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Up-regulation of type II collagen gene by 17 β -estradiol in articular chondrocytes involves Sp1/3, Sox-9 and estrogen receptor α

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Abstract

The existence of a link between estrogen deprivation and osteoarthritis (OA) in postmenopausal women suggests that 17 β -estradiol (17 β -E₂) may be a modulator of cartilage homeostasis. Here, we demonstrate that 17 β -E₂ stimulates, *via* its receptor hER α 66 (human estrogen receptor α 66), type II collagen expression in differentiated and dedifferentiated (reflecting the OA phenotype) articular chondrocytes. *Transactivation* of type II collagen gene (*COL2A1*) by ligand independent *transactivation* domain (AF-1) of hER α 66 was mediated by 'GC' binding sites of the -266/-63 bp promoter, through physical interactions between ER α , Sp1/Sp3, Sox9 and p300, as demonstrated in ChIP and Re-ChIP assays in primary and dedifferentiated cells. 17 β -E₂ and hER α 66 increased the DNA-binding activities of Sp1/Sp3 and Sox-9 to both *COL2A1* promoter and enhancer regions. Besides, Sp1, Sp3 and Sox-9 siRNAs prevented hER α 66-induced *transactivation* of *COL2A1*, suggesting that these factors and their respective *cis*-regions are required for hER α 66-mediated *COL2A1* up-regulation. Our results highlight the genomic pathway by which 17 β -E₂ and hER α 66 modulate Sp1/Sp3 heteromer binding activity and simultaneously participate in the recruitment of the essential factors Sox-9 and p300 involved respectively in the chondrocyte differentiated status and *COL2A1* transcriptional activation. These novel findings could therefore be attractive for tissue engineering of cartilage in OA, by the fact that 17 β -E₂ could promote chondrocyte redifferentiation.

Keywords

Type II collagen (*COL2A1*) gene • Estrogen receptor α • 17 β -estradiol • Sp1/Sp3 • Sox proteins • Chondrocytes • Cartilage • Osteoarthritis

Key Messages

- 17 β -E₂ up-regulates type II collagen gene expression in articular chondrocytes.
- An ER α 66/Sp1/Sp3/Sox-9/p300 protein complex mediates this stimulatory effect.
- This heteromeric complex interacts and binds to *Col2a1* promoter and enhancer *in vivo*.
- Our findings highlight a new regulatory mechanism for 17 β -E₂ action in chondrocytes.
- 17 β -E₂ might be an attractive candidate for cartilage engineering applications.

Introduction

Mature articular cartilage harbours a predominant cell type, the chondrocyte, which is responsible for the extracellular matrix (ECM) turnover regulation by synthesizing and secreting cartilage-specific matrix markers such as type II collagen and large aggregating proteoglycans, aggrecans. The role played by type II collagen, a phenotypic marker of healthy articular cartilage, in the homeostasis of ECM is critical, as illustrated by the loss of the physico-mechanical properties of the tissue leading to a variety of joint diseases such as OA and rheumatoid arthritis. During OA development and/or when cells are cultured as monolayers or passaged, chondrocytes undergo de-differentiation process: they lose their normal cartilage phenotype and have been found to progressively reduce their type II collagen synthesis in favour of non-specific articular cartilage collagens (isotypes I, III, V and X) . As a consequence, it is of special interest to get insight into the molecular mechanisms that govern type II collagen gene expression, in order to better understand the process of phenotype alteration in chondrocytes during OA.

Type II collagen is first synthesized as a procollagen triple-helix molecule including identical $\alpha 1(\text{II})$ chains encoded by the *COL2A1* gene . Sequence analysis of *COL2A1* has revealed crucial DNA regulatory elements within both the short promoter and the first intron regions (Fig. 1). Thus, several binding sites of the intronic enhancer have been shown to interact with transcription factors, such as Sox-9, Sox-6, and L-Sox-5 acting cooperatively and consequently activating expression of *COL2A1* in 10T1/2 and MC615 cells . Moreover, zinc finger transcription factors Sp1, Sp3 and C-Krox are able to bind not only to this region but also to several DNA sites localized in a 266-bp promoter of *COL2A1*. Interestingly, Sp1 was found to be a potent activator of *COL2A1* transcription by binding to GC-rich sequences in the promoter and in the intronic enhancer whereas Sp3 prevents this action by competing Sp1 for its GC responsive elements .

From epidemiological studies, the prevalence of OA is known to increase dramatically in women around the age of 50, coinciding with the onset of menopause, and suggesting the potential for estrogens in preventing OA. The menopause is associated with an increase in the urinary levels of CTX-II, a telopeptide fragment of type II collagen, and this increase correlates with collagen II degradation and joint damage, and can be antagonized by estrogens . Although there are some conflicting results among these studies, most of the clinical observations show that hormone replacement therapy (HRT) is associated with reduced severity and prevalence of OA in postmenopausal women . Another study demonstrated that the localized production of $17\beta\text{-E}_2$ by synovial cells inhibits IL-6 secretion by osteoarthritic chondrocytes in postmenopausal women highlighting the anti-inflammatory properties of $17\beta\text{-E}_2$. This chondroprotective effect of HRT was confirmed in animal models. For instance, a long-term (3 years) estrogen replacement therapy in ovariectomized monkeys significantly decreases the severity of OA lesions by maintaining intact articular cartilage structure and reducing number of osteophytes, chondrocyte cloning and proteoglycan loss . As estrogens are known to down-regulate the matrix metalloproteinases (MMPs) that are critical for cartilage collagenolysis, the main effect of estrogens relies upon the inhibition of the catabolic processes in articular chondrocytes. However $17\beta\text{-E}_2$ can also stimulate the anabolic pathway by interacting with synthesis and secretion of transforming growth factor- $\beta 1$ (TGF- $\beta 1$) and insulin-like growth factor-I (IGF-I). Indeed, compared with chondrocytes from non-treated ovariectomized monkeys, $17\beta\text{-E}_2$ -treated animals have two-fold higher synovial fluid levels of IGF-I . This growth factor is critical for the

regulation of chondrocyte proliferation, aggrecan synthesis and *COL2A1* expression as well as TGF- β whose expression is influenced by 17β -E₂ in dose-dependent and biphasic manner. In this context, molecular mechanisms by which estrogens mediate a chondroprotective action through type II collagen regulation remain to be elucidated.

Identification of two isoforms of estrogen receptor, alpha (ER α) and beta (ER β), in articular chondrocytes from several species including rabbits and human, provides strong evidence that cartilage can respond to estrogens. Deletion of both ERs leads to increased osteophytosis in six-month-old knockout mice. The majority of ERs are nuclear proteins belonging to the steroid receptor family of transcription factors, structurally organized in six distinct domains (A to F). According to the 'classical genomic model', ligand-activated ER α binds to specific DNA sequences called 'Estrogen Responsive Elements' (ERE); so that two *transactivation* functions, AF-1 (ligand independent) and AF-2 (ligand dependent), located respectively in B and E receptor domains, act cooperatively to modulate transcriptional activity of 17β -E₂-target genes. Nevertheless, 35% of the categorized human 17β -E₂-responsive genes are transcribed *via* indirect ER-DNA association through protein-protein interactions with several *trans* factors such as Sp1, nuclear factor-kappaB (NF- κ B) or activator protein-1 (AP-1). For instance, Sp1 and ER α can form a complex *in vivo* to mediate E₂-induced activation of kisspeptin 1 promoter in hypothalamic GT-1 cells.

The 46 kDa hER α isoform (hER α 46), which has been first identified in MCF-7 breast carcinoma cell line, lacks the N-terminal 173 amino acids of A and B domains and is consequently devoided of AF-1 *transactivation* sequence. In a cell context where AF-1-mediated *transactivation* predominates over AF-2, hER α 46 is an effective competitive inhibitor of hER α 66. Indeed, when both isoforms are co-expressed (as it seems to be the most frequent situation *in vivo*), hER α 46 efficiently represses the transcription of estradiol-target genes induced by hER α 66 by suppressing AF-1 activity of full-length estrogen receptor. Expression of hER α 46 was also reported in human primary osteoblasts at similar levels compared to hER α 66. To our knowledge, no information exists on the exact function of hER α 46 in articular chondrocytes, except our previous study demonstrating that, unlike hER α 66, hER α 46 isoform is not able to stimulate UDP-glucose dehydrogenase gene activity in primary rabbit articular chondrocytes.

In the present study, we aimed to investigate the role of 17β -E₂ in the regulation of *COL2A1* expression in rabbit articular chondrocytes (RAC). We demonstrated for the first time that *COL2A1* up-regulation by 17β -E₂ involves a -266/-63 bp promoter region and that this effect was mediated by AF-1 region of hER α 66 in both differentiated and dedifferentiated chondrocytes. Moreover, we showed that hER α 66 requires Sp1, Sp3, Sox-9 and p300 cooperation to increase *COL2A1* transcription in RAC. Therefore, association of 17β -E₂/hER α 66 complex to *COL2A1* regulatory sequences may contribute to reverse the loss of type II collagen expression during chondrocyte dedifferentiation, such an alteration currently observed in OA.

Materials and Methods

General materials

Chemical reagents were of the highest grade from Sigma-Aldrich Co (Saint Quentin-Fallavier, France), as well as IL-1 β , TGF- β 1, tamoxifen and mithramycin A. Trichloroacetic acid, Tris and glycine were purchased from Acros Organics (Noisy-le-Grand, France). Fetal calf serum (FCS), Dulbecco's modified Eagle's medium (DMEM), di-deoxynucleosidetriphosphate (dNTPs), RNase inhibitor, trypsin and phosphate-buffered saline (PBS) were purchased from Invitrogen (Cergy-Pontoise, France). Protein Assay kit was from Bio-Rad (Marnes-la-Coquette, France). 2X SYBR Green Master Mix was purchased from Applied Biosystems (Courtabœuf, France). All the primers and oligonucleotides used in this study (Real-time PCR, EMSAs, ChIP) were synthesized by Eurogentec Corporation (Seraing, Belgium) (Table 1). [3 H]proline and [γ - 32 P]dATP were purchased from PerkinElmer Life Sciences (Courtabœuf, France) and double-charcoal treated FCS was from Abcys (Paris, France).

Antibodies

Rabbit polyclonal anti-type II collagen was from Novotec (Lyon, France). Rabbit monoclonal anti- β -actin (C-2), anti-ER α (MC-20), anti-Sp1 (PEP-2), anti-Sp3 (D-20), anti-Sox-9 (P-20), anti-p300 (N-15), anti RNA polymerase II (H-224) and horseradish peroxidase (HRP)-conjugated goat anti-rabbit were purchased from Tebu-Bio (Le Perray en Yvelines, France).

Chondrocyte culture

RAC were isolated from articular cartilage slices of shoulders and knees of 3-week old male rabbits, by sequential digestion with hyaluronidase (1088 U/ml, Serva, Heidelberg, Germany), trypsin (124 U/ml, Coger, Paris, France) and type I collagenase (410 U/ml, Invitrogen). The cells were seeded generally at 3.5×10^5 cells per 9.6-cm 2 dishes or 1.5×10^6 cells per 55-cm 2 dishes in 2 or 8 ml of DMEM containing 10% heat-inactivated FCS, supplemented with glutamine (2 mM), fungizone (0.25 μ g/ml) and antibiotics: penicillin (100 UI/ml) and erythromycin (100 μ g/ml). They were grown for 8-12 days at 37°C in a 5% CO $_2$ humidified atmosphere, with medium change every 2-3 days. For dedifferentiation, in order to mimic some of OA phenotype characteristics (*i.e.* decrease of type II and increase of type I collagen productions), RAC cultures were passaged three times with 0.25% trypsin (Invitrogen) after reaching confluency. When chondrocytes were treated by 17 β -E $_2$ (Sigma-Aldrich Co), they were incubated in phenol red-free DMEM medium supplemented with 2% double-charcoal treated FCS. In some experiments, articular chondrocytes were incubated for 24 h with tamoxifen (1 μ M), a partial antagonist of estrogen receptors or mithramycin A (100 nM), a binding inhibitor to GC-rich sequences, in the same medium as for 17 β -E $_2$ treatment. MCF-7 cell line was cultured in the same conditions as primary RAC.

Collagen labeling and assay

To assay newly synthesized collagen, series of chondrocytes in 6-well plates were transiently transfected, at 80% confluency, with 10 μ g of the expression vector pCR3.1-hER α 66

or pCR3.1-hER α 46, encoding the long or the short estrogen receptor α isoforms respectively (pCR3.1 plasmid was used as control). Second series were not transfected and used to study the effect of increasing concentrations of 17 β -E $_2$. Fifteen hours later, all the cell culture media were changed to 10% FCS/DMEM supplemented with 100 μ g/ml sodium ascorbate. Twenty-four hours later, cells were incubated for 24 h in 2% double-charcoal treated FCS/DMEM medium supplemented with 50 μ g/ml sodium ascorbate, 100 μ g/ml β -aminopropionitrile and 2 μ Ci/ml [3 H]proline, containing or not 17 β -E $_2$ (0-5 nM), TGF- β 1 (3 ng/ml) or IL-1 β (1 ng/ml). Only the chondrocytes which were not submitted to transient transfection experiments were treated by the hormone or the cytokines. Twenty-four hours after treatments or 48 h post-transfection, the culture medium and the cell extracts were collected, and the amount of labeled collagen was assayed as previously described .

Western-blotting

Twenty-four hours after incubation with 17 β -E $_2$ or 48 h post-transfection, RAC cultures were washed three times with PBS and whole cell extracts were prepared as previously described . The cell extract-associated proteins (20 μ g) were resolved on a 8% polyacrylamide gel, using 1% SDS/Tris glycine buffer. The proteins were then electrotransferred onto polyvinylidene difluoride (PVDF) membrane (Millipore, Molsheim, France). Free protein-binding sites of the PVDF membranes were blocked for 1 h in Tris buffer saline (TBST, 20 mM Tris, 137 mM NaCl, 0.1% Tween 20) containing 10% non-fat dry milk and the membranes were incubated with anti-type II procollagen, anti-ER α , anti-Sp1, anti-Sp3 or anti- β -actin antibodies. After overnight incubation at 4 $^{\circ}$ C, the membranes were rinsed and incubated for 1 h with a secondary antibody (HRP-conjugated goat anti-rabbit antibody at 1:6000 dilution). Protein signals were revealed using a Western-blotting Chemiluminescence Luminol Reagent (Tebu-Bio) and quantified with the Image Quant software (Amersham Biosciences, Orsay, France). The type II collagen signal was normalized to that of β -actin.

Real-time RT-PCR

Total RNAs were extracted using TRizol[®] Reagent, according to the manufacturer's instructions (Invitrogen). Two μ g of RNAs, previously treated with DNase I (Invitrogen) were reverse transcribed into cDNA using 50 pmoles of oligo dT, 5 mM of each dNTPs, reverse transcriptase buffer 5X, 40 units/ μ l of RNase inhibitor and 200 units/ μ l of Moloney Murine Leukemia Virus enzyme (Invitrogen) in a final volume of 25 μ l. Real-time PCR amplifications were carried out with 5 μ l of cDNA (diluted 1:100) on an 'ABI Prism 7000 sequence detection system' (Applied Biosystems), using sequence-specific primers (Table 1) and 2X SYBR Green Master Mix protocol as outlined by the manufacturer. Each sample was run in triplicate, and analysis of relative gene expression was done by using the 2^{- $\Delta\Delta$ CT} method.

Transient transfection experiments

Eighty percent confluent RAC in six-well plates were transiently transfected by the calcium phosphate precipitation method. Luciferase reporter plasmids (10 μ g) containing various deletions of *COL2A1* promoter/first intron were co-transfected with 10 μ g of pCR3.1 vector containing or not the cDNA encoding the human estrogen receptor α (hER α). The reporter

constructs pGL2-3.374 kb, pGL2-3.316 kb, pGL2-0.387 kb and pGL2-0.110 kb cover, respectively, the -932/+2842 bp, -932/+2384 bp, -266/+121 bp and -63/+47 bp of the promoter and first intron of *COL2A1*, as previously described. Expression vectors used for hER α encode either long form of estrogen receptor α or short mutated inoperative form of the receptor (A/B domain deleted), denoted hER α 66 or hER α 46 respectively. After 12-15 h, the medium was changed to 10% FCS/DMEM. Twenty-four hours later, the samples were harvested and the protein content and luciferase activities were assayed on whole cell extract (Promega, Charbonnières les Bains, France) in a luminometer (Berthold Lumat LB 9501, Bad Wildbad, Germany). The protein amount was determined by the Bradford colorimetric method (Bio-Rad). Luciferase activities were normalized to protein content and represented as mean \pm S.D. of three independent samples. **For all the transcriptional activity assays, the *Escherichia coli lacZ* gene, encoding β -galactosidase (β -gal vector) was systematically transfected in combination with *COL2A1* reporter constructs and hER α expression plasmids to achieve for transfection efficiencies.** In an additional experiment (Fig. 5C), 10 μ g of pGL2-0.387 kb *COL2A1* reporter construct was co-transfected with 2 μ g of siRNA directed against ER α (Tebu-Bio). The corresponding negative siRNA (scrambled sequence of the siRNA target) was used as control. After 15 h of transfection, the medium was changed to 10% FCS/DMEM. Twenty-four hours later, the samples were harvested and analyzed as described above.

Small interfering RNAs (siRNAs) transfection

In knock-down experiments, hER α 66 and hER α 46 expression vectors were also co-transfected with siRNAs (Tebu-Bio) directed against the human Sp1, Sp3 and Sox-9 mRNAs. At 80% confluency, RAC were transiently transfected by the calcium phosphate precipitation method using 5 μ g of hER α 66 or hER α 46 expression vectors in combination with 2 μ g of Sp1, Sp3 or Sox-9 siRNAs. After an overnight transfection period, the cells were incubated for 24 h in absence or in presence of 17 β -E₂. The corresponding insertless plasmid pCR3.1 and negative siRNA were used as controls. Relative expression of *Col2a1*, *Sp1*, *Sp3*, *Sox-9* and *hER α 66* genes was determined by real-time RT-PCR.

Electrophoretic Mobility Shift Assays (EMSAs)

Nuclear proteins from RAC treated or not with increasing concentrations of 17 β -E₂ or transfected with estrogen receptors expression vectors, as described above, were extracted by a minipreparation procedure. EMSAs were performed with oligonucleotides presented in **Table 1**, which were end-labeled with [γ -³²P]dATP using T4 polynucleotide kinase (Promega). RAC nuclear extracts (10 μ g) were incubated for 20 min at room temperature with 2 fmoles of radioactive probe in a specific binding buffer (for +2817/+2846 probe, -96/-66 probe, -225/-188 probe and ERE/mutant ERE probes, 20% glycerol, 40 mM Tris pH 7.5, 2 mM DTT, 200 mM NaCl, 0.01% BSA, 0.2% Nonidet P-40; for +2353/+2415 probe or +2383/+2415 probe, 20 mM HEPES pH 7.9, 50 mM KCl, 10% glycerol, 0.5 mM EDTA, 0.5 mM DTT, 1 mM PMSF, 0.05% Nonidet P-40) in presence of 2 μ g of poly(dI-dC) (for +2817/+2846 probe, -96/-66 probe, -225/-188 probe or ERE probes) or 2 μ g of poly(dG-dC) (for +2353/+2415 or +2383/+2415 probe), used as non specific DNA competitors. For EMSAs performed with ERE and mutant ERE probes, samples were submitted for 20 min to a supplemental incubation in the presence or absence of a ER α antibody (4 μ g) or molecular excess (\times 100) of wild type non labelled ERE

probe (cold probe). Samples were fractionated on a 7% polyacrylamide electrophoresis gel for 2 h at 150 V in 0.5 X TBE buffer (Tris borate 450 mM, 10 mM EDTA) and visualized by autoradiography.

Immunoprecipitation assays

200 µg of protein nuclear extracts from control or 1 nM 17β-E₂ treated chondrocytes were pre-cleared with 2.5 mg of protein A-Sepharose (Sigma-Aldrich Co) for 2 h at 4°C. Pre-cleared extracts, relieved of protein A-Sepharose, were immunoprecipitated for 15 h at 4°C using an anti-Sp1 antibody. Then, protein-antibody complexes were captured by adding 3 mg of protein A-Sepharose and unbound proteins were removed by washing the solid phase four times with hypertonic lysis buffer (119 mM Tris pH 6.8, 5% glycerol, 0.4% SDS, 1% β-mercaptoethanol, 0.02% bromophenol blue). Samples were then resuspended in 50 µl of 2X sample loading buffer (20 mM HEPES, 25% glycerol, 1 mM MgCl₂, 420 mM NaCl, 0.2 mM EDTA) and boiled for 5 min. Remaining nuclear proteins were centrifuged at 14000 g for 2 min (4 °C) and supernatants were submitted to Western-blotting.

Chromatin Immunoprecipitation assays (ChIP)

RAC, incubated or not with 17β-E₂ (1 nM), were cross-linked, scraped, and lysed according to the manufacturer's instructions. Resulting chromatin was used in ChIP assays using a commercial chromatin immunoprecipitation kit (Active Motif, Rixensart, Belgium). In Re-ChIP experiments, a supplemental overnight immunoprecipitation with ERα antibody was performed to isolate specific DNA-protein complexes. ChIP primers (Table 1) were designed to amplify in PCR a 171 bp specific fragment of the *COL2A1* core promoter or a 229 bp fragment of the *COL2A1* intronic enhancer region.

Statistical analysis

Results were representative of at least three experiments with similar results, performed in triplicates unless otherwise precisions. Statistically significance was assessed by using the Student's *t* test. Statistically significant differences were set at ***p<0.001, **p<0.01 and *p<0.05.

Results

17 β -E₂ and its receptor hER α 66 stimulate type II collagen production in primary articular chondrocytes

We first determined whether 17 β -E₂ and its receptors hER α 66 or hER α 46 modulate collagen synthesis in primary RAC. 17 β -E₂ was found to enhance total collagen neosynthesis (Fig. 2A), mainly composed of type II collagen (80%) in primary RAC. The stimulating effect of the hormone, mainly observed in the cell extract associated fraction compared to supernatant culture medium, was biphasic with a maximal peak for concentrations of 0.5 and 2 nM. As expected, incubation of the cells with TGF- β 1 resulted in a marked increase (about 175%) of [³H]proline labeling in the cell extract fraction, whereas interleukin-1 β (IL-1 β) reduced the incorporation to 50% of the control value. Next, we found that hER α 66 stimulated total cell extract and culture medium associated collagen production in RAC whereas mutated receptor hER α 46 did not induce any significant effect on both fractions (Fig. 2B). However, a weak enhancing effect of hER α 46 was observed on the total production of neosynthesized collagens. Then, we specifically investigated the effect of 17 β -E₂ on type II collagen synthesis by Western-blotting. By comparison to untreated cells, we found that 17 β -E₂ stimulated type II procollagen protein synthesis by approximately 100% (Fig. 3A) in primary RAC. In the same way, forced expression of hER α 66 induced a two-fold increase in type II collagen protein amounts whereas hER α 46 slightly enhanced these amounts by approximately 30% (Fig. 3C). In dedifferentiated chondrocytes, a low dose of 17 β -E₂ (0.01 nM) remained activator for type II procollagen production, but to a lower level compared to primary RAC, since the induction produced by the hormone was only of 22% (Fig. 3B). In contrast, for higher concentrations (0.1 nM-5 nM), 17 β -E₂ significantly decreased type II collagen amounts in a dose-dependent manner.

17 β -E₂ and its receptor hER α 66 up-regulate Col2a1 mRNAs steady-state levels in primary articular chondrocytes

Similarly to collagen neosynthesis results, the steady-state levels of *Col2a1* mRNAs were increased under 17 β -E₂ treatment in a biphasic manner (*i.e.* only doses ranging between 1 and 5 nM increased the amounts of type II procollagen transcripts) (Fig. 4A), suggesting a transcriptional control. As shown in Fig. 4B, the stimulatory effect of 17 β -E₂ was dependent on estrogen receptors. Indeed, the addition of tamoxifen, a partial antagonist of estrogen receptors, induced about 55-60% decrease of type II collagen mRNAs steady-state levels and prevented the stimulatory action of 17 β -E₂ on the transcripts levels. According to these results, we found that intermediate amounts (5-10 μ g) of hER α 66 strongly increased *Col2a1* mRNAs steady-state levels whereas higher quantity (15 μ g) of expression vector induced an approximate 30% decrease of mRNAs levels (Fig. 4C and 4D). Moreover, these last data have a similar pattern as those observed in Panel A where RAC were incubated with 17 β -E₂, indicating once again that the hormone mediates its effects on *Col2a1* gene through hER α 66.

A -266/-63-bp region of COL2A1 promoter mediates the up-regulatory effect of hER α 66 in both primary and dedifferentiated RAC

To delineate the genomic sequences involved in hER α -mediated effect, in both the promoter and/or the first intron regions of *COL2A1*, we co-transfected different *COL2A1* reporter constructs together with hER α 66 or hER α 46 expression vectors. Whatever the construct size, the transcriptional activity of the reporter gene was always found to be enhanced by hER α 66, compared to the respective controls, except for the shortest construct -63/+47 bp (Fig. 5A and 5B). Therefore, it is likely that a minimal -266/-63 bp region of *COL2A1* promoter mediates hER α 66-induced *COL2A1* transactivation in both primary and dedifferentiated RAC. Moreover, hER α 46 isoform did not significantly modify the basal expression of the reporter *COL2A1* (except for the shortest construct -63/+47 bp), indicating that hER α 66 stimulation of *COL2A1* is specific of this isoform and depends directly on AF-1 ligand-independent transactivation domain of hER α .

Then, in order to check whether ER α 66 was involved in basal transregulation of type II collagen gene, we co-transfected the pGL2-0.387 kb *COL2A1* reporter construct together with an ER α specific siRNA. ER α 66 silencing was accompanied by a 75% down-regulation of *COL2A1* transcription levels compared to control siRNA (Fig. 5C), demonstrating the central role played by ER α 66 to mediate 17 β -E₂-induction of *COL2A1* transcription in articular chondrocytes.

Additionally, since no ERE is present in the -266/-63-bp sequence of *COL2A1* and since we have identified several GC boxes binding Sp1 and Sp3 in this region, experiments were performed with mithramycin A, a binding inhibitor to GC-rich sequences. The objective of such an assay was to determine if hER α 66 effect on *COL2A1* could involve a protein/protein type of interaction with Sp1/Sp3, these latter *trans* factors binding to their proper *cis* elements. The results showed that, not only incubation of primary RAC with mithramycin A strongly decreased basal expression of *Col2a1* mRNAs but also prevented, at least in part, the 17 β -E₂-induced stimulation of type II collagen mRNAs expression (Fig. 5D). Thus, these data indicate that hER α 66 has a transactivating effect on *COL2A1*, probably through an interaction with Sp factors binding to their cognate *cis* elements.

17 β -E₂ increases the DNA binding activity of Sp1 and Sp3 to the COL2A1 proximal promoter

As previously shown in Fig. 5A/B, 17 β -E₂ and its receptor hER α 66 stimulate transcriptional activity of *COL2A1* by the -266/-63 bp region. Six specific C-Krox/Sp1/Sp3-binding sites have been characterized in this promoter region (Fig. 1). To determine the capacity of 17 β -E₂ to modulate Sp1/Sp3-binding sites activity of *COL2A1*, EMSAs were carried out with the -96/-66 and -225/-188 *COL2A1* radiolabeled oligonucleotides which were already proven to contain both one GC-rich sequence (Fig. 6C). As shown in Fig. 6A and 6B, the binding activity of Sp1/Sp3 proteins involved in the formation of the different complexes was increased by 17 β -E₂ in a biphasic manner. Indeed, the intermediate concentrations 0.1 and 1 nM induced a significant increase in the Sp1/Sp3 binding activities to -96/-66 and -225/-188 *COL2A1* radiolabeled probes whereas lower or higher doses of the hormone induced a weaker effect. These data highlight the potential for 17 β -E₂ to increase transcriptional activity of *COL2A1* by probably promoting the binding of Sp1, and to a lesser extent, of Sp3 to *COL2A1* promoter.

17β-E₂ and its receptor hERα66 increase the DNA binding activity of Sp1 and Sp3 to the COL2A1 first intron

First, to obtain additional information on the ability of 17β-E₂ and hERα66 to modify Sp1/Sp3-binding sites activity of *COL2A1*, EMSAs were also performed with the +2817/+2846 *COL2A1* radiolabeled oligonucleotide (Fig. 7C). This enhancer probe was already demonstrated to represent a high affinity binding site for Sp1/Sp3. Two retarded protein-DNA complexes were previously observed; a major one designated 'Sp1/Sp3' and another minor involving Sp3. As shown in Fig. 7A, the DNA-binding activity of Sp1 and Sp3 involved in the formation of the first complex was found to be increased by 17β-E₂ in a dose-dependent manner in primary RAC. To a lesser extent, the specific binding activity of Sp3 was also increased by the hormone as reflected by the modulation of the second 'Sp3 complex'. Moreover, a strictly similar pattern also applied for 3-passages dedifferentiated chondrocytes (Fig. 7B).

Secondly, the presence of ERα and its binding specificity in articular chondrocytes were validated by EMSAs experiments using a consensus ERE or mutated ERE probes and RAC nuclear extracts incubated or not with antibody directed against ERα (Fig. 8). As shown in Fig. 8A, forced expression of hERα66 was effective and its binding is specific as demonstrated by the addition of a molar excess of cold wild-type ERE probe that decreases the binding of hERα66. The specificity was also evidenced by using a mutated ERE probe in direct binding experiments leading to the prevention of hERα66 binding. Furthermore, addition of a hERα66 antibody provoked a huge decrease in the hERα66/probe complex, indicating that this nuclear receptor is involved in the formation of such a complex. In the same sense, hERα66 binding is increased in dedifferentiated chondrocytes under 17β-E₂ exposure and it was also specific (Fig. 8B).

Altogether, these EMSAs assays indicate that 17β-E₂ and hERα66 enhance transcription of *COL2A1* by increasing the binding activity of Sp1 and to a lesser extent of Sp3, not only to *COL2A1* promoter but also to *COL2A1* specific enhancer.

17β-E₂ increases the binding activity of the Sox proteins to the COL2A1 specific enhancer

Since IGF-I stimulatory effects on *COL2A1* transcription have been already shown by our laboratory to be mediated by an increase in DNA binding activity of Sox-9/Sox-6/L-Sox-5 to their functional *cis* elements in the enhancer of the gene, EMSAs analyses were performed using the +2353/+2415 bp (4 HMG ('High Mobility Group') binding sites) or +2383/+2415 bp (Sox-9 *cis*-elements and one HMG binding site only) probes (Fig. 9C). As shown in Fig. 9A and 9B, the binding activity of Sox-9/Sox-6/L-Sox-5 involved in the formation of the different complexes was found to be increased by 17β-E₂ in primary articular chondrocytes as well as in dedifferentiated chondrocytes. By contrast to transient transfection data obtained with reporter construct pGL2-3.316 kb, these last results suggest that Sox-9/Sox-6/L-Sox-5, as well as the *COL2A1* enhancer region, might also participate in the anabolic effect of 17β-E₂ on *COL2A1* in primary and dedifferentiated chondrocytes since the hormone significantly increases their DNA-binding activity to this region.

Sp1, Sp3 or Sox-9 siRNAs prevent hER α 66-induced stimulation of Col2a1 gene expression

To finally demonstrate that Sp1, Sp3 and Sox-9 proteins are required for hER α 66-induced up-regulation of type II collagen expression, we knocked-down their expression by siRNAs experiments. First, hER α 66 produced a ~3-fold increase in type II collagen mRNAs steady-state levels under control and 17 β -E₂-treated conditions (Fig. 10A and 10B). Next, we verified the siRNAs efficiency to silence Sp1, Sp3 and Sox-9 expression by RT-PCR analysis (Supplemental Fig. 1A). As expected, cell transfection with Sp1 siRNA produced a decrease of about 65% of Sp1 mRNAs levels in the control and 17 β -E₂-treated samples. In parallel, endogenous Sp3 and Sox-9 silencing was accompanied by an important down-regulation of Sp3 and Sox-9 mRNAs levels (about 75% in presence of 17 β -E₂ and 90% in its absence). Then, the effect of Sp1, Sp3 and Sox-9 silencing on hER α 66-induced activation of *Col2a1* expression was evaluated (Fig. 10A and 10B). Our data demonstrate that Sp1, Sp3 and Sox-9 siRNAs inhibit hER α 66-induced stimulation of type II collagen mRNAs steady-state levels, in presence or not of 17 β -E₂, providing further evidence that these factors play a central role to mediate hER α 66 stimulation of *COL2A1* transcription in articular chondrocytes. Additionally, the efficiency of hER α 66 overexpression in RAC was effective (Supplemental Fig. 1B), in agreement with previous experiments (Fig. 4C).

Sp1 interacts with ER α 66 and Sp3 in primary articular chondrocytes

Since ER α 66 appears as a key regulatory factor in the modulation of DNA-binding activity of Sp *trans* factors to *COL2A1*, we therefore investigated the potential protein-protein interactions between these factors by immunoprecipitation (IP) experiments using an anti-Sp1 antibody. First, ER α 66 was found to physically interact with Sp1, independently of the presence of 17 β -E₂ (Fig. 11A). Furthermore, Sp1 was also co-immunoprecipitated with Sp3 (Fig. 11Bi and 11Bii) in the same conditions. Western blots were carried out with an anti-Sp1 antibody and a negative IgG, as positive and negative controls of the assay, respectively (Fig. 11C and 11D). Additionally, nuclear extracts bound to pre-cleared protein A-Sepharose beads, protein A-Sepharose beads incubated with an anti-Sp1 antibody in absence of nuclear extracts, and finally, protein A-Sepharose beads incubated with nuclear extracts in absence of anti-Sp1 antibody were also loaded on SDS-PAGE gel as a supplementary control of antibodies specificity (Fig. 11Bii). All together, these data strongly support the hypothesis that ER α 66 can regulate type II collagen expression by physically interacting with a heteromeric Sp1/Sp3 complex and therefore, modulating Sp1/Sp3 DNA-binding activity to *COL2A1*.

*ER α 66, Sp1, Sp3 and Sox-9 proteins interact and bind to Col2a1 promoter *in vivo**

Computer sequence analysis of *COL2A1* has revealed that the promoter region did not contain ERE binding sites (data not shown). Therefore, in order to confirm our *in vitro* data and to determine if ER α 66 was effectively implicated in the regulation of *COL2A1* by 17 β -E₂, we further clarified ER α 66 involvement by ChIP assays. Experimental results demonstrated for the first time that, despite the absence of ERE binding sites, ER α 66 can be recruited *in vivo* onto the *Col2a1* short promoter in primary and dedifferentiated articular chondrocytes (Fig. 12A and 12B). Similar amounts of ER α 66 seem to be recruited onto the promoter both in control and

17 β -E₂-treated conditions. As expected, Sp1 and Sp3 factors also bind to *Col2a1* promoter, confirming our previous work . Moreover, although type II collagen gene promoter does not contain HMG-like binding sites, we demonstrated that Sox-9 was able to bind indirectly to *Col2a1* promoter in primary RAC, *via* protein-protein interactions with Sp1/Sp3 (this study and reference) and/or changes in spatial conformation/folding between the intronic enhancer and the promoter of the gene (Fig. 13). The PCR primers used in ChIP assays map the -119/+52 bp region of *COL2A1* promoter, including three specific Sp *cis*-elements (-119/-112 bp, -81/-74 bp and -41/-33 bp).

To further demonstrate if an interaction between ER α 66 and these three *trans* factors could be effective on *Col2a1* promoter, Re-ChIP assays were performed using an anti-ER α antibody. As shown in Fig. 12D, Sp1, Sp3 and Sox-9 were always recruited onto the *Col2a1* promoter after specific protein interaction with ER α 66 receptor. When the dedifferentiated chondrocytes are incubated in the presence of 17 β -E₂, although Sp1 was still bound to the *Col2a1* promoter in the same amounts, it seems that lower amounts of Sp3 and Sox-9 interact with this sequence compared to the control conditions. These novel findings strongly suggest that an ER α 66/Sp1/Sp3/Sox-9 heteromeric complex formation could be necessary to mediate the stimulatory effect of 17 β -E₂ on type II collagen gene expression (Fig.13).

*ER α 66, Sp1, Sp3 and Sox-9 proteins interact and bind to Col2a1 first intron *in vivo**

As previously suggested in EMSAs experiments carried out with *COL2A1* first intron probes (Fig. 7 and Fig. 9), a multimeric complex composed of ER α 66/Sp1/Sp3/Sox-9/L-Sox-5 and Sox-6 transcription factors could interact on the *COL2A1* enhancer region to mediate 17 β -E₂-induced *COL2A1* transactivation. Therefore, in order to validate our *in vitro* hypothesis and to determine whether these transcription factors were effectively able to bind *in vivo* to *Col2a1* specific enhancer, we performed ChIP assays in primary chondrocytes using primers mapping the +2383/+2611 bp region of *COL2A1* first intron. This region includes a Sox-9 *cis*-element (+2384/+2404 bp), one HMG binding site (+2388/+2394 bp) and one Sp1/Sp3 binding sequence (+2440/+2485 bp) but does not harbor ERE *cis*-sequence. After PCR amplification, a 229 bp fragment was observed in samples that were immunoprecipitated with anti-Sp1, anti-Sp3, and anti-Sox-9 antibodies, demonstrating that these factors are recruited on endogenous +2383/+2611 bp region of *Col2a1* (Fig. 12C). Furthermore, we demonstrated, for the first time, that despite the absence of ERE *cis*-sequences, ER α 66 is also recruited *in vivo* onto the *Col2a1* enhancer in articular chondrocytes.

As *COL2A1* does not contain any ERE region, ER α 66 necessarily interacts with the +2383/+2611 bp *Col2a1* enhancer in an indirect way. To identify what protein partners could be involved in the ER α 66 recruitment, we performed Re-ChIP experiments using an anti-ER α antibody. Our data showed that ER α 66 was bound indirectly to *Col2a1* enhancer through protein-protein interactions with Sp1, Sp3 and Sox-9 transcription factors in primary as well as dedifferentiated articular chondrocytes (Fig. 12D). As expected, and since *COL2A1* enhancer region does not represent a binding site for RNA polymerase II, even though some molecules of RNA polymerase II are transcribing the gene, ER α 66 does not interact with this enzyme. These results suggest that ER α 66 acts in concert with Sp1, Sp3 and Sox-9 transcription factors to bind the +2383/+2611 bp region of *Col2a1* enhancer *in vivo*.

p300 is also involved in the regulation of Col2a1 transcription by ER α 66

Presumably, the ER α 66 binding to Sp and Sox proteins induces the recruitment of co-regulatory proteins required for *transactivation*. Nevertheless, no identified hER α 66 co-regulatory proteins have been characterized in articular chondrocytes. To further investigate whether hER α 66 co-activators can occupy the same *Col2a1* promoter/enhancer together as part of a complex, we performed a sequential chromatin immunoprecipitation (Re-ChIP) assay using primers mapping the -119/+52 bp *COL2A1* promoter and +2383/+2611 bp enhancer regions. Chromatin from both primary and dedifferentiated RAC was first immunoprecipitated with an anti-ER α antibody and then with a second antibody directed against p300. Our results clearly indicate that ER α 66 and p300 are present as a complex on the *Col2a1* promoter and enhancer (Fig. 12E). In addition, it seems that 17 β -E₂ increases the protein interactions between ER α 66 and p300 co-activator on both *Col2a1* promoter and enhancer, supporting the stimulatory role of this hormone on *COL2A1* transcription.

Taken together, these results support a pivotal role for Sp1, Sp3 and Sox-9 proteins in indirect ER α 66 recruitment on *Col2a1*, and strongly suggest that up-regulation of type II collagen by 17 β -E₂/ER α 66 complex is mediated by these transcription factors which interact with euchromatin associated co-factors such as p300 on both enhancer and promoter regions of the gene.

Discussion

In the degenerative pathologies of cartilage such as OA, alteration of type II collagen expression is a critical step leading to the loss of differentiated articular chondrocyte phenotype. From epidemiological and biochemical studies, there is already a substantial evidence for a role of estrogens in cartilage matrix homeostasis. Nevertheless, these studies still do not identify molecular mechanisms by which articular chondrocytes or synoviocytes might be directly impacted by low levels of 17β -E₂.

The main novel findings of the present study were that ER α 66-induced activation of *COL2A1* transcription is mediated by Sp1/Sp3 together with Sox-9 and euchromatin associated factors such as p300, and that these factors are recruited *in vivo* both to the first intron specific enhancer and to the promoter region, the two major regulatory regions of this gene. We particularly investigated and compared the effects mediated by 17β -E₂ and its receptor ER α 66 on type II collagen expression in primary and dedifferentiated articular chondrocytes. In view of the contradictory reports concerning the action of the hormone on the ECM components, we first focused on the biological effect of 17β -E₂ on type II collagen production in chondrocytes. Our results demonstrate that 17β -E₂ stimulates type II collagen neosynthesis and *Col2a1* mRNAs steady-state levels in primary RAC, suggesting that 17β -E₂ acts at the transcriptional level through a genomic pathway mediated by ER α 66. Furthermore, because of a possible autocrine TGF- β stimulation in mediating 17β -E₂ activity on type II collagen, we have evaluated the dose-response effect of 17β -E₂ on the gene expression of TGF- β 1 and TGF- β type II receptor (T β RII), known as some of the major components of the TGF- β system which play key roles in the physiopathology of articular chondrocytes. 17β -E₂ at concentrations ranging from 0.01 to 5 nM is not able to modulate the steady-state amounts of the transcripts encoding *TGF- β 1* and *T β RII* (data not shown), whereas this estrogen enhances the *Col2a1* mRNA amounts between 1 and 5 nM. These results suggest that eventhough 17β -E₂ was demonstrated in other cell models to induce TGF- β expression that could in turn modulate target genes expression, the observed induction of type II collagen in our study does not seem to be mediated through autocrine stimulation of TGF- β in articular chondrocytes.

In a second time, because of a putative 17β -E₂ genomic action mediated by ER α 66, we focused on the transcriptional action of this receptor on *COL2A1* regulation. The present data revealed that hER α 66-induced stimulation of *COL2A1* activity is mediated by the -266/-63 bp promoter region. From a transcriptional point of view, nucleotide sequence analysis of this promoter region revealed six C-Krox/Sp1/Sp3-binding sites ; in particular two of them were specific for Sp proteins (-119/-112 bp and -81/-74 bp). Our particular interest for hER α 66 function in articular chondrocytes comes from the fact that this receptor has been previously described as a partner of Sp1, a key *transactivator* of *COL2A1*, in several different cell lines . Indeed, the interaction of hER α 66 with other transcription factors such as AP-1, NF- κ B and Sp1 which, in turn, bind their cognate DNA elements, modulates gene expression and transcription factors activity by stabilizing DNA-protein complexes and/or recruiting co-activators . Our data established that hER α 66 interacts physically with Sp1 in chondrocytes. This is in agreement with the observations of Porter *et al.* who showed that the major site of interaction of hER α 66 with Sp1 protein is associated with the C-terminal DNA-binding domain of Sp1, which is a region within Sp1 that can also bind a multitude of other transcription factors, including steroid hormone receptors such as progesterone or androgen receptors . In addition, hER α 66/Sp1 complex can activate transcription through a consensus GC-rich Sp1 binding site in transient

transfection studies in MCF-7 human breast cancer cells, and this response is also observed with hER α 66 variants lacking the DNA-binding domain .

In our cellular model, we demonstrated that ER α 66 increases the DNA binding activity of Sp1 and, to a lesser extent, of Sp3 to the *COL2A1* promoter and enhancer, in both differentiated and dedifferentiated chondrocytes. Interestingly, in primary RAC, we also found that 17 β -E₂ increases significantly Sp1 protein levels in a biphasic manner without affecting Sp3 protein expression, except for a 10 nM concentration (Supplemental Fig.2). Similar results were observed in dedifferentiated RAC for Sp1 protein levels whereas protein expression of long (110 kDa) and short (70 kDa) Sp3 isoforms is significantly reduced, in a dose-dependent manner, following 17 β -E₂ treatment. These results indicate therefore that ER α 66 increases the Sp1/Sp3 ratio; which is in accordance with the positive effect of 17 β -E₂ on type II collagen expression levels at low or medium-range concentrations. For high concentration treatment, it is possible that the strong inhibition of Sp1 expression by 17 β -E₂ while Sp3 expression is more slightly reduced, may lead to a reduction in the Sp1/Sp3 ratio and therefore to a suppression of the stimulatory effect on type II collagen expression. This ‘dose-related effect’ may be due in part to the ability of 17 β -E₂ to modulate differentially Sp1 and Sp3 protein levels in articular chondrocytes. Indeed, Sp1/Sp3 modulation has already been shown as a critical parameter for the regulation of *COL2A1* transcription: for instance, a decrease of Sp1/Sp3 ratio is required to mediate IL-1 β , interleukin-6 and TGF- β 1 inhibition of *COL2A1* transcription in RAC . So far, interactions of ER α 66 with other Sp proteins different from Sp1 have not been well characterized; however, ER α 66 interacts with multiple domains of Sp3. Interestingly, the interacting domains of both proteins are different from those previously observed for interactions between Sp1 and hER α protein . Thus, the ability of ER α 66 to differentially modulate DNA-binding activity of these Sp proteins could be explained, in part, by the capacity of ER α 66 to bind different domains of Sp proteins. Furthermore, the present work, together with previous results from our laboratory , established that Sp1 and Sp3 proteins interact each other in chondrocytes. Taken together, these data strongly suggest that a heteromeric Sp1/Sp3/ER α 66 complex could mediate the *transactivating* effect of 17 β -E₂ on *COL2A1* promoter. These results are in agreement with those obtained by Schultz *et al.* who reported that hER α 66 confers estrogen responsiveness to the progesterone gene by enhancing Sp1 interaction with a ‘GC box’ in the -80/-34 bp region of the human progesterone gene.

By ChIP assays, we showed for the first time that ER α 66 indirectly binds to -119/+52 bp sequence of the *Col2a1* promoter in primary or dedifferentiated chondrocytes. Higgins *et al.* showed that hER α 66 is constitutively associated with 17 β -E₂-responsive GC-rich promoter elements that also bind Sp1, Sp3 and Sp4 factors. We demonstrated here the DNA binding of ER α 66 in combination with Sp1 and Sp3 factors to the -119/+52 bp promoter region of *COL2A1*, which includes three specific Sp *cis*-elements (-119/-112 bp, -81/-74 bp and -41/-33 bp). Thus, these ChIP data combined with transient transfection experiments of *COL2A1* reporter vectors indicate that the two upstream Sp binding sites mediate the-hER α 66 *transactivating* effect in both primary and dedifferentiated chondrocytes. Besides, despite the absence of HMG-like binding sites in type II collagen gene promoter, Sox-9 also binds indirectly to the -119/+52 bp *Col2a1* region in primary RAC (this study and reference). This transcription factor was demonstrated to be an activator of *COL2A1* transcription . Sox9 is co-expressed with type II collagen during chondrogenesis in the mouse and in cultured chondrocytes, and has been shown to be absolutely essential for early events in chondrocyte differentiation and for expression of

the cartilage-specific matrix genes in human articular chondrocytes . In addition, it was recently demonstrated through the development and use of mice misexpressing Sox-9 specifically in hypertrophic chondrocytes that Sox-9 is an important negative regulator of cartilage vascularisation and endochondral ossification .

Concerning the enhancer region, we reported for the first time an indirect interaction between ER α 66 and the +2383/+2611 *Col2a1* sequence in both primary and dedifferentiated chondrocytes. Our EMSAs analysis clearly indicated that 17 β -E₂ increased Sox-9, Sox-6 and L-Sox-5 DNA-binding to their *cis*-elements in the first intron of *COL2A1*, strongly suggesting that this region was involved in the up-regulation of *COL2A1* by the hormone. Moreover, Re-ChIP experiments demonstrated that ER α 66/Sp1, ER α 66/Sp3 and ER α 66/Sox-9 complexes were all recruited onto the *Col2a1* promoter and enhancer in the presence or the absence of 17 β -E₂. In dedifferentiated RAC, Sp3 recruitment to the *Col2a1* gene seemed to be decreased after interaction with ER α 66 following exposure to the hormone. This modulation could be a way by which ER α 66 may finely regulate the DNA-binding activity of the well-known Sp1/Sp3 heteromer and favor Sp1 recruitment to the detriment of Sp3 leading to the *transactivation* of *COL2A1*. Finally, from our siRNAs experiments, we deduced that inhibition of Sp1, Sp3 or Sox-9 expression was sufficient to prevent hER α 66-induced stimulation of *Col2a1* mRNA levels. **Interestingly, some of our previous experiments revealed that Sp1 is an activator of Sox9 DNA binding activity and Sox9 gene transcription in chondrocytes, but reciprocal combination is also effective, i.e. Sox9 increases the transcription of Sp1 gene .** Therefore, considering that transcription factors are known to act in concert, it is conceivable that 17 β -E₂ *in vivo* effect could be mediated by a bridging complex, composed of ER α 66, Sp1, Sp3, Sox-9 and certainly of several other transcription factors, which could establish a physical link between the two main *transregulatory* regions of the gene, i.e. the proximal promoter and the first intron, and consequently, may facilitate chromatin decondensation and its accessibility to the transcriptional machinery in order to initiate transcription process (Fig. 13). Indeed, a relationship between *COL2A1* promoter and first intron is required for type II collagen expression in cartilage during chondrogenesis . It has been reported that the expression of a human *COL2A1* transgene in a mouse model is governed by a 309-bp enhancer intronic fragment (+2388 to +2696 bp) and requires the presence of a 90-bp promoter region for tissue-specific expression in the developing cartilaginous skeleton . Hence, stimulation of the synthesis and/or binding activity by 17 β -E₂ of one of the transcription factors involved in this main molecular complex, may facilitate the formation of a 'loop structure' and would increase type II collagen gene expression in RAC.

Despite their different transcriptional functions, Sp1 and Sp3 generally compete for the same DNA-binding sites. They form homotypic and heterotypic complexes with numerous transcriptional co-regulators which determine the role of Sp proteins as either transcriptional activators or repressors. Presumably, ER α 66 binding to Sp proteins induces recruitment of co-regulatory proteins required for the *transactivation*. Thus, the mechanism proposed to explain 17 β -E₂ *transactivating* effect in chondrocytes is related to the interaction of its receptor hER α 66 with co-activators, such as steroid receptor co-activators (SRC), CREB binding protein (CBP) or p300. To date, no identified hER α 66 co-regulatory proteins have been characterized in articular chondrocytes. Nevertheless, our Re-ChIP experiments performed on *Col2a1* promoter and enhancer raised the hypothesis that p300 is the major co-activator of ER α 66 in both primary and dedifferentiated RAC. ER α 66-p300 interactions on *Col2a1* are significantly increased following

17 β -E₂ stimulation, which may contribute to *COL2A1* transactivation. Indeed, p300 acts as a bridging factor to form multicomponent complexes and connects DNA-binding transcription factors to the transcription machinery. Furthermore, p300 is known to interact directly with the AF-2 domain and can potentiate the synergistic activity that results from AF-1 and AF-2 interaction by facilitating binding of TATA binding protein (TBP) on estrogen target promoters. Otherwise, p300/CBP also presents an intrinsic histone acetyltransferase activity and facilitates the action of associated transcription factors by modulating histone acetylation. For instance, p300 amplifies stimulatory effects of Sox-9 during chondrogenesis. Additionally, p300 physically binds to C-terminal activation domain of Sox-9, and acts in synergy with this one to activate *COL2A1* transcription by connecting its specific enhancer sequences with the transcription initiation complex. Thus, we may postulate without ambiguity that ER α 66 acts as a co-activator/linker in a transcription factor crosstalk between Sp/Sox proteins and other co-activators such as p300 or SRC-3 in articular chondrocytes.

As demonstrated by using the AF-1 dominant negative action of hER α 46, the transcriptional activation of human *COL2A1* by hER α 66 requires the AF-1 transactivation domain of the receptor. Moreover, preliminary studies from our laboratory using hER α 66 mutants harboring progressive deletions of A/B domain indicate that the entire AF-1 domain (*i.e.* Box1, Box2 and Box3) is required for hER α 66-induced type II collagen mRNA stimulation (Supplemental Fig. 3A and 3B). Corroborating these results, several studies clearly demonstrated the importance of AF-1 activity in the estrogenic induction of genes, as well as the requirement of AF-1 region for full hER α 66 activity. For example, the progressive deletion of the AF-1 domain of hER α 66 leads to a corresponding decrease in the activity of the MMP-13 promoter. The AF-1 domain is well characterized as the ligand independent transactivation domain of the hER α 66 and synergizes with the AF-2 domain to elicit the overall estrogen response on promoters. Nevertheless, recent data from Billon-Gales *et al.* reported that AF-1 domain of hER α 66 is completely dispensable for mediating the major atheroprotective effects of estrogens using a mouse model missing the hER α 66 A/B domains. This discrepancy between our results and this last study could be in part explained by the fact that the respective contribution of AF-1 and AF-2 to the transcriptional activity of the full-length hER α 66 varies in a promoter and cell type specific manner. As our results failed to show a stimulatory transactivity when hER α 46 expression vector is used, we can postulate that the AF-1 domain of hER α 66 probably plays the major positive regulatory role in modulating the activity of *COL2A1* promoter/enhancer.

In order to better understand the exact role of hER α 46 isoform, additional experiments were performed, where primary RAC were co-transfected with hER α 66 expression vector in combination with increasing amounts of hER α 46 expression vector. These data show for the first time that hER α 46 has the ability to repress hER α 66-induced *Col2a1* and *Sp1* gene expression in a dose-dependent manner in primary articular chondrocytes (Supplemental Fig. 4). *In vivo*, both isoforms are frequently co-expressed. In this situation, hER α 46 efficiently represses the transcription of estradiol-target genes induced by hER α 66 by suppressing AF-1 activity of full-length estrogen receptor [25]. In terms of transcription, we can postulate that hER α 46 competes with hER α 66 for its binding to Sp1 and Sox proteins on both the promoter and the first intron of *Col2a1* gene and prevents hER α 66 from binding to these factors and exerting its stimulatory effect on *Col2a1* transcription. However, since we observed a faint but significant stimulatory effect of hER α 46 on type II collagen synthesis in collagenase and Western-blot assays, a weaker

positive regulatory role can likely be assigned to AF-2 domain too. Additionally, our data reveal that the deletion of any of the functional domains of hER α 66 suppresses the positive regulatory effect of this receptor on *Col2a1* transcription, indicating that all of these functional domains are indispensable in hER α 66 action (Supplemental Fig. 3). In addition, as the transfection of hER α -deleted isoforms also decreases *Sp1* mRNA levels, this confirms that the receptor involves Sp1 in its regulation of *Col2a1* gene. Altogether, our results demonstrate that articular chondrocytes are mainly sensitive to the AF-1 function of hER α 66, however, with low permissiveness to AF-2.

Another novel and relevant finding in our study is that 17 β -E₂ as well as hER α 66 are able to increase and therefore reactivate type II procollagen expression in dedifferentiated RAC through a transcriptional control of type II collagen by increasing the DNA binding activities of Sp1 and Sox9 to their *cis* responsive elements in *COL2A1*. In fact, we previously demonstrated that these two transcription activators are able to allow recovering, at least in part, of the differentiated phenotype in dedifferentiated cells. For example, Sp1 is an activator of *COL2A1* transcription in differentiated and dedifferentiated chondrocytes, mediating at least the partial recovery of chondrocyte phenotype, once it has been lost. Besides, our previous study showed that 17 β -E₂ and hER α 66 stimulate UDP-glucose dehydrogenase gene activity in primary rabbit articular chondrocytes. Consequently, 17 β -E₂ would be not only able to reactivate type II collagen expression in dedifferentiated chondrocytes but could also elicit a cellular redifferentiation through an increased glycosaminoglycans synthesis in these cells. As stem cells used for cartilage repair seem to have a similar fate as chondrocytes that drive endochondral ossification, making the repair tissue inadequate for normal joint function, our data are therefore attractive in view of the estrogens use in articular cartilage engineering.

Preliminary studies from our laboratory indicate that changes within the respective levels of expression of hER α isoforms are likely to occur during chondrocyte dedifferentiation process (data not shown), as it already occurs in MCF-7 cell line where hER α 66/hER α 46 ratios change with the cell growth status. Recent works indicate that differences in the expression of hER α isoforms can influence gene regulation and cell growth and/or apoptosis. Altered expression of hER α 66/hER α 46 may account for differential effects of 17 β -E₂ on *COL2A1* expression and could explain the differential sensitivity of type II collagen protein to 17 β -E₂ in dedifferentiated chondrocytes where lower doses of 17 β -E₂ activate type II collagen protein production compared to primary RAC. This differential effect could also be explained by the fact that limitative quantities Sp1 and Sox-9 are present in dedifferentiated RAC and therefore high doses of 17 β -E₂ fail to mobilize supplementary quantities of such transcription factors to activate transcription more. Besides, Webb *et al.* have demonstrated that the more differentiated a cell is, the more likely it will use the AF-1 domain of hER α 66 to mediate estrogen responses, and dedifferentiated cells tend to depend more on AF-2 domain of hER α 66. Nevertheless, from a transcriptional point of view, we observed similar results of hER α 66 or hER α 46 on *COL2A1* transcriptional activity between primary and dedifferentiated chondrocytes. This is why further studies are now required to clarify the potential changes in hER α 66/hER α 46 ratio during chondrocyte dedifferentiation and OA process.

Our IP and Re-ChIP data showed that unliganded hER α 66, is associated with Sp protein, bound to *Col2a1* and addition of 17 β -E₂ does not significantly alter the ER α 66 promoter

interactions. Previous studies have confirmed that hER α 66 could interact with Sp proteins in the absence of ligand . Nevertheless, estrogens can be synthesized locally from androgens *via* aromatase suggesting that the intracrine pathway contributes, beside the known endocrine one, to the estrogens production in articular chondrocytes. This hypothesis is supported by a study of Richette *et al.* who showed that 17 β -E₂ is present in human synovial fluid from OA joints, at concentrations closely reflecting serum levels. We may postulate that estrogens produced by chondrocytes or synovial tissues, acting both as autocrine or paracrine regulators of ECM components synthesis, could have a profound effect on the development of OA; so that the increased incidence of OA in postmenopausal women might thus be explained by a decrease in local estrogen concentrations, because 17 β -E₂ has been shown to have anti-erosion properties at physiological levels.

In summary, our data further corroborate that 17 β -E₂ and its receptor ER α 66 are critical actors in *COL2A1* transcriptional regulation; making them motivating targets in order to better understand the OA dedifferentiation process and facilitate the recovery of differentiated articular cartilage in osteoarthritic chondrocytes. Such insights are needed not only to implement our basic understanding of articular cartilage biology, but also to help developing novel and improved strategies for cartilage repair and treatments for degenerative diseases such as OA. From this point of view, the use of this hormone and/or its nuclear receptor in the tissue engineering of articular cartilage could be a promising strategy in order to repair this tissue.

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Disclosure of potential conflict of interest

The authors declare that they have no conflict of interest.

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Figure legends

Figure 1: Schematic representation of the human COL2A1 gene. Localization of binding sites of some of the transcription factors which have been characterized to interact with the promoter or the enhancer region (in the first intron) of COL2A1. CIIS: Type II collagen silencer; TBP, TATA Binding Protein; C/EBP, CCAAT Enhancer Binding Protein; NFYA, Nuclear transcription Factor Y α .

Figure 2: Effect of 17 β -E₂, hER α 66 and hER α 46 on collagen neosynthesis in primary chondrocytes. **A**, Collagen radiolabeling assay on both medium and cell extract fractions from primary RAC cultured for 24 h in the presence or absence of TGF- β , IL-1 β or 17 β -E₂. **B**, Collagen radiolabeling assay on primary RAC transiently transfected with hER α 66 or hER α 46 cDNA. The values, normalized to the amount of total protein, were expressed as percentage of the control (absence of 17 β -E₂ (**A**) or empty pCR3.1 plasmid (**B**)) and represent the mean \pm S.D. of three (**A**) and four (**B**) independent experiments performed in triplicate. Statistically significance was assessed by using the Student's *t* test and differences were set at ***p<0.001, **p<0.01 and *p<0.05.

Figure 3: Effect of 17 β -E₂, hER α 66 and hER α 46 on type II collagen protein expression in primary and dedifferentiated RAC. **A**, Primary chondrocytes were treated with increasing concentrations of 17 β -E₂ for 24 h and type II collagen expression was assayed using Western-blotting analysis of whole cell extracts. β -actin was used as a loading control. The same experiment as in **A** was performed on dedifferentiated articular chondrocytes (**B**) or on primary RAC transiently transfected with hER α 66 or hER α 46 expression vectors (**C**). Histograms represent the relative expression of type II procollagen normalized to β -actin protein signal and estimated after densitometric analysis of the blots using the Image J software. Results are representative of two (**B**) and three (**A** and **C**) independent experiments.

Figure 4: Effect of 17 β -E₂ and hER α 66 on the steady-state levels of type II collagen mRNAs in primary chondrocytes. **A**, Real-time RT-PCR analysis of Col2a1 mRNAs expression using total RNAs isolated from primary RAC, treated or not with increasing concentrations of 17 β -E₂ for 24 h. Results were normalized to 18S rRNAs. **B**, Primary RAC were treated or not for 24 h with tamoxifen (Tam.), a partial antagonist of estrogen receptors in our model, and assayed for real-time RT-PCR analysis. **C**, Articular chondrocytes were transiently transfected with increasing amounts of hER α 66 expression vector and Col2a1 expression was measured by real-time RT-PCR. Results were normalized to glyceraldehyde 3-phospho dehydrogenase (GAPDH) mRNAs. **D**, Verification of hER α 66 overexpression using specific primers for the long isoform of human estrogen receptor. Results are representative of three independent experiments and values are the means \pm S.D. of triplicate samples. Statistically significance was assessed by using the Student's *t* test and differences were set at ***p<0.001, **p<0.01 and *p<0.05.

Figure 5: Effect of 17 β -E₂, hER α 66, hER α 46 and ER α siRNA on the transcription activity of human COL2A1 in cultured chondrocytes. Luciferase assays on primary (**A**) or 3-passages dedifferentiated (**B**) chondrocytes transiently transfected with different COL2A1 reporter constructs together with either hER α 66 (wild type) or hER α 46 (mutated isoform).

Transcriptional activities of each construct were corrected for protein amounts. **C**, Luciferase assays on primary chondrocytes transiently transfected with 10 µg of pGL2-0.387 kb reporter construct (covering the -266/+121 bp sequence of *COL2A1*) together with 2 µg of ERα siRNA (siERα). Results represent the mean ± S.D. of triplicate samples. **D**, Primary RAC were incubated for 24 h with 17β-E₂ (1 nM), mithramycin A (Mith., 100 nM) or both and type II collagen mRNA expression was assayed by RT-PCR as described under Materials and Methods. Values are the means of two independent experiments performed in triplicate. CIIS, type II collagen silencers. Statistical significance was assessed by using the Student's *t* test and differences were set at ****p*<0.001, ***p*<0.01 and **p*<0.05.

Figure 6: 17β-E₂ increases the DNA binding activity of Sp1 and Sp3 to the COL2A1 promoter.

A, Electrophoretic mobility shift assays (EMSAs) were performed using the 5' end-radiolabeled -96/-66 *COL2A1* probe, incubated with nuclear extracts (NE) from primary RAC treated with increasing concentrations of 17β-E₂ for 24 h. Negative controls lacking nuclear extracts are shown (probe). Sp1/Sp3 and Sp3 protein-DNA complexes are indicated by an arrow. **B**, EMSAs were performed as described in **A**, using the 5' end-radiolabeled -225/-188 *COL2A1* probe. **C**, Sequences of the -96/-66 and -225/-188 *COL2A1* radiolabeled probes used. Sp1/Sp3 binding site is highlighted in bold characters.

Figure 7: Effect of 17β-E₂, hERα66 and hERα46 on the DNA binding activity of Sp1 and Sp3 to the COL2A1 enhancer.

A, Electrophoretic mobility shift assays (EMSAs) were performed using the 5' end-radiolabeled +2817/+2846 *COL2A1* probe, incubated with nuclear extracts (NE) from primary RAC transfected with either hERα66 or hERα46 expression vectors or treated with increasing amounts of 17β-E₂ for 24 h. **B**, 3-passages dedifferentiated RAC were incubated with increasing concentrations of 17β-E₂ for 24 h and resulting nuclear extracts were analyzed by EMSA as described in **A**. Negative controls lacking nuclear extracts are shown (probe). Sp1/Sp3 and Sp3 protein-DNA complexes are indicated by an arrow. Nuclear extracts from MCF-7 cell line were also used as control. **C**, Sequence of the +2817/+2846 *COL2A1* radiolabeled probe used. Sp1/Sp3 binding site is highlighted in bold characters.

Figure 8: A, ERα66 binds specifically to an ERE consensus probe in primary articular chondrocytes.

EMSA analysis was carried out with the nuclear extracts from primary RAC transfected with either 10 µg of the expression vector hERα66 or hERα46. Double-stranded radiolabeled wild-type ERE consensus or mutant ERE probes were incubated with nuclear extracts (10 µg) in the presence or absence of ERα antibody (4 µg) or molar excesses (× 100) of wild type nonlabeled ERE probe (cold probe). Negative controls lacking nuclear extracts are shown (probe). ERα-DNA complexes are indicated by an arrow. Nuclear extracts (NE) from MCF-7 cell line (positive cells for estrogen receptors hERα) were also used as control. **B, 17β-E₂ increases ERα DNA-binding to an ERE consensus probe in dedifferentiated chondrocytes.** Three-passages dedifferentiated RAC were incubated with 17β-E₂ for 24 h at concentrations ranging from 0 to 10 nM and resulting nuclear extracts were analyzed by EMSA as described in **A**.

Figure 9: 17β-E₂ enhances the binding activity of the Sox proteins to the +2353/+2415 and +2383/+2415 sequences of the COL2A1 enhancer.

A and B, EMSA analysis was carried out

with the 5' end-radiolabeled +2353/+2415 (four Sox DNA binding sites) or +2383/+2415 (two Sox DNA binding sites) *COL2A1* double-stranded probes incubated with nuclear extracts from primary (A) or dedifferentiated (B) articular chondrocytes treated with increasing amounts of 17β -E₂ for 24 h. Protein-DNA complexes are indicated by an arrow. C, Sequences of the +2353/+2415 and +2383/+2415 *COL2A1* radiolabeled probes used. HMG binding sites are highlighted in bold characters.

Figure 10: *Sp1*, *Sp3* and *Sox-9* siRNAs prevent the *hER α 66*-induced stimulation of type II collagen mRNA expression. Primary RAC were transfected with 2 μ g of siRNAs directed against *Sp1*, *Sp3* or *Sox-9* (respectively siSp1, siSp3 and siSox-9) in combination with 5 μ g of *hER α 66* expression vector. After an overnight transfection period, the cells were incubated for 24 h in the presence (B) or absence (A) of 17β -E₂. At the end of the experiment, RT-PCR analysis of *Col2a1* mRNA expression was performed and expression of type II collagen transcripts was normalized to *GAPDH* mRNA. Results are representative of two independent experiments and each represents the mean \pm S.D. of triplicate samples. Statistically significant differences relative to the controls pCR3.1 plasmid (denoted by *) or to *hER66* expression vector (denoted by #) were obtained by the Student's t test (**p<0.001, *p<0.01, ### p<0.001 and ###p<0.01).

Figure 11: *ER α 66* and *Sp3* transcription factors interact with *Sp1* in the nucleus of primary articular chondrocytes. Nuclear extracts from primary chondrocytes cultured in presence or absence of 17β -E₂ for 24 h were submitted to immunoprecipitation (IP) procedure with anti-*Sp1* antibody (IP *Sp1*). Immunoprecipitated complexes were incubated 2 h with protein A-Sepharose beads and then, submitted to Western-blotting (W.B.) in order to detect *ER α* (A) and *Sp3* (Bi) proteins. Twenty μ g of nuclear extracts, which were not submitted to IP (W.B. w/o IP), were also loaded onto SDS-PAGE gels. Bii, As a supplementary control of the specificity, a Western-blotting experiment using an anti-*Sp3* antibody was performed on nuclear extracts bound to pre-cleared protein A-Sepharose beads, on protein A-Sepharose beads incubated with an anti-*Sp1* antibody in absence of nuclear extracts and finally, on protein A-Sepharose beads incubated with nuclear extracts in absence of anti-*Sp1* antibody. Positive and negative controls of the experiment were realized by immunoprecipitating *Sp1* and submitting immunoprecipitated complexes to Western-blotting using an anti-*Sp1* antibody (C, positive control) and IgG (D, negative control).

Figure 12: *ER α 66*, *Sp1*, *Sp3*, *Sox-9* and *p300* interact in vivo on the *Col2a1* promoter and enhancer. Chromatin immunoprecipitation (ChIP) assays were performed on primary (A, C) or 3-passages dedifferentiated (B) rabbit articular chondrocytes (RAC) incubated in presence or absence of 1 nM 17β -E₂ for 24 h, according to the manufacturer's instructions. Resulting DNA was submitted to PCR analysis (40 cycles) using specific primers flanking the -119/+52 bp *Col2a1* region (A, B) or the +2383/+2611 bp *Col2a1* region (C). PCR products were separated on a 2.5% agarose gel and visualized by UV-illumination following ethidium bromide staining. As positive control, the same primers were used on the genomic DNA (*Input*) and DNA samples immunoprecipitated with anti-RNA polymerase II antibody (*RNA pol. II*). Non specific immunoglobulin antibody (*IgG*) was used as negative control. D and E, In order to perform Re-ChIP experiments, the sheared chromatin isolated from primary or dedifferentiated chondrocytes was first immunoprecipitated with 6 μ g of antibody directed against *ER α* , followed by a second

IP using antibodies raised against Sp1, Sp3 and Sox-9 (**D**) or p300 (**E**). The released DNA, treated with proteinase K, was amplified by PCR (35 cycles) using specific primers flanking -119/+52 bp *Col2a1* region or +2383/+2611 bp *Col2a1* region and visualized as described above. IP, immunoprecipitation; C, control.

Figure 13: Schematic representation of 17β -E₂ and hER α 66 genomic pathway involved in the up-regulation of type II collagen gene in articular chondrocytes. *COL2A1* does not contain ERE binding sites, so that hER α 66 interacts with *COL2A1* promoter in a non classical genomic pathway involving protein-protein interactions with transcription factors Sp1, Sp3 and Sox-9. Some co-activators such as p300 are also involved in the *transactivation* process of *COL2A1*.