 h and incubated with anti-TGF $\beta$ i (1:200, Proteintech, Manchester) and anti- $\beta$ actin (1:5,000, Sigma) antibodies at 4°C overnight. Membranes were then incubated with Horseradish peroxidase-labeled anti-mouse IgG antibody (1:100,000, Sigma) for

2 h. Bands were scanned using ChemiDoc XRS + Imager (Bio Rad, Les Ulis).

### Immunohistological analysis

Tissue samples from mice were fixed in 3.7% formaldehyde for 2 days and decalcified using 10% EDTA for 21 days before being processed. Pellets were fixed in 3.7% formaldehyde at room temperature for 1 h. Antigen retrieval was done on pellets with 1 mg/mL hyaluronidase (Sigma Aldrich) at 37°C for 1 h or on tissue sections with citrate buffer (10 mM citric acid, 0.05% Tween 20, pH 6.0) at 70°C overnight followed by 1 mg/mL hyaluronidase at 37°C for 15 min and 0.1 U/mL chondroitinase ABC (Sigma Aldrich) at 37°C for 1 h. Immunolabelling was performed using anti-type II collagen (1:50, Acris, Interchim), anti-aggrecan (1:1000, Merck, Molsheim), anti-TGFβ1 (1:100, Proteintech) primary antibodies at 4°C overnight and UltraVision Detection System Anti-Polyvalent kit (Lab Vision, Interchim, Montluçon).

### RNA extraction and RT-qPCR

RNA was extracted from pellets or cells using the RNeasy kit and from infrapatellar fat pad or synovium using the RNeasy Lipid Tissue Kit (Qiagen, Courtaboeuf). For cartilage and bone, RNA was isolated with 0.1 g/mL TRIzol reagent (ThermoFisher Scientific) followed by chloroform and phenol acid extraction. RNA (0.5 μg) was reverse transcribed using 100 units of the M-MLV reverse transcriptase (ThermoFisher Scientific, Illkirch) and PCR reactions were performed as described<sup>16</sup>. All details for primer sequences (SYBR Green technologies) are described in Table 1. All values were normalized to RPS9 housekeeping gene and expressed as relative expression or fold change using the respective formulae  $2^{-\Delta\Delta Ct}$  or  $2^{-\Delta\Delta Ct}$ .

### Statistical analyses

Statistical analysis was performed with GraphPad Prism Software. Each sample/cell was independent and represented an experimental unit providing a single outcome. Normal distribution and variance homogeneity of values were determined with

Shapiro–Wilk and Fisher (2 groups) or Bartlett (>2 groups) tests, respectively, followed by appropriate tests. Description of the tests used are detailed in each figure. Data are presented as the mean ± SD. \*: P value < 0.05.

## Results

### TGFβ1 is expressed in MSCs from healthy individuals and down-regulated in MSCs from OA patients

From a previous proteomic study investigating the secretome of BM-MSCs and ASCs<sup>11</sup>, we discovered that among members of the TGFβ family, latent binding protein (LTBP)1, LTBP2 and TGFβ1 were mutually expressed [Fig. 1(A)]. We selected TGFβ1 because its functional role in MSCs and cartilage homeostasis or physiopathology is still unclear. TGFβ1 expression was confirmed in BM-MSCs and ASCs at the mRNA and protein levels but at significantly higher levels in BM-MSCs [Fig. 1(B)–(C)]. In addition, TGFβ1 was expressed at significantly lower levels in cells belonging to other embryonic origin, such as endoderm-derived primary hepatocytes. Of interest, mRNA and protein expression of TGFβ1 was dramatically down-regulated in BM-MSCs from late stage OA patients, as compared to healthy subjects [Fig. 1(D)–(E)].

### Expression of TGFβ1 is up-regulated in cartilage and bone from OA patients

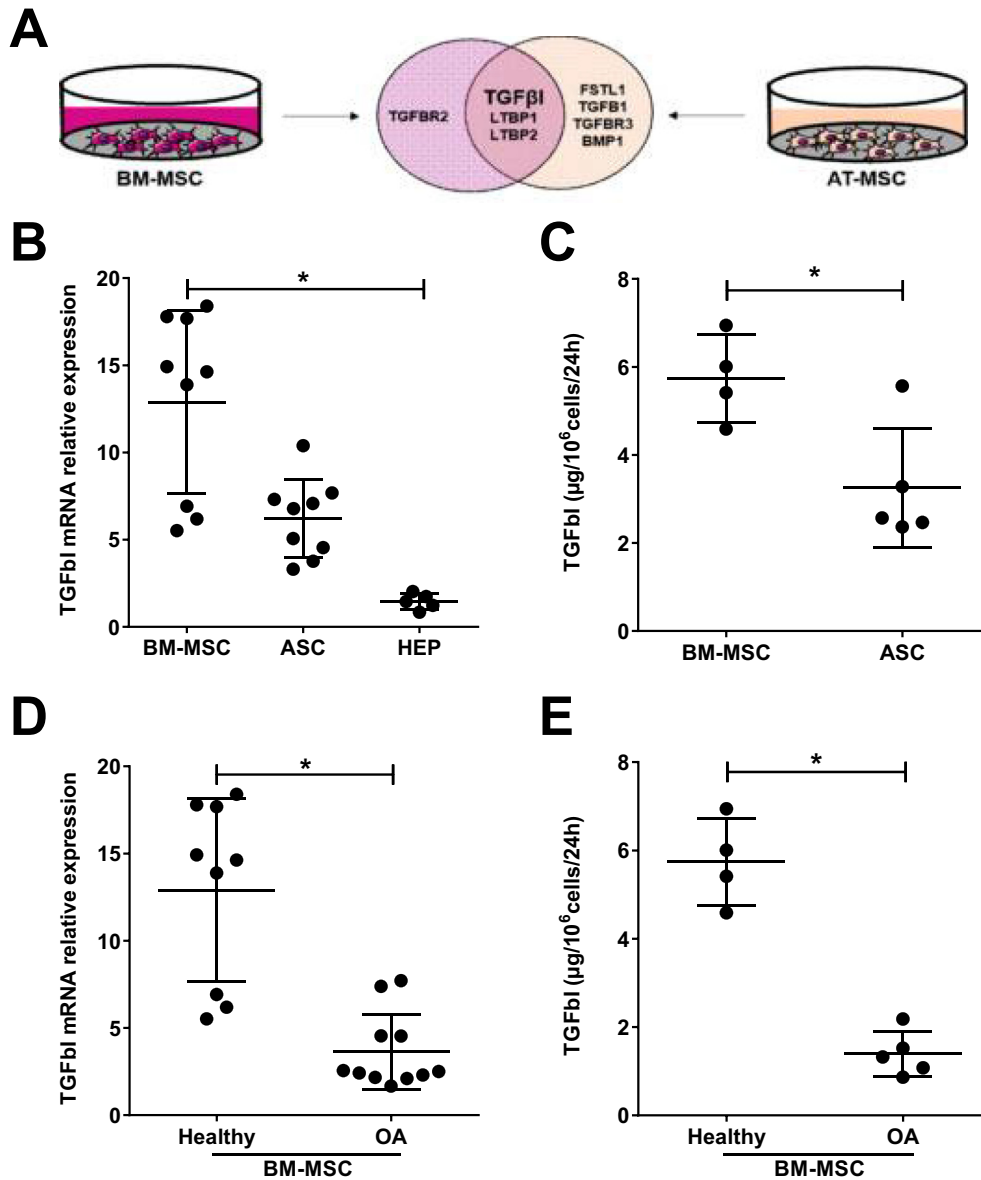
Demonstration that TGFβ1 is down-regulated in OA BM-MSCs questioned on its expression in other joint tissues from OA patients. We therefore compared TGFβ1 expression in cartilage, bone, synovium and infrapatellar fat pad from healthy subjects and patients at latest stage of OA, who were undergoing surgery. Expression levels of TGFβ1 mRNA were significantly up-regulated in cartilage and bone from OA patients but unchanged in synovium or infrapatellar fat pad [Fig. 2(A)]. Similar results were observed at the protein level [Fig. 2(B)]. Immunohistological analysis revealed absence or low staining for TGFβ1 in cartilage from healthy subjects, predominantly found in the superficial layer of cartilage [Fig. 2(C)]. By contrast, intense staining for TGFβ1 was observed in the upper layers of cartilage from OA patients, in areas with signs of chondrocyte proliferation, of high erosion or in osteophytes (not shown). Similarly, in the CIOA mouse model, strong staining for TGFβ1 was visualized in the articular cartilage and particularly, in osteophytes (Supl. figure, panel (A)). In this model, we also revealed up-regulation of TGFβ1 mRNA at all time times during the course of the disease (Supl. figure, panel (B)). Similar findings were obtained in the aging and destabilization of the median meniscus (DMM) models (data not shown). Altogether, these data supported a dysregulation of TGFβ1 in OA.

### TGFβ1 is up-regulated in IL1β-treated chondrocytes

Expression of TGFβ1 being dysregulated in OA samples, we wanted to determine its expression kinetics in an *in vitro* model of OA-like chondrocytes. We first used the model of freshly isolated chondrocytes induced to dedifferentiate by serial passages, in which expression of chondrocyte anabolic markers is lost, reproducing characteristics of OA cartilage<sup>17</sup>. As expected, we observed a down-regulation of type II collagen and aggrecan while type I collagen was up-regulated as soon as passage 1 [Fig. 3(A)]. However, concomitantly with decreased expression of anabolic markers, expression of TGFβ1 was down-regulated in dedifferentiated chondrocytes [Fig. 3(B)]. We therefore investigated the modulation of TGFβ1 expression in another *in vitro* model of OA: freshly isolated chondrocytes cultured with IL-1β. In this model, IL-

**Table 1**  
List of primers and assays for PCR analysis

| A– Primer sequences                 |                         |                        |
|-------------------------------------|-------------------------|------------------------|
| Gene                                | Sequence forward        | Sequence reverse       |
| ADAMT55                             | CTCCACGCAGCCTTCACTGT    | TGGGTGGCATCGTAGGTCTG   |
| AGG                                 | TCGAGGACAGCGAGGCC       | TCGAGGGGTAGCGGTAGAGA   |
| AP                                  | CCACGTCTCACATTGGTG      | GCAGTGAAGGGCTTCTGTC    |
| COL11B                              | CAGACGCTGGTGTCTGT       | TCCTGGTTCGCCGACAT      |
| COLX                                | GTGACCAGGAGTACCTTGC     | TGCTGCCCAAATACCCITT    |
| ITGαV                               | AGGAGAAGGTGCTACGAAGCT   | GCACAGGAAAGTCTTGTAAGGC |
| ITGβ1                               | GGATTCTCCAGAAGGTGGTTTCG | TGCCACCAAGTTTCCCATCTCC |
| ITGβ3                               | CATGGATTCCAGCAATGTCTCC  | TTGAGGCAGGTGGCATTGAAGG |
| ITGβ5                               | GCCTTCTGTGAGTCGCAAC     | CCGATGTAACCTGCATGGCACT |
| MMP13                               | TAAGAGCATGGCGACTTCT     | GTCTGGCGTTTTTGGATGTT   |
| N-CAD                               | CCTCCAGAGTTTACTGCCATGAC | GTAGGATCTCCGCCACTGATTC |
| OC                                  | GGCGCTACCTGTATCAATGG    | TCAGCCAACCTGCACAGTC    |
| RUNX2                               | CGGAATGCCTCTGCTTTAT     | TTCCCGAGGTCCATCTACTG   |
| TGFβ1                               | AAGAAGCGTGCCTTTGGATGCGG | ATGCTCCAGCACAGAAGTTGGC |
| TGFβ2                               | AAGAAGCGTGCCTTTGGATGCGG | ATGCTCCAGCACAGAAGTTGGC |
| TGFβ3                               | CTAAGCGGAATGACGAGGATC   | TCTCAACAGCCACTCACGCACA |
| B– TaqMan® Gene Expression Assay ID |                         |                        |
| Gene                                | ID                      |                        |
| RPS9                                | Hs02339424_m1           |                        |
| TGFβ1                               | Hs00932747_m1           |                        |

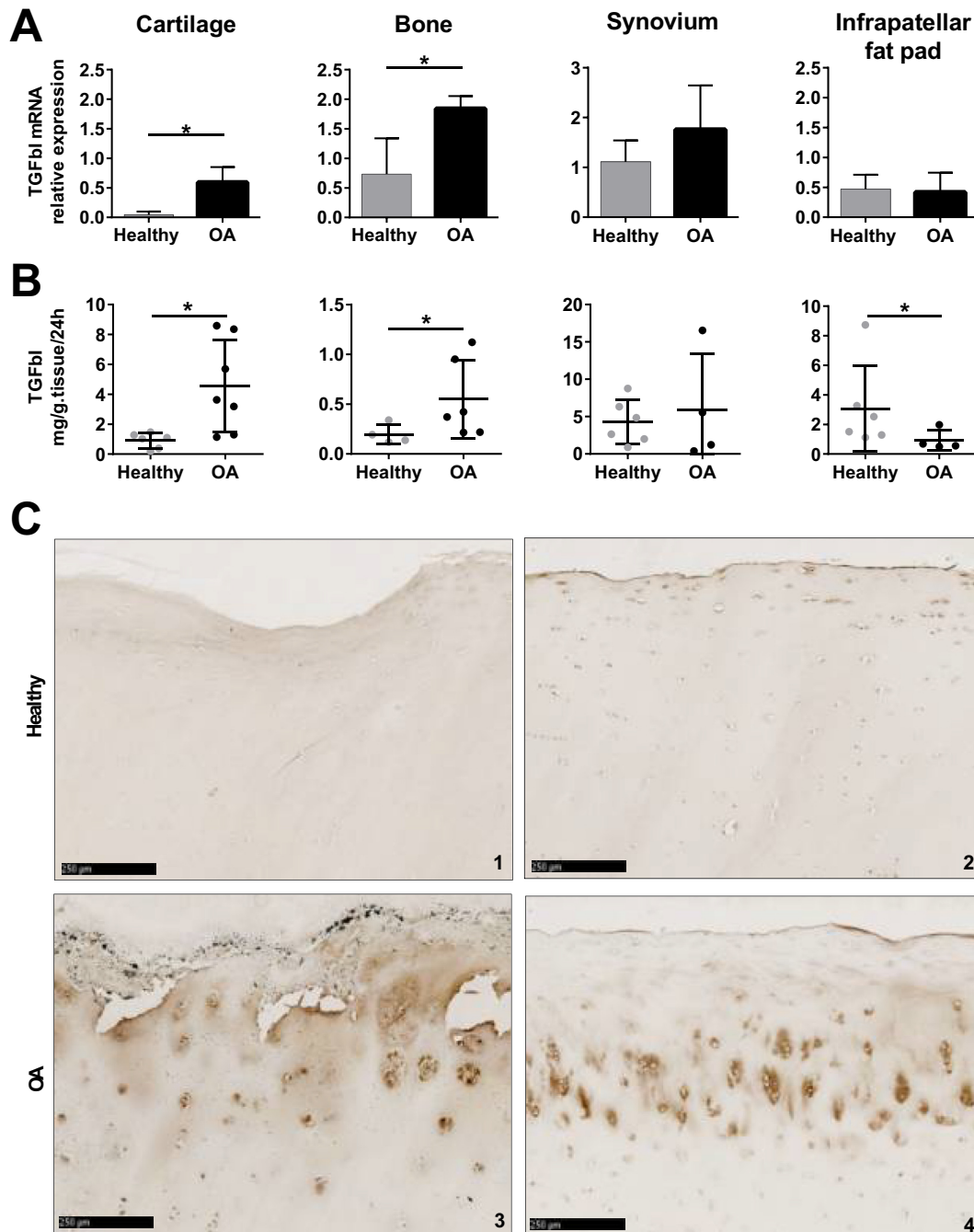


**Fig. 1.** TGFβi is downregulated in mesenchymal stem cells (MSCs) from OA patients. (A) Identification of members of the TGFβ family secreted by human MSCs from bone marrow (BM-MSC) and adipose tissue (ASC) by mass spectrometry. (B–C) Expression of TGFβi in BM-MSC, ASC and primary hepatocytes (Hep) from healthy subjects at the mRNA and protein level ( $n = 4–9$  individuals). (D–E) Expression of TGFβi in BM-MSC from healthy subjects and late stage OA patients at the mRNA and protein level ( $n = 4–11$  individuals). Results are expressed as mean  $\pm$  SD. Statistical analysis used Kruskal–Wallis test followed by Dunn’s multiple comparisons test in (B) or Mann–Whitney test in (C–E) ( $*p < 0.05$ ).

1β down-regulated aggrecan, type II collagen and up-regulated MMP13, ADAMTS5 confirming the induction of OA phenotype [Fig. 3(C)]. In parallel, expression of TGFβi was increased at the mRNA and protein levels, as observed in OA chondrocytes [Fig. 3(D)–(E)]. Analysis of TGFβ isoforms modulated in IL1β-treated chondrocytes revealed down-regulation of TGFβ2 and up-regulation of TGFβ3 suggesting that TGFβ3 might be the inducer of TGFβi [Fig. 3(F)]. We validated that TGFβ3 can upregulate TGFβi mRNA and protein levels by a 7-fold factor in chondrocytes [Fig. 3(G)–(H)]. Finally, we investigated the effect of TGFβi silencing in chondrocytes. Both TGFβi mRNA and protein levels were down-regulated by a two-fold factor using siRNA interference approach, although statistically only for mRNA levels [Fig. 3I]. This down-regulation did not significantly modulate most of chondrocyte genes but significantly increased the expression of the hypertrophic chondrocyte marker, type X collagen [Fig. 3(J)].

#### Upregulation of TGFβi during the early stage of chondrogenic differentiation of BM-MSCs

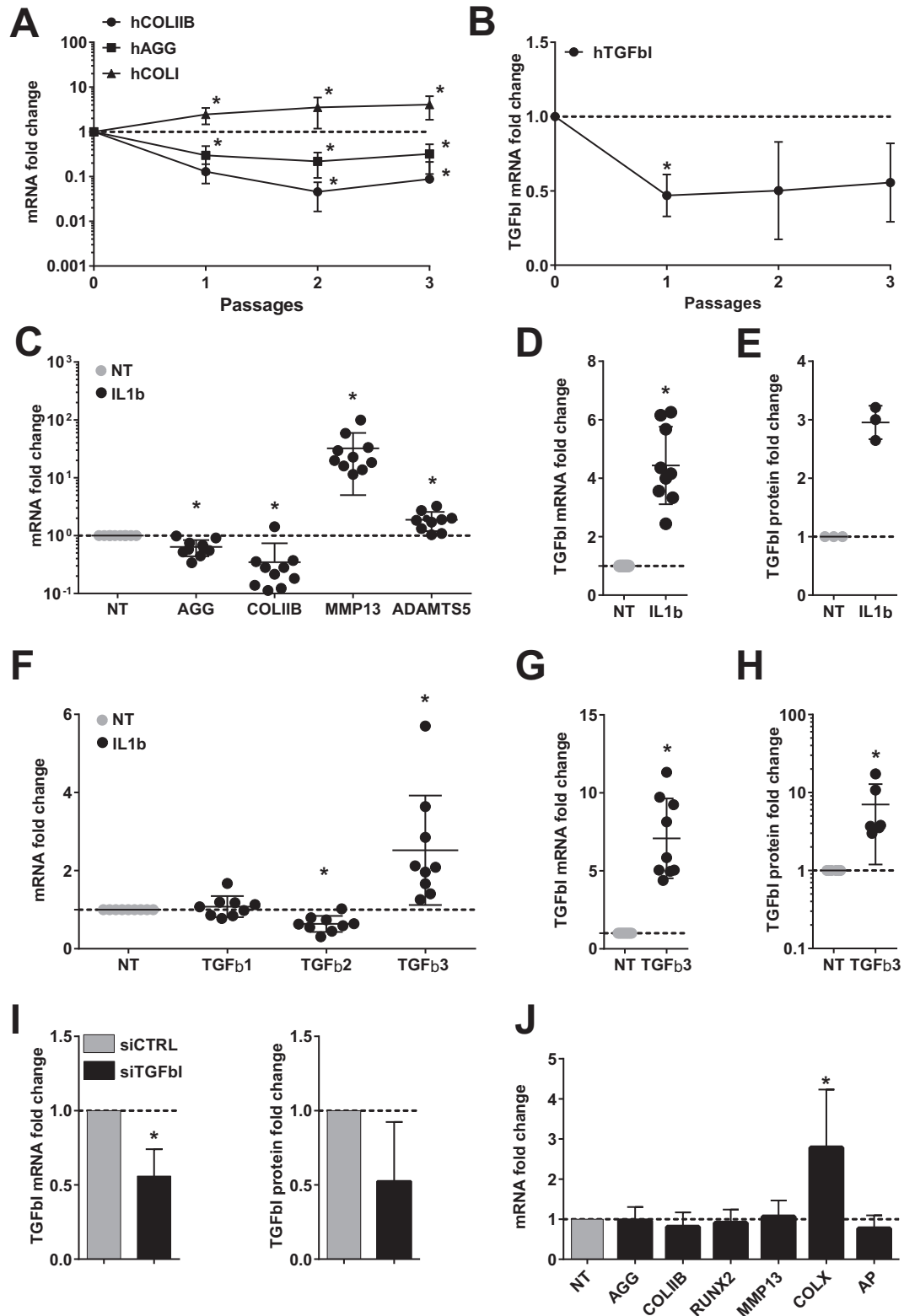
With regards to the expression of type X collagen in late stage of chondrogenesis, we investigated the expression of TGFβi during the differentiation of BM-MSCs. Chondrogenic differentiation of BM-MSCs was induced by culture in micropellet in presence of TGFβ3 for 21 days. TGFβi expression peaked at days 1–3 and returned to basal levels as soon as day 7, till day 21 [Fig. 4(A)]. Up-regulation of TGFβi was also noticed in control conditions (MSCs cultured in aggregates in absence of TGFβ3) but the expression levels were not statistically different from day 0, except for day 3. Of interest, expression of TGFβi is low when the expression of the chondrocyte markers, Sox9, type IIB collagen, Aggrecan and type X collagen are high at day 21 (compared to day 0 or to micropellets cultured without TGFβ3) [Fig. 4(B)]. Protein levels of TGFβi tended to be



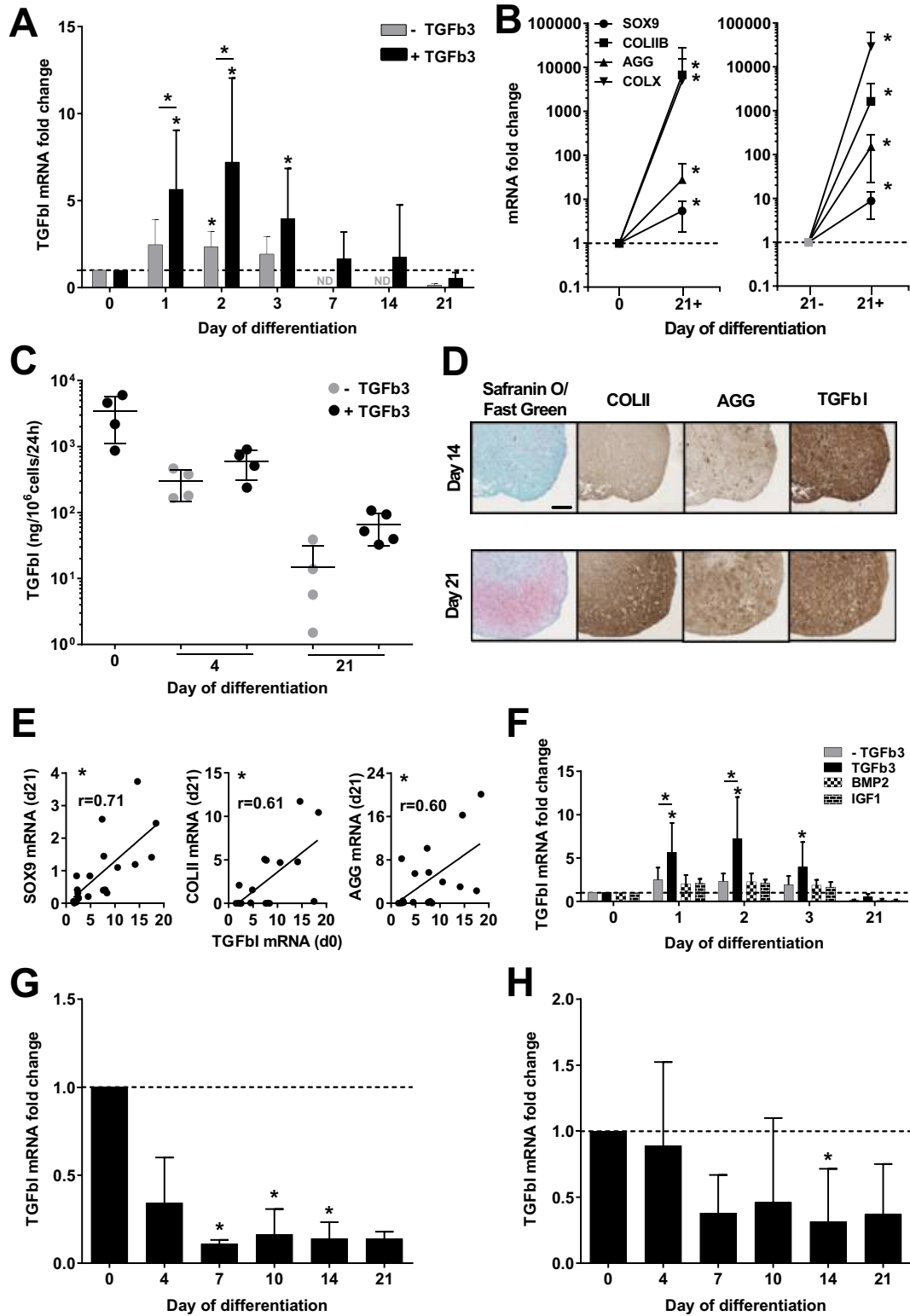
**Fig. 2.** TGFβ1 is upregulated in cartilage and bone from OA patients. (A) Expression of TGFβ1 mRNA in cartilage, bone, synovium and infrapatellar fat pad from healthy (grey) and OA (black) human individuals ( $n = 4$ ). (B) Quantification of TGFβ1 protein in cartilage, bone, synovium and infrapatellar fat pad from healthy (grey;  $n = 4-6$ ) and OA (black;  $n = 4-7$ ) human individuals. (C) Immunohistological analysis of TGFβ1 in human cartilage from healthy and OA patients. Representative pictures of 2 healthy (#1-2) and 2 OA (#3-4) individuals. Note TGFβ1 expression in the superficial layer of healthy cartilage (#2) and upper layer of articular cartilage from OA samples (#3-4). Scale bar is 250 μm. Results are expressed as mean ± SD. Statistical analysis used Mann–Whitney test (\* $p < 0.05$ ).

increased in pellet culture supernatants of TGFβ3-induced pellets (2-fold factor at day 4 and 4.3-fold factor at day 21), as compared to un-induced pellets [Fig. 4(C)]. However, they were significantly lower at day 21 as compared to day 4. Lower amounts of TGFβ1 were observed in pellet supernatants than in MSC supernatants (day 0), which was likely due to retention of the protein in the pellet extracellular matrix. Immunohistochemical analysis detected TGFβ1 protein in TGFβ3-induced pellets at day 7 (not shown) and at day 14 while at day 21, the staining appeared less intense [Fig. 4(D)]. By contrast, chondrocyte markers, aggrecan and type II collagen, as

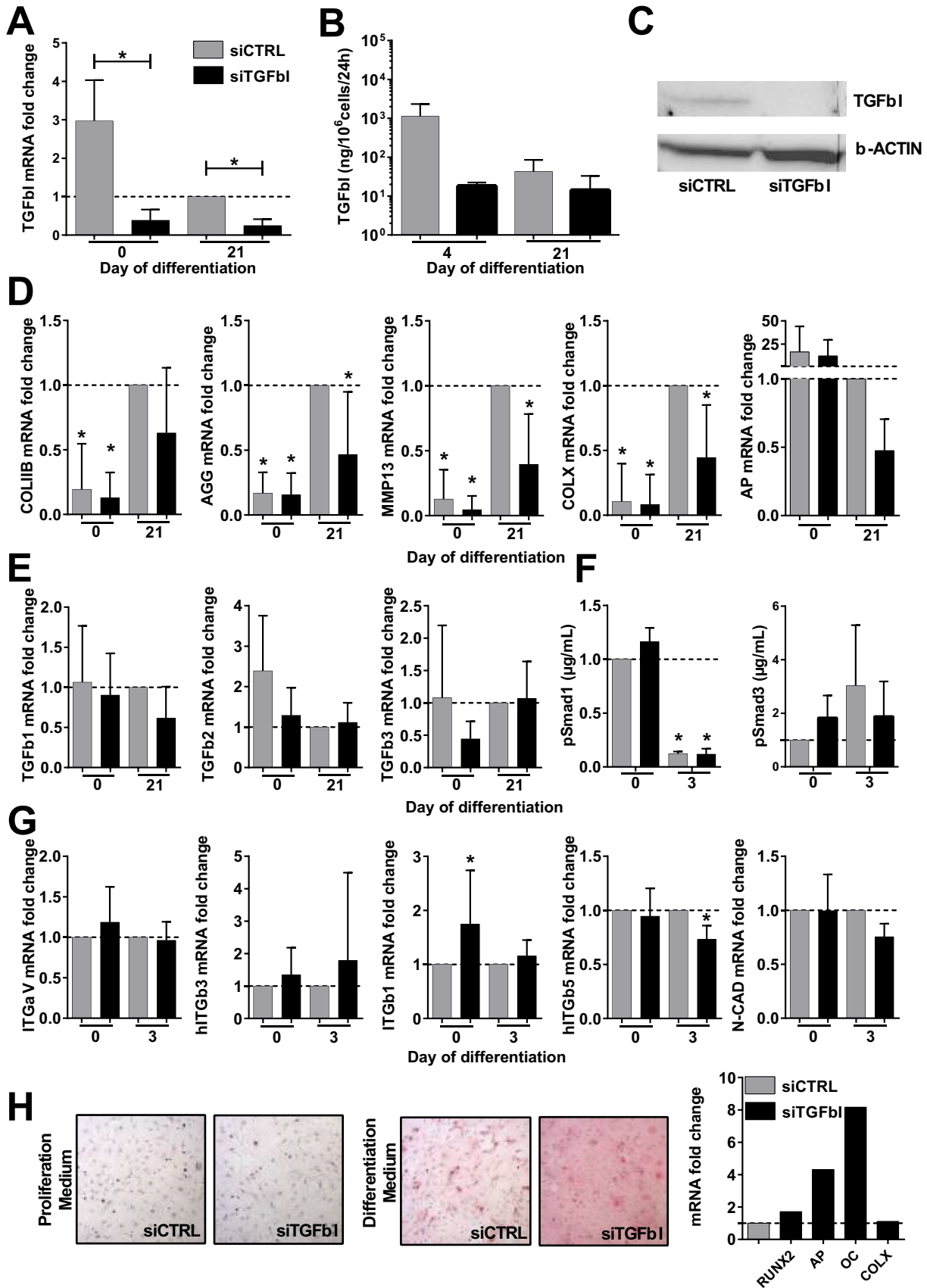
well as proteoglycan secretion were slightly detected at day 14 but clearly distinguished at day 21. Interestingly, a significant positive correlation was found between TGFβ1 mRNA level at day 0 and mRNA levels of the 3 main chondrocyte markers (Sox9, type IIB collagen, aggrecan) at day 21 [Fig. 4(E)]. We also noticed that TGFβ1 was up-regulated by TGFβ3 from day 1 to day 3 of pellet culture but not by IGF1 or by another member of the TGFβ family (BMP2) [Fig. 4(F)]. Finally, TGFβ1 was not a marker of commitment of BM-MSCs to progenitor cells but was specific for chondrogenesis since a significant down-regulation of TGFβ1 was observed during



**Fig. 3.** TGFβi is downregulated during chondrocyte dedifferentiation and upregulated in OA chondrocytes. (A–B) Expression level of type I collagen, type IIB collagen, aggrecan and TGFβi mRNA with passages of primary human OA chondrocytes ( $n = 4$  individuals). (C) Expression of chondrocyte markers in not treated (NT) or IL-1β-treated (IL-1β) primary human OA chondrocytes ( $n = 9$  individuals). (D–E) Expression of TGFβi in NT or IL-1β-treated (IL-1β) primary human OA chondrocytes at the mRNA ( $n = 9$  individuals) or protein ( $n = 3$ ) levels. (F) Expression of TGFβ isoforms in NT or IL-1β-treated (IL-1β) primary human OA chondrocytes at the mRNA level ( $n = 9$  individuals). (G–H) Expression of TGFβi in NT or TGFβ3-treated (TGFβ3) primary human OA chondrocytes at the mRNA ( $n = 9$  individuals) and protein ( $n = 6$ ) levels. (I) Expression of TGFβi mRNA ( $n = 9$  individuals) at day 7 or TGFβi protein ( $n = 4$ ) at day 4 after transfection of primary human OA chondrocytes with siCTRL (grey) or siTGFβi (black). (J) Expression of mature and hypertrophic chondrocyte markers at day 7 after transfection with siCTRL (grey) or siTGFβi (black) ( $n = 9$  individuals). Results are expressed as mean  $\pm$  SD. Statistical analysis used Kruskal–Wallis test followed by Dunn's multiple comparisons test in (A–B) or Wilcoxon signed rank test in (C, E, F, H) or One sample *t*-test in (D, G, I, J) ( $*p < 0.05$ ).



**Fig. 4.** TGFβi is upregulated during the early stages of chondrogenic differentiation of MSCs. (A) Expression of TGFβi at different time points during the chondrogenic differentiation of human BM-MSCs induced in pellets by TGFβ3 (black) or in absence of TGFβ3 (grey) at the mRNA levels ( $n = 11–12$  individuals). (B) Expression of chondrocyte markers in human BM-MSCs induced in pellets by TGFβ3 (21+) in (A) and normalized to day 0 (left panel) or to pellets cultured in absence TGFβ3 (21-; right panel). (C) Quantification of TGFβi protein in supernatants from TGFβ3-induced BM-MSC pellets ( $n = 4–5$ ). (D) Histological analysis of BM-MSC pellets at day 14 and day 21 after chondrogenesis induction. Safranin O Fast Green staining (left panel), type IIB Collagen and aggrecan immunostaining (middle panels, respectively), TGFβi immunostaining (right panel); scale bar is 100 μm. (E) Correlation analysis between the expression level of TGFβi mRNA at day 0 and those of SOX9, type IIB Collagen and Aggrecan at day 21. (F) Expression of TGFβi at different time points during the chondrogenic differentiation of human BM-MSCs induced in pellets by TGFβ3, bone morphogenetic protein (BMP)2 or IGF1 ( $n = 3$  individuals). (G) Expression of TGFβi at different time points during the osteogenic differentiation of human BM-MSCs ( $n = 4$  individuals). (H) Expression of TGFβi at different time points during the adipogenic differentiation of human BM-MSCs ( $n = 6$  individuals). Results are expressed as mean ± SD. Statistical analysis used 2-way ANOVA test followed by Sidak's multiple comparisons test in (A, F) or One sample *t*-test in (B) or Pearson correlation test in (E) or Kruskal–Wallis test followed by Dunn's multiple comparisons test in (C, G, H) (\* $p < 0.05$ ).



**Fig. 5.** Down regulation of TGFβi expression in MSCs impairs chondrogenesis. (A) Expression level of TGFβi at day 0 and 21 after specific siRNA transfection (siTGFβi) and chondrogenesis induction at the mRNA level (n = 8 individuals) as compared to control (siCTRL). (B) Expression level of TGFβi at day 4 and 21 after specific siRNA transfection (siTGFβi) and chondrogenesis induction at the protein level (n = 3). (C) Expression of TGFβi at the protein level at day 4 after chondrogenesis induction of BM-MSCs transfected with



osteoblastogenesis [Fig. 4(G)]. In addition, TGF $\beta$ i expression remained stable or tended to decrease during adipogenesis [Fig. 4(H)]. Indeed, we demonstrated that TGF $\beta$ i expression was specifically increased at early stages of chondrogenesis but was decreased upon chondrocyte maturation, indicating that the overall process was associated with a tight regulation of TGF $\beta$ i.

#### Critical role of TGF $\beta$ i in the chondrogenic differentiation of BM-MSCs

To determine whether TGF $\beta$ i has a cell-autonomous function in chondrogenesis, we used a loss-of-function approach. TGF $\beta$ i silencing resulted in a reduction of mRNA expression by 89% and 74% at day 0 and day 21, respectively [Fig. 5(A)]. TGF $\beta$ i protein was reduced by 98% at day 4% and 66% at day 21 [Fig. 5(B)]. The TGF $\beta$ i protein was undetectable by western blotting at day 4 after siRNA-mediated silencing [Fig. 5(C)]. Down-regulation of TGF $\beta$ i reduced the expression of mature and hypertrophic chondrocyte markers, type IIB collagen, aggrecan, MMP13, type X collagen and alkaline phosphatase by day 21 [Fig. 5(D)]. The reduction was however not significant for type IIB collagen and alkaline phosphatase. To determine if the down-regulation of TGF $\beta$ i alters TGF $\beta$  signalling, we quantified the expression of TGF $\beta$  isoforms or phosphorylated Smad proteins and found no significant change as compared to control MSCs [Fig. 5(E–F)]. However, at early stages, we noticed that siTGF $\beta$ i-transfected pellets were flat and less dense than control pellets (not shown). We therefore investigated the effect of TGF $\beta$ i silencing on adhesion molecules known to interact with TGF $\beta$ i and/or to be important during initial stages of chondrogenesis. Of interest, down-regulation of TGF $\beta$ i led to a low but significant increase of integrin (ITG) $\beta$ 1 at day 0 and a decrease of ITG $\beta$ 5 and N-cadherin (N-CAD) at day 3 [Fig. 5(G)]. Finally, the down-regulation of TGF $\beta$ i increased MSC differentiation towards osteoblasts as shown by increased mineralization and expression of osteoblast markers [Fig. 5(H)]. Altogether, these data indicated a key role of TGF $\beta$ i at the early stage of chondrogenesis, possibly through the modulation of important adhesion molecules and, at the late stage of chondrocyte hypertrophy, when mineralization occurs. TGF $\beta$ i may act as an anti-mineralizing factor whose expression is decreased during both osteoblastogenesis and chondrogenesis allowing mineralization to occur.

#### Discussion

Here, we show that TGF $\beta$ i regulated the chondrogenic differentiation of adult BM-MSCs. TGF $\beta$ i revealed a dual role stimulating the early phase of proliferation and differentiation while inhibiting the late phase of hypertrophy and mineralisation. For the first time, we further evidenced that TGF $\beta$ i was upregulated in articular cartilage and bone of patients with OA suggesting a deregulated function in the disease.

Our study shows that TGF $\beta$ i was up-regulated in early stages of chondrogenic differentiation of adult BM-MSCs and down-regulated in terminal stages. TGF $\beta$ i upregulation in early stages is likely occurring upon TGF $\beta$  and Smad signaling pathway activation as proposed elsewhere<sup>18</sup>. In mouse, previous studies on embryonic and post-natal limb development reported that TGF $\beta$ i was

abundantly expressed in mesenchymal condensation areas, perichondrium, periosteum, prehypertrophic chondrocytes but absent in hypertrophic chondrocytes<sup>19,20</sup>. Increased expression of TGF $\beta$ i was also observed at early stages of differentiation of the pre-chondrogenic cell line ATDC5 while it was decreased at late stages<sup>19</sup>. Other studies in chick embryos have shown that TGF $\beta$ i was expressed in the prehypertrophic zone of vertebral cartilage but not in the proliferative zone. Moreover, addition of TGF $\beta$ i on growth plate chondrocytes resulted in decreased mineralization<sup>21</sup>. These studies suggested an inhibitory role of TGF $\beta$ i on mineralization and late chondrogenic differentiation. This is also supported by our data showing its downregulation during the osteoblastogenic differentiation of BM-MSCs. TGF $\beta$ i was previously shown to inhibit the differentiation of the pre-osteoblastic cell line KS-483 and to be down-regulated in BM-MSCs induced to differentiate into osteoblasts<sup>22,23</sup>. In mature osteoblasts, TGF $\beta$ i inhibited late differentiation and mineralization<sup>24</sup>. Here we confirmed these data using a RNA interference strategy. Our data and those from the literature indeed support a biphasic function of TGF $\beta$ i during the chondrogenic differentiation of adult BM-MSCs. During the early stage of chondrogenesis, TGF $\beta$ i likely regulates the condensation of BM-MSCs, a process involving cell proliferation and cell-to-cell contact, by bridging interactions between cells, collagens and proteoglycans. Our results revealed that TGF $\beta$ i modulated expression of the adhesion molecules ITG $\beta$ 1, ITG $\beta$ 5, N-CAD, which are required at early stages of MSC condensation and chondrogenesis. It may also stimulate the proliferation of BM-MSCs and pre-chondrocytes at this early stage<sup>21</sup>. TGF $\beta$ i expression is then down-regulated at the terminal stage of chondrogenesis, suggesting an inhibitory role on hypertrophy and mineralization. TGF $\beta$ i contains gamma-carboxylated glutamic acid residues that are known to bind calcium with high affinity thereby inhibiting mineralization. However, whether TGF $\beta$ i is subject to extensive gamma-carboxylation is still under debate<sup>25</sup>. In our study, silencing of TGF $\beta$ i in BM-MSCs before inducing differentiation resulted in the down-regulation of both mature and hypertrophic chondrocyte markers. This evoked an impact primarily on the early condensation phase by reducing and/or delaying the overall differentiation process together with the inhibition of late differentiation.

Role of TGF $\beta$ i has not been described in OA. Some transcriptomic studies have listed the upregulation of TGF $\beta$ i at 2 weeks after OA induction in the DMM model or in damaged zones of cartilage from OA patients<sup>26–28</sup>. Proteomic studies have reported the up-regulation of TGF $\beta$ i in the cartilage from OA patients<sup>29,30</sup>. However to our knowledge, a single study validated an increased expression of TGF $\beta$ i transcripts in damaged vs non damaged regions from OA joints<sup>27</sup>. Nevertheless, cartilage matrix degradation was reported in TGF $\beta$ i knock-out mice that was associated with reduced type II collagen levels and higher MMP13 expression in cartilage<sup>31</sup>. Although other features of OA were not investigated, these data suggested that TGF $\beta$ i deficiency was associated with the degradation of cartilage matrix similar to what occurs in OA. Here, we demonstrate for the first time the up-regulation of TGF $\beta$ i at the mRNA and protein levels in cartilage and bone from OA patients as compared to healthy subjects. We observed a preferential localization of TGF $\beta$ i in osteophytes and upper layers of cartilage, in areas

siCTRL or siTGF $\beta$ i by Western blotting.  $\beta$ -actin is used as loading control. (D) Expression of chondrocyte markers (type IIB collagen, aggrecan, MMP-13, type X collagen, Alkaline phosphatase) at day 0 and 21 of chondrogenesis after transfection of BM-MSCs with siCTRL (grey) or siTGF $\beta$ i (black) ( $n = 8$  individuals). (E) Expression of TGF $\beta$  isoforms after specific siRNA transfection (siTGF $\beta$ i) at day 0 and chondrogenesis induction at day 21 at the mRNA level ( $n = 3$ ). (F) Expression of phosphorylated Smad proteins after specific siRNA transfection (siTGF $\beta$ i) at day 0 and chondrogenesis induction at day 3 ( $n = 3$ ). (G) Expression of adhesion markers (integrin (ITG)- $\alpha$ V, ITG- $\beta$ 3, ITG- $\beta$ 1, ITG- $\beta$ 5, N-cadherin (CAD)) at day 0 and 3 of chondrogenesis after transfection of BM-MSCs with siCTRL (grey) or siTGF $\beta$ i (black) ( $n = 7$  individuals). (H) Mineralization assessment after 21 days of osteogenic differentiation of human BM-MSCs transfected with siTGF $\beta$ i or siCTRL by alizarin red S staining. Proliferation medium was used as control (left panels). Expression of osteoblast markers (RUNX2, alkaline phosphatase, osteocalcin) and of type X collagen at day 21 of osteogenesis after transfection of BM-MSCs with siCTRL (grey) or siTGF $\beta$ i (black) ( $n = 1$ ). Results are expressed as mean  $\pm$  SD. Statistical analysis used 2-way ANOVA test followed by Sidak's multiple comparisons test in (A–B, D–E) (\* $p < 0.05$ ).

with clusters of chondrocytes, both in OA patients and in mice with OA. This likely indicates that TGF $\beta$ i upregulation may be involved in the modulation of signalling pathways that are essential for the integrity and repair of cartilage. By reference to the role of TGF $\beta$ i during chondrogenesis, it may reflect an attempt of chondroprogenitor cells to differentiate and secrete extracellular matrix components to induce cartilage regeneration or repair. This might occur at the early stages of the disease as shown in the DMM model where TGF $\beta$ i expression was only detected till week 2 after disease induction<sup>26</sup> but could be not the case in samples at the latest stages as used here. This may also reveal an attempt to inhibit mineralisation that occurs in cartilage and sub-chondral bone as a result of TGF $\beta$  pathway activation at late stages of OA<sup>32</sup>. Of interest in the model of chondrocyte dedifferentiation, the expression of both TGF $\beta$ i and other chondrocyte markers decreased while TGF $\beta$ i silencing did not affect the expression of chondrocyte markers. Only type X collagen was increased after siTGF $\beta$ i transfection. Expression of type X collagen was previously shown to precede alkaline phosphatase expression and mineralization in chondrocytes<sup>33</sup>. In the pellet model of BM-MSCs differentiated into chondrocytes, alkaline phosphatase secretion was detected at day 21 and type X collagen expression at day 14 but no mineralization was observed<sup>34</sup>. Indeed, our data indicated that TGF $\beta$ i regulates type X collagen expression and hypertrophic chondrocyte phenotype, which could precede cartilage calcification. Alternatively, TGF $\beta$ i up-regulation may reflect the deregulation of the TGF $\beta$  pathway in OA<sup>3,7,35</sup>. TGF $\beta$ i up-regulation was seen both in IL1 $\beta$ -induced OA chondrocytes *in vitro* and in cartilage samples from OA patients. Interestingly, TGF $\beta$ i was down-regulated in infrapatellar fat pad and BM-MSCs recovered from OA patients. This may indicate a lower capacity of BM-MSCs from OA patients to undergo a differentiation program and/or to counteract the inflammatory and pathological environment in OA. MSC-like chondroprogenitor cells with the capacity to migrate into and populate diseased cartilage tissue *ex vivo* has been reported<sup>36</sup>. Presence of native MSCs in the joint cavity and spontaneous MSC-mediated repair of cartilage has also been described *in vivo* (for review, see<sup>10</sup>). Evidence that multiple niches of MSCs exist in the joint cavity has put forward the possibility that MSCs with proliferative and unipotent differentiation potential may efficaciously repair microdefects in injured cartilage. Studies on exogenous MSC injection in the joint space have also reported neo-meniscus formation and integration into synovium confirming differentiation of MSCs into joint tissues<sup>37</sup>. Less is known about a deregulated function of MSCs in OA *in situ* but knocking-out the TGF $\beta$  pathway in nestin-positive MSCs *in vivo* was shown sufficient to attenuate OA<sup>8</sup>. Whether the down-regulation of TGF $\beta$ i may be predictive of BM-MSCs efficiency to repair cartilage lesions *in vivo* warrants further investigation.

Altogether, our study identified TGF $\beta$ i as a novel factor involved in the chondrogenic differentiation of BM-MSCs. Its expression is deregulated in OA joint tissues, suggesting a role in the formation of hypertrophic cartilage and mineralization. Modulating TGF $\beta$ i expression in BM-MSCs might be of interest to enhance their therapeutic effect in cartilage regenerative medicine.

#### Author contributions

DN, CJ designed the experiments. Experimental work was performed by MR, MM, GF, YMP, RF, LD, CD, XH, FB, FR. MR, FB, FR, CJ, DN analyzed the data and prepared the manuscript. All authors have contributed to writing or revising the manuscript and final approval.

#### Conflict of interest

The authors disclose any financial or personal conflict of interest.

#### Role of the funding source

We gratefully acknowledge funding support from the Inserm Institute, the University of Montpellier, the Agence Nationale pour la Recherche for support of the national infrastructure: "ECELL-FRANCE: Development of a national adult mesenchymal stem cell based therapy platform" (ANR-11-INSB-005). Study was also supported by the Arthritis R&D through the program "ROAD: Research on OsteoArthritis Diseases" and the European Union's Horizon 2020 Programme (project ADIPOA2, grant agreement no: 643809). The materials presented and views expressed here are the responsibility of the authors only. The EU Commission takes no responsibility for any use made of the information set out.

#### Acknowledgements

We thank Martine Daujat (IRMB, Montpellier, France) for providing total RNA extracted from primary human hepatocytes and the "Réseau d'Histologie Expérimentale de Montpellier" histology facility for processing our tissues.

#### Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.joca.2018.11.005>.

#### References

1. Goldring MB, Berenbaum F. Emerging targets in osteoarthritis therapy. *Curr Opin Pharmacol* 2015;22:51–63.
2. Berenbaum F, Griffin TM, Liu-Bryan R. Review: metabolic regulation of inflammation in osteoarthritis. *Arthritis Rheum* 2017;69:9–21.
3. Zhai G, Dore J, Rahman P. TGF-beta signal transduction pathways and osteoarthritis. *Rheumatol Int* 2015;35:1283–92.
4. Chen JL, Colgan TD, Walton KL, Gregorevic P, Harrison CA. The TGF-beta signalling network in muscle development, adaptation and disease. *Adv Exp Med Biol* 2016;900:97–131.
5. van der Kraan PM, Goumans MJ, Blaney Davidson E, ten Dijke P. Age-dependent alteration of TGF-beta signalling in osteoarthritis. *Cell Tissue Res* 2012;347:257–65.
6. Madej W, van Caam A, Blaney Davidson E, Buma P, van der Kraan PM. Unloading results in rapid loss of TGFbeta signaling in articular cartilage: role of loading-induced TGFbeta signaling in maintenance of articular chondrocyte phenotype? *Osteoarthritis Cartilage* 2016;24:1807–15.
7. van der Kraan PM. The changing role of TGFbeta in healthy, ageing and osteoarthritic joints. *Nat Rev Rheumatol* 2017;13:155–63.
8. Zhen G, Wen C, Jia X, Li Y, Crane JL, Mears SC, et al. Inhibition of TGF-beta signaling in mesenchymal stem cells of subchondral bone attenuates osteoarthritis. *Nat Med* 2013;19:704–12.
9. Fellows CR, Williams R, Davies IR, Gohil K, Baird DM, Fairclough J, et al. Characterisation of a divergent progenitor cell sub-populations in human osteoarthritic cartilage: the role of telomere erosion and replicative senescence. *Sci Rep* 2017;7:41421.
10. McGonagle D, Baboolal TG, Jones E. Native joint-resident mesenchymal stem cells for cartilage repair in osteoarthritis. *Nat Rev Rheumatol* 2017;13:719–30.
11. Maumus M, Manferdini C, Toupet K, Chuchana P, Casteilla L, Gachet M, et al. Thrombospondin-1 partly mediates the cartilage protective effect of adipose-derived mesenchymal stem cells in osteoarthritis. *Front Immunol* 2017;8:1638.
12. Maria AT, Toupet K, Maumus M, Fonteneau G, Le Quellec A, Jorgensen C, et al. Human adipose mesenchymal stem cells as

- potent anti-fibrosis therapy for systemic sclerosis. *J Autoimmun* 2016;70:31–9.
13. Maumus M, Manferdini C, Toupet K, Peyrafitte JA, Ferreira R, Facchini A, et al. Adipose mesenchymal stem cells protect chondrocytes from degeneration associated with osteoarthritis. *Stem Cell Res* 2013;11:834–44.
  14. Toupet K, Maumus M, Luz-Crawford P, Lombardo E, Lopez-Belmonte J, van Lent P, et al. Survival and biodistribution of xenogenic adipose mesenchymal stem cells is not affected by the degree of inflammation in arthritis. *PLoS One* 2015;10:e0114962.
  15. Fonteneau G, Bony C, Goulabchand R, Maria ATJ, Le Quellec A, Riviere S, et al. Serum-mediated oxidative stress from systemic sclerosis patients affects mesenchymal stem cell function. *Front Immunol* 2017;8:988.
  16. Domergue S, Bony C, Maumus M, Toupet K, Frouin E, Rigau V, et al. Comparison between stromal vascular fraction and adipose mesenchymal stem cells in remodeling hypertrophic scars. *PLoS One* 2016;11:e0156161.
  17. Monteagudo S, Cornelis FMF, Aznar-Lopez C, Yibmantasiri P, Guns LA, Carmeliet P, et al. DOT1L safeguards cartilage homeostasis and protects against osteoarthritis. *Nat Commun* 2017;8:15889.
  18. Poncelet AC, Schnaper HW. Sp1 and Smad proteins cooperate to mediate transforming growth factor-beta 1-induced alpha 2(I) collagen expression in human glomerular mesangial cells. *J Biol Chem* 2001;276:6983–92.
  19. Han MS, Kim JE, Shin HI, Kim IS. Expression patterns of betaig-h3 in chondrocyte differentiation during endochondral ossification. *Exp Mol Med* 2008;40:453–60.
  20. Ferguson JW, Mikesch MF, Wheeler EF, LeBaron RG. Developmental expression patterns of Beta-ig (betaIG-H3) and its function as a cell adhesion protein. *Mech Dev* 2003;120:851–64.
  21. Ohno S, Doi T, Tsutsumi S, Okada Y, Yoneno K, Kato Y, et al. RGD-CAP ((beta)ig-h3) is expressed in precartilaginous condensation and in prehypertrophic chondrocytes during cartilage development. *Biochim Biophys Acta* 2002;1572:114–22.
  22. Thapa N, Kang KB, Kim IS. Beta ig-h3 mediates osteoblast adhesion and inhibits differentiation. *Bone* 2005;36:232–42.
  23. Dieudonne SC, Kerr JM, Xu T, Sommer B, DeRubeis AR, Kuznetsov SA, et al. Differential display of human marrow stromal cells reveals unique mRNA expression patterns in response to dexamethasone. *J Cell Biochem* 1999;76:231–43.
  24. Merle B, Bouet G, Rousseau JC, Bertholon C, Garnerio P. Periostin and transforming growth factor beta-induced protein (TGFBeta1p) are both expressed by osteoblasts and osteoclasts. *Cell Biol Int* 2014;38:398–404.
  25. Mosher DF, Johansson MW, Gillis ME, Annis DS. Periostin and TGF-beta-induced protein: two peas in a pod? *Crit Rev Biochem Mol Biol* 2015;50:427–39.
  26. Gardiner MD, Vincent TL, Driscoll C, Burleigh A, Bou-Gharios G, Saklatvala J, et al. Transcriptional analysis of micro-dissected articular cartilage in post-traumatic murine osteoarthritis. *Osteoarthritis Cartilage* 2015;23:616–28.
  27. Sato T, Konomi K, Yamasaki S, Aratani S, Tsuchimochi K, Yokouchi M, et al. Comparative analysis of gene expression profiles in intact and damaged regions of human osteoarthritic cartilage. *Arthritis Rheum* 2006;54:808–17.
  28. Aigner T, Zien A, Gehrsitz A, Gebhard PM, McKenna L. Anabolic and catabolic gene expression pattern analysis in normal versus osteoarthritic cartilage using complementary DNA-array technology. *Arthritis Rheum* 2001;44:2777–89.
  29. Ikeda D, Ageta H, Tsuchida K, Yamada H. iTRAQ-based proteomics reveals novel biomarkers of osteoarthritis. *Biomarkers* 2013;18:565–72.
  30. Lourido L, Calamia V, Mateos J, Fernandez-Puente P, Fernandez-Tajes J, Blanco FJ, et al. Quantitative proteomic profiling of human articular cartilage degradation in osteoarthritis. *J Proteome Res* 2014;13:6096–106.
  31. Lee JM, Lee EH, Kim IS, Kim JE. Tgfb1 deficiency leads to a reduction in skeletal size and degradation of the bone matrix. *Calcif Tissue Int* 2015;96:56–64.
  32. Yuan XL, Meng HY, Wang YC, Peng J, Guo QY, Wang AY, et al. Bone-cartilage interface crosstalk in osteoarthritis: potential pathways and future therapeutic strategies. *Osteoarthritis Cartilage* 2014;22:1077–89.
  33. Chen-An P, Andreassen KV, Henriksen K, Karsdal MA, Bay-Jensen AC. Investigation of chondrocyte hypertrophy and cartilage calcification in a full-depth articular cartilage explants model. *Rheumatol Int* 2013;33:401–11.
  34. Pelttari K, Winter A, Steck E, Goetzke K, Hennig T, Ochs BG, et al. Premature induction of hypertrophy during in vitro chondrogenesis of human mesenchymal stem cells correlates with calcification and vascular invasion after ectopic transplantation in SCID mice. *Arthritis Rheum* 2006;54:3254–66.
  35. van der Kraan PM, van den Berg WB. Chondrocyte hypertrophy and osteoarthritis: role in initiation and progression of cartilage degeneration? *Osteoarthritis Cartilage* 2012;20:223–32.
  36. Koelling S, Kruegel J, Irmer M, Path JR, Sadowski B, Miro X, et al. Migratory chondrogenic progenitor cells from repair tissue during the later stages of human osteoarthritis. *Cell Stem Cell* 2009;4:324–35.
  37. Murphy JM, Fink DJ, Hunziker EB, Barry FP. Stem cell therapy in a caprine model of osteoarthritis. *Arthritis Rheum* 2003;48:3464–74.