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The cellular response to transglutaminase-cross-linked collagen

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Abstract

Collagen, type I, is a highly abundant natural protein material which has been cross-linked by a variety of methods including chemical agents, physical heating and UV irradiation with the aim of enhancing its physical characteristics such as mechanical strength, thermal stability, resistance to proteolytic breakdown, thus increasing its overall biocompatibility. However, in view of the toxicity of residual cross-linking agents, or impracticability at large scales, it would be more useful if the collagen could be cross-linked by a milder, efficient and more practical means by using enzymes as biological catalysts.

We demonstrate that on treating native collagen type I (from bovine skin) with both tissue transglutaminase (TG2; tTG) and microbial transglutaminase (mTG; *Streptovorticillium mobaraense*) leads to an enhancement in cell attachment, spreading and proliferation of human osteoblasts (HOB) and human foreskin dermal fibroblasts (HFDF) when compared to culture on native collagen. The transglutaminase-treated collagen substrates also showed a greater resistance to cell-mediated endogenous protease degradation than the native collagen. In addition, the HOB cells were shown to differentiate at a faster rate than on native collagen when assessed by measurement of alkaline phosphatase activity and osteopontin expression.

Keywords: Bioactivity; Biocompatibility; Collagen; Fibroblasts; Osteoblasts; Tissue engineering

1. Introduction

Collagen is a very popular biomaterial due to its biocompatibility, i.e. the ability to support cell adhesion and proliferation. It is also biodegradable and only weakly antigenic—able to persist in the body without developing a foreign body response that could lead to its premature rejection [1]. The replacement of skin with artificial collagen–GAG matrices has been investigated since the early 1980s and is now in clinical use [2,3]. The primary reason for the usefulness of collagen in biomedical applications is that collagen can form fibres with extra strength and stability through its self-

aggregation and in vivo cross-linking [4]. Unfortunately, collagen, like many natural polymers, once extracted from its original source and then reprocessed, suffers from weak mechanical properties, thermal instability and ease of proteolytic breakdown. To overcome these problems, collagen has been cross-linked by a variety of agents—a subject of much recent research to find methods of preventing rapid absorption by the body [4]. However, these methods suffer from the problem that the residual catalysts, initiators and unreacted or partially reacted cross-linking agents used can be toxic or cause inflammatory responses if not fully removed or, simply, not cost-effective or practical at the large scale [5–7]. As a consequence, research continues to find alternative methods to stabilise collagen which are *natural*, milder, efficient and more practical.

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1 Transglutaminases (EC 2.3.2.13) are a group of
2 enzymes that can catalyse several types of post-transla-
3 tional modifications to proteins. The most important of
4 these reactions results in the cross-linking of peptides or
5 proteins to form multimers via a $\epsilon(\gamma$ -glutamyl)lysine
6 linkage using the side chains of lysine and glutamine
7 residues. Transglutaminases are also able to covalently
8 attach primary amine containing compounds to peptide
9 bound glutamine, facilitating modification of the phys-
10 ical, chemical and biological properties of proteins [8].
11 For these reasons, transglutaminases have been utilised
12 by the commercial sector in many different processes
13 and have attracted much attention from the research
14 community [9]. Microbial transglutaminase has been
15 used to cross-link gelatin matrices to further increase
16 their strength [10] and, also, to incorporate cell adhesion
17 factors within the gel matrix, resulting in an enhance-
18 ment of cell proliferation [11].

19 Interestingly, a novel component of the cell/tissue
20 response to cell damage and stress is tissue transgluta-
21 minase (tTG), a Ca^{2+} -dependent mammalian form of
22 the enzyme, which modulates cell-matrix interactions,
23 tissue stability and a variety of other cell functions
24 [12,13]. The entire tissue repair process is regulated by
25 the interaction of cells with the surrounding extracel-
26 lular matrix (ECM), ensuring cell adhesion, survival and
27 proliferation [14,15]. To date, the cross-linking function
28 of tTG in the ECM leading to ECM stabilisation/
29 remodelling has been identified in a number of
30 biological processes important for tissue repair [12]: in
31 addition, at least three of the nine genes so far
32 characterised are thought to be naturally involved in
33 the wound healing response process [see review, 16].

34 The aim of this study was to investigate the use of the
35 two different transglutaminases; the mammalian (tTG;
36 TG2; TG-2; isolated from guinea pig liver) and the
37 microbial enzyme (mTG; isolated from *Streptovorticil-*
38 *ium mobaraense*) in the modification of collagen type I
39 with the view to investigate potential application as a
40 biocompatible natural polymer for use in soft and hard
41 tissue repair.

42 2. Materials and methods

43 All water used was deionised using an Elgastat System
44 2 water purifier (ELGA Ltd., UK) and a Milli-Q water
45 purifier (Millipore Waters, UK). All chemicals were
46 purchased from Sigma-Aldrich, Poole, UK, unless
47 otherwise stated. Sterile preparation of stock solutions
48 and chemicals were performed either by filtration
49 through a 0.22 μm Whatmann sterile filter and/or
50 autoclaving at 121 $^{\circ}\text{C}$ at 1 bar for 1 h.

51 2.1. Cell culture

52 Human osteoblast (HOB) cells, isolated from explants
53 of trabecular bone dissected from femoral heads
54 following orthopaedic surgery as previously described
55 [17] were kindly supplied by Professor S. Downes and
56 Dr. S. Anderson (School of Biomedical Sciences,
57 University of Nottingham) and used during this
58 investigation. Human foreskin dermal fibroblast
59 (HFDF) cells isolated from human neonatal foreskin
60 were also used. Both cell lines were used during their
61 low-passage number, ranging from 11 to 15 passages.
62 Cell lines were cultured and maintained, in vitro, as
63 monolayers in T-flasks using DMEM, supplemented
64 with 10% heat-inactivated (56 $^{\circ}\text{C}$ for 1 h) FCS, 1% non-
65 essential amino acids and 2 mM L-glutamine. Periodic
66 additions of 1% penicillin-streptomycin were used to
67 avoid bacterial contamination. Flasks were kept in a
68 humidified-atmosphere incubator at 37 $^{\circ}\text{C}$ and with 5%
69 CO_2 . Cells were routinely passaged and never allowed to
70 reach greater than 90% confluency at any one time. For
71 detachment, standard trypsinisation was performed
72 using 0.25% (w/v) trypsin/2 mM EDTA solution in
73 PBS solution.

74 2.2. Cell viability and proliferation

75 Cell counts and viability estimations were performed
76 using the standard trypan blue exclusion technique by
77 means of a 0.22 μm sterile filtered 0.5% (w/v) trypan
78 blue solution and a haemocytometer. Non-viable cells
79 stained blue due to the loss of their membrane integrity
80 and, hence, allowed the passage of dye into the cell.
81 Viable cells remained colourless.

82 Cell proliferation and viability were also measured
83 using the CellTiter AQ One Solution Cell Prolifera-
84 tionTM assay kit (Promega, Southampton, UK. Cat no.
85 G3580). Assays were performed, with reduced lighting,
86 simply by the addition of 20 μl of CellTiter AQ reagent
87 into the relevant samples in 100 μl of culture medium.
88 These samples were then incubated in a humidified-
89 atmosphere incubator at 37 $^{\circ}\text{C}$ and with 5% CO_2 for
90 90 min before the absorbance was read at 490 nm using a
91 SpectraFluor[®] plate reader.

92 2.3. Attachment and spreading

93 Cells were seeded on the relevant substrate at a
94 density of 625 cells/ mm^2 . After allowing cells to attach
95 and spread, they were fixed in 3.7% (w/v) paraformal-
96 dehyde, permeabilised by the addition of 0.1% (v/v)
97 Triton X-100 in PBS, before staining with May-
98 Grunwald (0.25% (w/v) in methanol) and Giemsa stains
99 (0.4% (w/v) in methanol, diluted 1:50 with water). Cells
100 were then viewed at $\times 400$ magnification using an
101 Olympus CK2 microscope. Three separate fixed-size
102

1	random fields per sample were photographed with an	57
3	Olympus DP10 digital camera. Pictures were analysed	59
5	using Scion Image™ software (Scion Corporation,	61
7	Maryland, USA). Spread cells were distinguished and	63
9	characterised based upon the presence of a clear halo of	65
	cytoplasm surrounding their nucleus as previously	67
	described [18].	
11	<i>2.4. Alkaline phosphatase (ALP) activity</i>	
13	The ALP Optimized Alkaline Phosphatase EC 3.1.3.1	
15	Colorimetric Test® kit (obtained from Sigma-Aldrich,	
17	Poole, UK. Cat no. DG1245-K) was used to quantify	
19	the ALP activity. Alkaline phosphatase hydrolyses <i>p</i> -	
21	nitrophenyl phosphate to <i>p</i> -nitrophenol and inorganic	
23	phosphate. The hydrolysis occurs at alkaline pH and the	
25	<i>p</i> -nitrophenol formed shows an absorbance maximum at	
27	405 nm. The rate of increase in absorbance at 405 nm is	
29	directly proportional to ALP activity in the sample.	
31	Samples were treated according to the manufacturers'	
33	instructions and analysed using a Beckmann DU530	
35	UV/Vis spectrophotometer.	
37	<i>2.5. Osteopontin (OPN) concentration</i>	
39	The OPN ELISA kit (obtained from CalBiochem,	
41	UK. Cat no. 499262) was used to quantify the	
43	concentration of OPN in the samples. The kit uses a	
45	polyclonal antibody to human OPN immobilised on a	
47	micro-titre plate to bind to the human OPN. The	
49	measured absorbance (450 nm) is directly proportional	
51	to the concentration of human OPN. Samples were	
53	treated according to the manufacturers' instructions and	
55	analysed using a SpectraFluor® plate reader.	
	<i>2.6. Transglutaminase</i>	
	tTG was isolated and purified from guinea pig livers	
	using a combination of anion exchange, gel filtration	
	and affinity chromatography as previously described	
	[19]. Commercial samples of TG were also used during	
	this investigation: tTG from guinea pig liver (Sigma-	
	Aldrich, Poole, UK. Cat no. T5398) and microbial	
	transglutaminase, mTG (Ajinomoto Corporation Inc.,	
	Japan), isolated from <i>Streptovorticillium mobaraense</i> , as	
	the commercially available product, Activa™ WM.	
	This required further purification steps to remove the	
	maltodextrin ingredient: briefly, the Activa™ WM was	
	dissolved in ice-cold 20 mM phosphate buffer, 2 mM	
	EDTA pH 6.0 and filtered, before being loaded onto a	
	100 ml SP-Sepharose FF column overnight at a con-	
	tinuous flow rate of 5 ml/min. The column was then	
	washed and proteins eluted, at the same flow rate, with a	
	0–1000 mM gradient of NaCl in 20 mM phosphate buffer,	
	2 mM EDTA pH 6.0. Fractions were assayed for protein	
	using the Bio-Rad DC protein assay (Bio-Rad Labora-	
	tories, Hertfordshire, UK. Cat no. 500-0120). Fractions	
	containing mTG were pooled, aliquoted, freeze dried	
	and stored at –70 °C. Before immediate use, tTG was	
	pre-treated in 2 mM DTT in 50 mM Tris buffer (pH 7.4)	
	for 10 min at room temperature to activate any oxidised	
	enzyme, before addition to a final buffered solution	
	containing 5 mM CaCl ₂ and, a minimum of 1 mM DTT in	
	Tris buffer. Typical activities for the transglutaminases	
	used in this investigation were as follows: tTG:	
	11500–13000 U/mg and mTG: 16000–25000 U/mg.	
	<i>2.7. Transglutaminase activity</i>	
	The incorporation of [¹⁴ C]-putrescine into <i>N,N</i> -	
	dimethylcasein, as described previously [20], was used	
	to assay for TG activity and monitor the effects of the	
	inhibitors. Unit of transglutaminase activity is 1 nmol of	
	putrescine incorporated per hour.	
	<i>2.8. Collagen</i>	
	Commercial calf skin collagen type I (Sigma-Aldrich,	
	Poole, UK. Cat no. C9791) was used during this	
	investigation. Native collagen samples were solubilised	
	in 0.2 M acetic acid (Fisher Scientific, Loughborough,	
	UK. Cat no. A/0400/PB17) at 4 °C with constant	
	stirring for 24 h before use. Neutralisation of the	
	collagen mixture was performed using a [5:3:2] ratio of	
	[collagen: 2 × DMEM: 0.2 M NaOH buffer] respectively	
	to a final of pH 7.2. Tissue culture plastic was then	
	covered using this collagen mix (recommended at	
	6–10 µg/cm ²) before being placed into a humidified-	
	atmosphere incubator for 12 h to allow gelation to	
	occur. In general, 50 µl of the collagen mix was added to	
	each well of a 96-well plate. Plates were used within 48 h	
	of the collagen matrix formation.	
	<i>2.9. Modified collagen by transglutaminase</i>	
	Neutralised collagen mixture was subjected to treat-	
	ment with both tTG and mTG. Samples of the	
	neutralised collagen, as described above, were treated	
	with 50–1000 µg/ml of tTG, in a reaction mix consisting	
	of 2 mM DTT and 5 mM CaCl ₂ in 10 mM Tris buffer (pH	
	7.4). Microbial enzyme was added in 10 mM Tris buffer	
	(pH 7.4). Stock solutions of: 2 mg/ml tTG and mTG, 1 M	
	DTT and 1 M CaCl ₂ were used to minimise total volume	
	changes. The enzymes were always added last to the	
	collagen-reaction mix to minimise any self-imposed	
	cross-linking. Controls using 10 mM EDTA (to block	
	tTG activity) and an active-site directed inhibitor, R281	
	(a synthetic CBZ-glutaminy-glycine analogue; 500 µM),	
	were also included in each assay. For 96-well plates,	
	50 µl of the pre-treated collagen mixture was added to	
	each well before being placed into a humidified-atmo-	
	sphere incubator, at 37 °C and with 5% CO ₂ , for 8 h. On	

1	removal, wells were washed twice with sterile distilled	
3	water and used immediately.	
5	<i>2.10. Determination of ϵ-(γ-glutamyl)lysine cross-link</i>	
7	Cross-linked and native samples of collagen were	
9	proteolytically digested as previously described [21]	
11	which included an initial digestion with microbial	
13	collagenase (<i>Clostridiopeptidase A.</i> ; 1 mg/ml, Sigma-	
15	Aldrich, Poole, UK. Cat no. C9891) prior to the	
17	addition of further proteases. After digestion, samples	
19	were freeze dried and then resuspended in 0.1 M HCl and	
21	sonicated for 2 min to aid dispersion. An aliquot (90 μ l)	
23	was mixed with 110 μ l of loading buffer (0.2 M lithium	
25	citrate, 0.1% phenol pH 2.2) and loaded onto a Dionex	
27	DC-4A resin column 0.5 cm \times 20 cm using a Pharmacia	
29	Alpha Plus amino acid analyser. Derivatisation was	
31	performed post-column using <i>o</i> -phthaldialdehyde (0.8 M	
33	boric acid, 0.78 M potassium hydroxide, 600 mg/ml <i>o</i> -	
35	phthaldialdehyde, 0.5% (v/v) methanol, 0.75% (v/v) 2-	
37	mercaptoethanol, 0.35% (v/v) Brij 30) and the absor-	
39	bance was measured at 450 nm. Dipeptide was deter-	
41	mined by addition of known amounts of ϵ (γ -	
43	glutamyl)lysine to the sample and comparing peak	
45	areas.	
47	<i>2.11. Coomassie blue staining assay of cell cultures</i>	
49	The capacity of both the HOB and HFDF cells to	
51	degrade type I collagen was assessed as previously	
53	described [22]. Briefly, native and TG pre-treated	
55	collagen samples gels were plated out at 50 μ l per well	
	of a 96-well plate. Hundred microlitres of 2×10^4 cells/	
	ml, cultured in complete media, was then added to the	
	wells in triplicates. Plates were then kept in a humidified-	
	atmosphere incubator for the relevant time point(s).	
	After incubation, cells were removed from the collagen	
	matrix by addition of 0.5% (w/v) sodium deoxycholate	
	in 10 mM Tris-HCl. A rinse with distilled water was	
	performed before the collagen samples were stained with	
	a 0.1% (w/v) Coomassie Brilliant blue stain solution	
	(50% (v/v) methanol; 10% (v/v) acetic acid; 40% (v/v)	
	dH ₂ O). Samples were allowed to stain for 5 min before a	
	further rinse with distilled water. Unstained areas, which	
	appeared lighter blue, gave an indication of collagen	
	degradation by cells. Two separate fixed-size random	
	fields per triplicate samples were photographed using an	
	Olympus CK2 microscope and DP10 digital camera.	
	<i>2.12. Protein concentration</i>	
	The total protein content of the collagen samples was	
	determined by the Lowry method [23] using the Bio-Rad	
	DC protein assay kit (Bio-Rad Laboratories, Hertford-	
	shire, UK. Cat no. 500-0120).	
	<i>2.13. Collagenase degradation of matrices following cell</i>	57
	<i>culture</i>	59
	Collagen substrates were subjected to digestive treat-	
	ment with 100 μ l of a 1 mg/ml microbial collagenase	
	solution (<i>Clostridium histolyticum</i> , Sigma-Aldrich,	
	Poole, UK. Cat no. C9891) followed by 100 μ l 0.25%	
	(w/v) trypsin/2 mM EDTA solution in PBS solution for	
	24 h at 37 $^{\circ}$ C. Samples were washed twice with PBS	
	followed by a wash with distilled water before the	
	enzymatic digestion treatment.	
	<i>2.14. Zymography</i>	
	Gelatin and collagen zymography were carried out as	
	previously described [24] with the following adaptations:	
	resolving gels were mixed with the following compo-	
	nents, in order: 1 ml of 5 mg/ml of type I collagen	
	solution (Sigma C9791) in 20 mM acetic acid (for	
	collagen zymography)/1 ml of 5 mg/ml porcine gelatin	
	(Sigma G2625) in H ₂ O (for gelatin zymography), 3.1 ml	
	H ₂ O, 2.5 ml of 1.5 M Tris-HCl pH 8.8, 3.33 ml of 29%	
	acrylamide/1% <i>N,N'</i> -methylene bisacrylamide, 50 μ l of	
	10% ammonium persulphate, 10 μ l of <i>N,N,N',N'</i> -tetra-	
	methylethylenediamine (TEMED). SDS was found to	
	cause precipitation of the collagen and so was not added	
	to the resolving gel. Stacking gels were poured in the	
	usual way, i.e. 0.65 ml of 29% acrylamide/1% <i>N,N'</i> -	
	methylene bisacrylamide, 3 ml H ₂ O, 1.25 ml 0.5 M	
	Tris-HCl pH 6.8, 50 μ l of 10% SDS, 25 μ l of 10%	
	ammonium persulphate, 5 μ l of TEMED.	
	Samples containing matrix metalloproteinases	
	(MMPs) were diluted 1:1 with loading buffer (1 M	
	Tris-HCl pH 6.8, 50% glycerol, 0.4% bromophenol	
	blue) and electrophoresed at 100 V in standard Laemmli	
	running buffer (24 mM Tris-HCl, 192 mM glycine,	
	3.47 mM SDS, pH 8.3), avoiding overheating (approx.	
	4–5 h). After electrophoresis, gels were washed twice,	
	with shaking, for 30 min each in 200 ml of 2.5% Triton	
	X-100, to remove SDS and recover MMP activity. The	
	gels were then placed in digestion buffer (100 mM	
	Tris-HCl, 5 mM CaCl ₂ , 0.005% Brij-35, 1 μ M ZnCl ₂ ,	
	0.001% NaN ₃ , pH 8) for 16–48 h at 37 $^{\circ}$ C. Gels were	
	stained with 0.2% Coomassie Brilliant blue R-250 in	
	50% ethanol, 10% acetic acid for 2 h and destained by	
	microwaving for 15 min (full power 850 W) in three	
	changes of deionised H ₂ O.	
	<i>2.15. Statistical analysis of data</i>	
	Differences between datasets (shown as mean \pm SD)	
	were determined by the Student's <i>t</i> -test at a significance	
	level of $p < 0.05$.	

3. Results

3.1. Cross-linking of collagen by microbial and tissue transglutaminases

Native collagen (type I) was treated with both tTG and mTG, separately, in order to catalyse the formation of ϵ -(γ -glutamyl)lysine cross-linking. The extent of cross-linking for each of the TG treatments is shown in Table 1. Treatment of collagen with increasing concentrations of TG led to a corresponding increase in the amount of ϵ -(γ -glutamyl)lysine bonds present—with up to 1 mol of cross-link per mole of collagen monomer. Treatment with mTG gave a much greater increase (almost two-fold) in the amount of isopeptide formed for the equivalent protein concentration of transglutaminase used. However, the increased specific activity of the mTG probably accounts for the differences noted.

3.2. Resistance of native and cross-linked collagen to cell-mediated degradation

Collagen treated with 50 μ g/ml TG showed a greater resistance to cell-mediated degradation as compared to the native collagen, when HOB cells and HFDF were seeded onto the collagen matrices and incubated for

72 h. Following removal of cells, visual comparison of the Coomassie blue stained matrices and measurement of the residual collagen indicated the mTG-treated collagen to be more resistant than tTG-treated collagen (Table 2).

3.3. Matrix metalloproteinases secreted by HFDF cells grown on transglutaminase collagen matrices

Following growth on type I collagen, fibroblasts showed an induction of a wide array of collagenases and gelatinases when compared with growth on tissue culture plastic-ware alone (Fig. 1). After growth on transglutaminase cross-linked type I collagen, the induction of active MMP1 (45 kDa), Fig. 1A, is much less pronounced compared to growth on native collagen, whereas the induction of active MMP2 (66 kDa) and MMP9 (86 kDa), Fig. 1B, was increased particularly when the cells were grown on collagen cross-linked by tTG.

3.4. Proliferation rates of HOB and HFDF cells on native and TG-treated collagen substrates

Proliferation rates of both HOB and HFDF cell lines were enhanced on TG-treated collagen substrates with a

Table 1
Measurement of ϵ -(γ -glutamyl)lysine in TG-cross-linked collagen

Sample	TG concentration (μ g/ml) ^a	nmol of cross-link/mg protein sample	\pm Relative change to native collagen ^b	mol cross-link/mol of collagen ^c
Collagen	—	0.16	—	0.02
Coll-tTG	50	1.09	6.81	0.13
Coll-tTG	100	2.40	15.00	0.29
Coll-tTG	200	4.60	28.75	0.55
Coll-tTG	500	5.40	33.75	0.65
Coll-tTG	1000	8.90	55.63	1.07
Coll-mTG	10	0.90	5.63	0.11
Coll-mTG	50	2.00	12.5	0.24
Coll-mTG	200	4.90	30.63	0.59
Coll-mTG	500	8.40	52.50	1.00

Cross-linking of collagen type I by different amounts of tTG and mTG after 8 h at 37 °C was undertaken as described in the Methods.

^aTG activity: tTG = 11500–13000 U/mg; mTG = 16000–25000 U/mg.

^bNative collagen = 0.16 nmol cross-link.

^cM_w collagen: 120 kDa.

Table 2
Degradation of native and TG-treated collagen type I by HOB and HFDF cells

Cell line	Collagen	Collagen-tTG (50 μ g/ml)	Collagen-mTG (50 μ g/ml)
HOB	24% \pm 3.1	55% \pm 1.9	59% \pm 2.1
HFDF	14% \pm 2.6	30% \pm 2.3	38% \pm 2.5

After 72 h culture, cells were removed with sodium deoxycholate, residual collagen was digested with microbial collagenase and trypsin, and solubilised protein was measured and expressed as a percentage of the initial level. Values are expressed as the mean \pm SD from three independent experiments, each with triplicate samples.

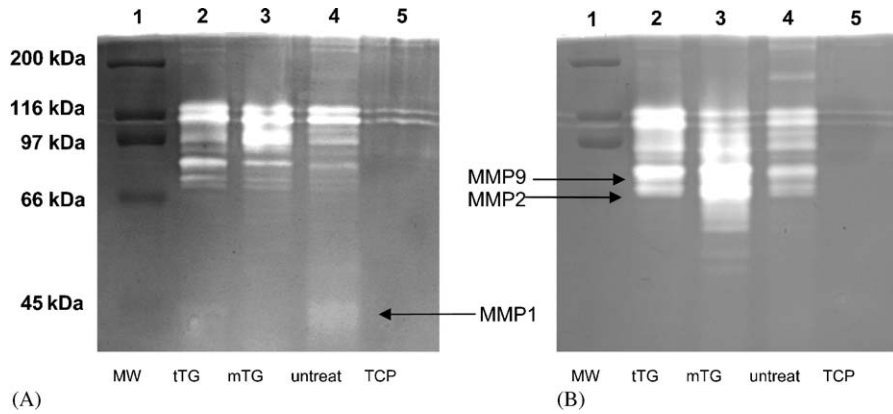


Fig. 1. Collagen (A) and gelatin (B) zymography of HFDF cell culture supernatants after 24 h growth on different media. Lane 1: molecular weight markers (BioRad 161-0317); lane 2: tTG-treated collagen; lane 3: mTG-treated collagen; lane 4: untreated collagen; lane 5: no collagen.

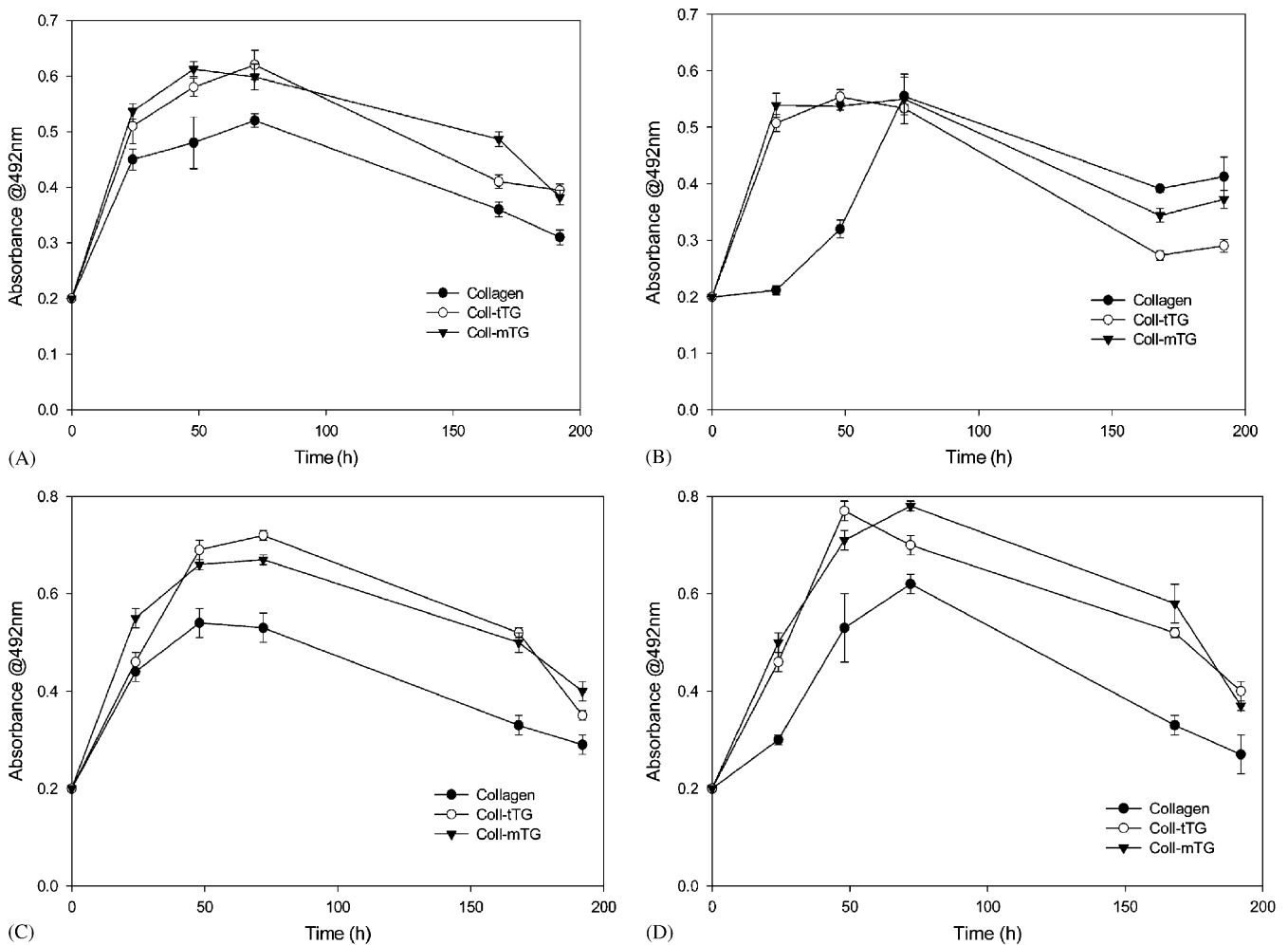


Fig. 2. Proliferation of HOB and HFDF cells cultured on native and TG-treated collagen substrates. HOB cells: (A) 50 µg/ml TG and (C) 100 µg/ml TG; HFDF cells: (B) 50 µg/ml TG and (D) 100 µg/ml. Proliferation rates were determined using CellTiter AQ solution. Results are the mean values \pm SD from four independent experiments, each having triplicate samples.

greater level of viability achieved throughout the 196-h culture when compared with non-cross-linked collagen (Fig. 2). In the case of HOB cells, no significant difference in number of viable cells was observed with

collagen treated with 100 µg/ml TG compared to 50 µg/ml TG. However, the HFDF cells showed an extended period of enhanced proliferation when cultured on collagen treated with 100 µg/ml TG (up to 48 h),

1 compared to 50 µg/ml TG (up to 24h), and maintained
 3 an increase in number of viable cells until 168 h of
 5 culture.

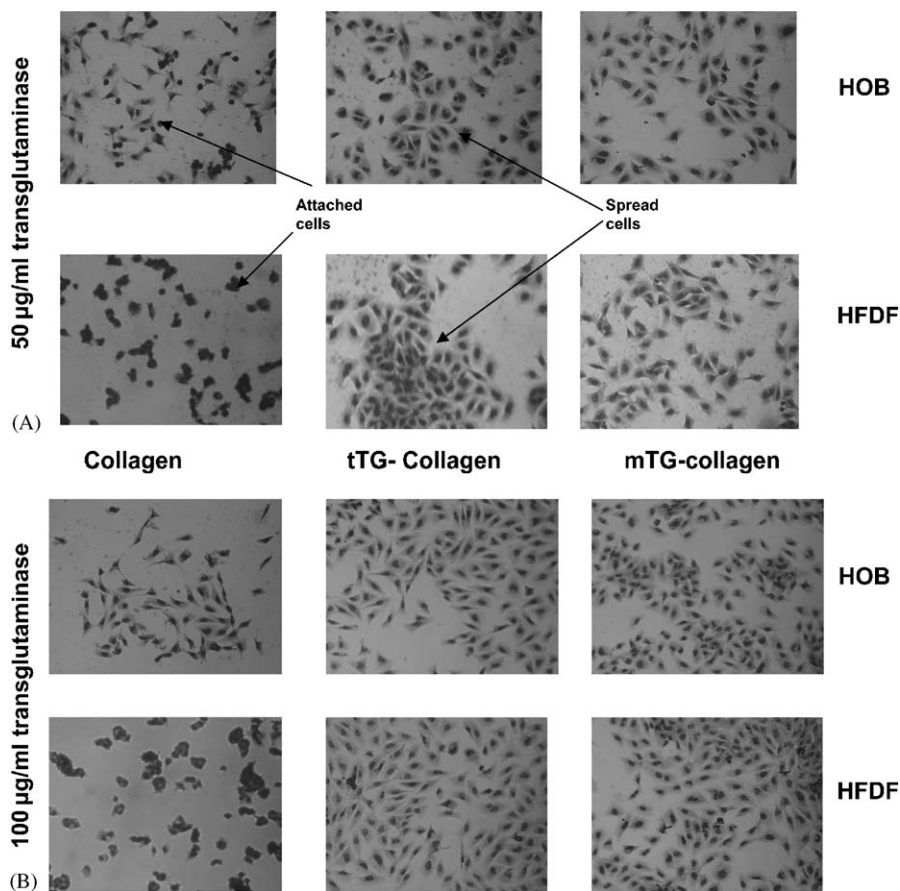
7 **3.5. Attachment characteristics of HOB and HFDF cells**
 9 **on native and TG-treated collagen substrates**

11 Figs. 3 and 4 show the short-term cell-attachment
 13 characteristics of HOB and HFDF cells, when cultured
 15 on native and TG-treated collagen. Increased numbers
 17 of both HOB and HFDF cells attached when cultured
 19 on transglutaminase cross-linked collagen. For the HOB
 21 cells, comparable cell attachment was observed on both
 23 50 and 100 µg/ml TG-treated collagens (Fig. 4A and 4C)
 25 giving a significant increase of around ~20% in attached
 27 cells for the corresponding time points over the non-
 29 cross-linked collagen ($p < 0.05$). Comparable enhance-
 31 ments in cell attachment on the cross-linked collagens
 33 were also observed for the HFDF cells ($p < 0.05$) (Fig.
 35 4B and 4D).

57 **3.6. Spreading characteristics of HOB and HFDF cells**
 59 **on native and TG-treated collagen substrates**

61 Figs. 3 and 5 show the short-term cell-spreading
 63 characteristics of HOB and HFDF cells when cultured
 65 on native and TG-treated collagen. Increased numbers
 67 of cells spread when cultured on 50 µg/ml transglutami-
 69 nase cross-linked collagen. In the case of the HOB cells,
 71 a comparable increase of 5% in the spreading of the
 73 HOB cells, at each time point, is seen on both of the TG-
 75 treated collagens (Fig. 5A). In contrast, the HFDF cells
 77 showed significant non-spread cells on the 50 µg/ml TG-
 79 treated collagen—with increases of at least 10%
 81 observed for both of the TG-treated variants (Fig. 5B)
 83 ($p < 0.05$).

85 A further increase in the number of spread cells was
 87 also observed on cross-linked collagen using 100 µg/ml
 89 transglutaminase. In the case of HOB cells, an increase
 91 of approximately 5% can be observed in spread cells
 93 (Fig. 5C). This behaviour increased with increasing time
 95 of culture. In contrast for the HFDF cells, although
 97 there was still an increase in the spreading characteristics
 99 on the TG-treated collagen, a much more distinct and
 101 and



111 Fig. 3. Attachment and spreading of HOB and HFDF cells on native and TG-treated collagen type I. After 6h incubation, cells were fixed using 3.7% (w/v) paraformaldehyde before being stained with May-Grunwald and Giemsa stains and then viewed at ×400 magnification.

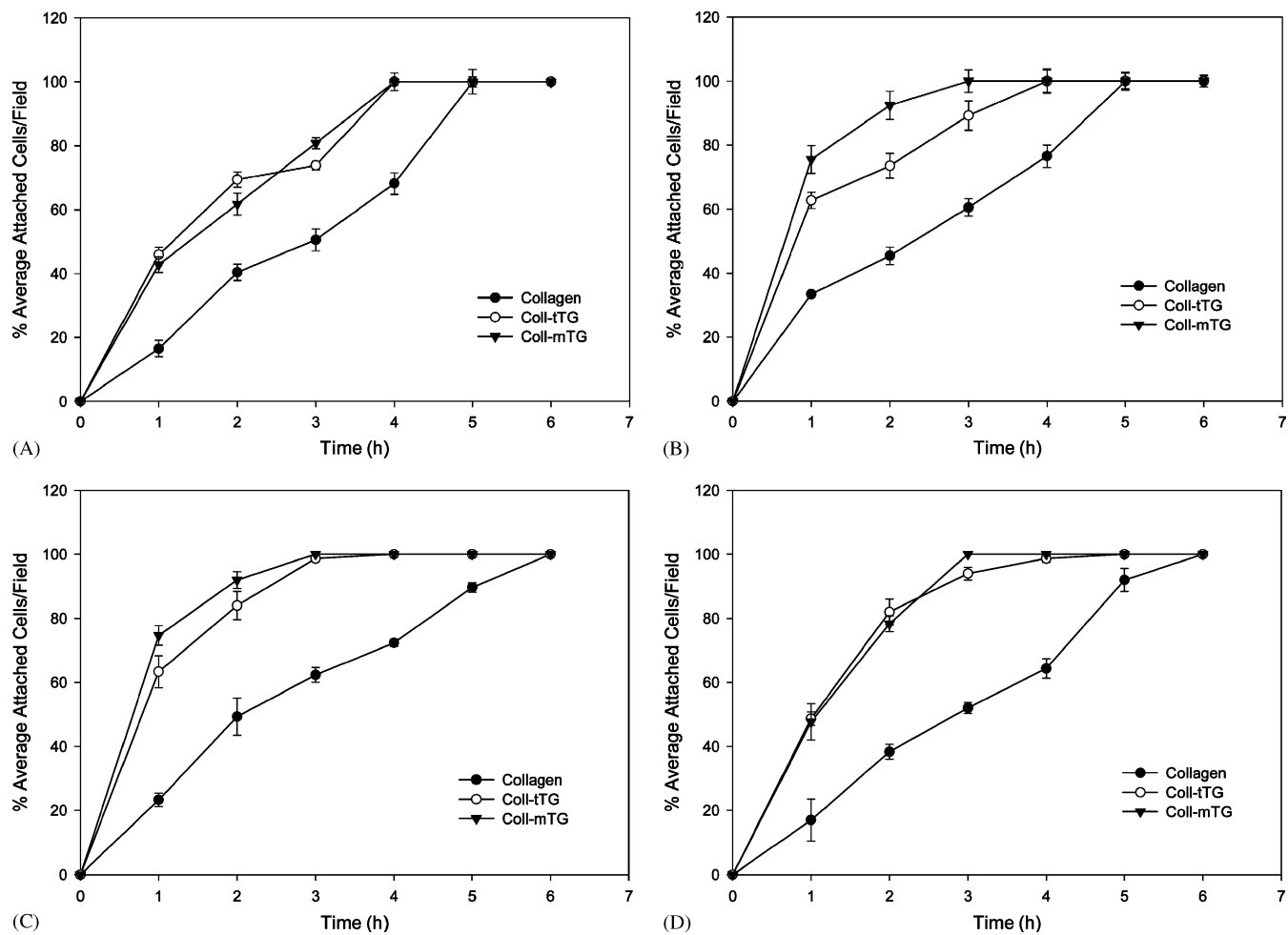


Fig. 4. Attachment of HOB cells and HFDF on native and TG-treated collagen substrates. HOB cells: (A) 50 µg/ml TG and (C) 100 µg/ml TG; HFDF cells: (B) 50 µg/ml TG and (D) 100 µg/ml TG. Attachment is expressed as a percentage of the total number of attached cells after 6 h. Results are the mean values \pm SD from four independent experiments, each having triplicate samples.

significant behaviour was identified on the tTG-treated collagen with spread cells increasing by 15% for many of the time points. In contrast, the microbial-TG-treated collagen showed only a slight improvement in the spreading characteristics of cells (Fig. 5D) ($p < 0.05$).

3.7. Differentiation of HOB cells cultured on native and TG-treated collagen

Increases in ALP activity were observed in all the TG-cross-linked collagens, with the greatest increase seen with the tTG-treated collagen (Fig. 6A). A dose-dependent relationship between the concentration of TG and the increase in the ALP activity of the HOB cells ($p < 0.05$) was observed. However, with the highest concentration of mTG (250 µg/ml), there appeared to be a reduction in the corresponding amount of ALP activity when compared to tTG. In addition, higher OPN levels were observed in all the TG-cross-linked collagens—with the greatest increases seen with the 250 µg/ml concentration of transglutaminase (Fig. 6B).

This gave rise to a two-fold increase of OPN expression over non-cross-linked collagen. In summary, a dose-dependent relationship between the concentration of TG and the increase in the OPN levels of the HOB cells ($p < 0.05$) was observed.

4. Discussion

We have confirmed previous work [25], in demonstrating that treatment of collagen type I matrices with transglutaminases results in the incorporation of $\epsilon(\gamma$ -glutamyl)lysine, with both mTG and tTG introducing similar amounts of cross-link per unit activity. It has been previously demonstrated that collagen type I shows greater resistance to proteolytic degradation by matrix metalloproteinase 1 (MMP-1) in vitro after cross-linking by tTG [26]. Importantly, we have shown that collagen modified with tTG and mTG demonstrated greater resistance to the total complement of cell-secreted proteases and, as a consequence, improved resistance

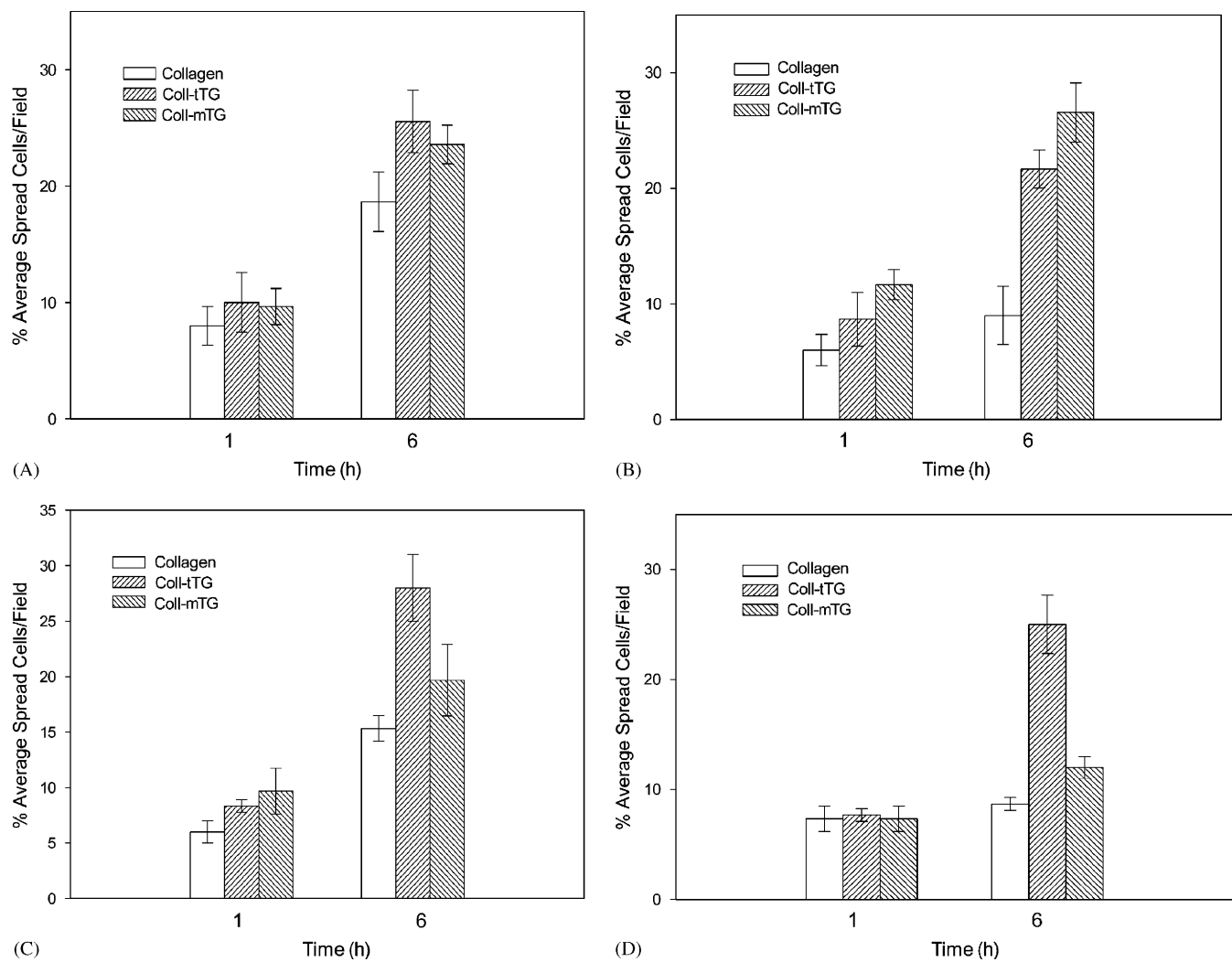


Fig. 5. Spreading of HOB cells on native and TG-treated collagen substrates. Cells were cultured for 1 and 6 h as described in the Methods. HOB cells: (A) 50 $\mu\text{g/ml}$ TG and (C) 100 $\mu\text{g/ml}$ TG; HFDF cells: (B) 50 $\mu\text{g/ml}$ TG and (D) 100 $\mu\text{g/ml}$ TG. Spreading is expressed as a percentage of the total number of cells in the field of view. Results are the mean values \pm SD from four independent experiments, each having triplicate samples.

to cell-mediated degradation from cultured HOB and HFDF cells. The MMP expression profile of HFDF cells was found to alter as a result of growth on cross-linked collagen, with a reduction of active MMP-1 and a corresponding increase in active MMP-2, when compared to growth on untreated collagen. It is possible that this alteration in active MMP-1 accounts for the increased resistance of cross-linked collagen to cellular degradation. However, there is recent evidence to indicate that growth of either cultured hepatic stellate cells [27], rabbit periosteal fibroblasts [28] or human dermal fibroblasts [29] on collagen type I results in an increase in active MMP-2, which is associated with increased degradation of collagen in the matrix, independently of the collagenases [30]. In addition, changes in the mechanical characteristics of the collagen, which could be brought about by the introduction of $\epsilon(\gamma\text{-glutamyl})\text{lysine}$ cross-link, can elicit mechano-

chemical signalling via an integrin-dependent mechanism, resulting in alterations in gene expression, thus accounting for the changes in active MMP expression observed [28,28,31]. The importance of the mechanical nature of the matrix in MMP production is exemplified by the finding that bovine aortic or human umbilical endothelial cells repress their secretion of MMP-2 entirely when subjected to shear stress for as little as 30 min [32]. Transglutaminase-cross-linked collagen may be more efficient than native collagen at inducing this response to the ECM, either through the presence of cross-links which may disturb the native conformation, or via disruption of the native fibrillar form during fibrillogenesis. Alternatively, due to the increased resistance of the cross-linked collagen to MMP degradation, fibroblasts may elicit an enhanced MMP response in a futile attempt to increase the rate of collagen breakdown.

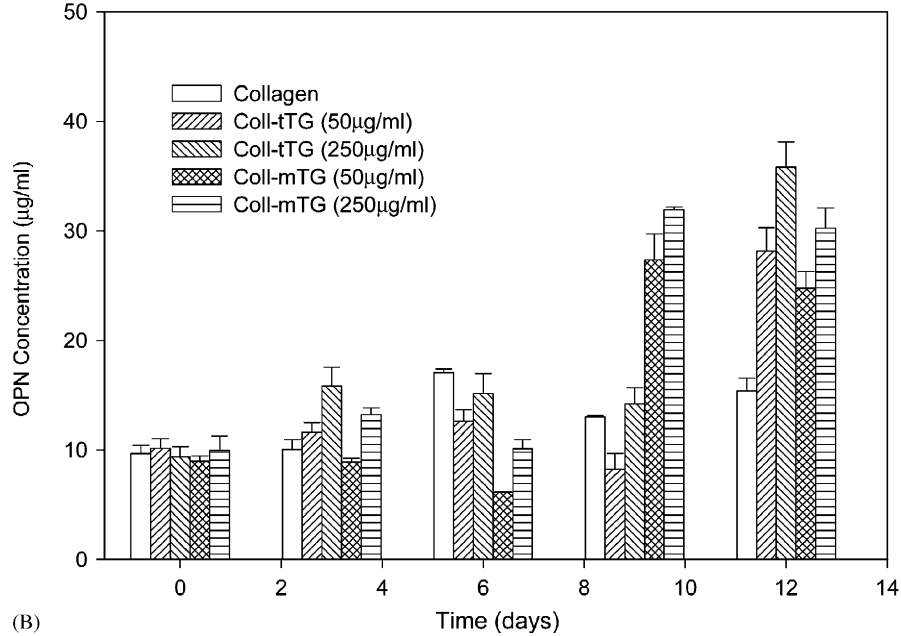
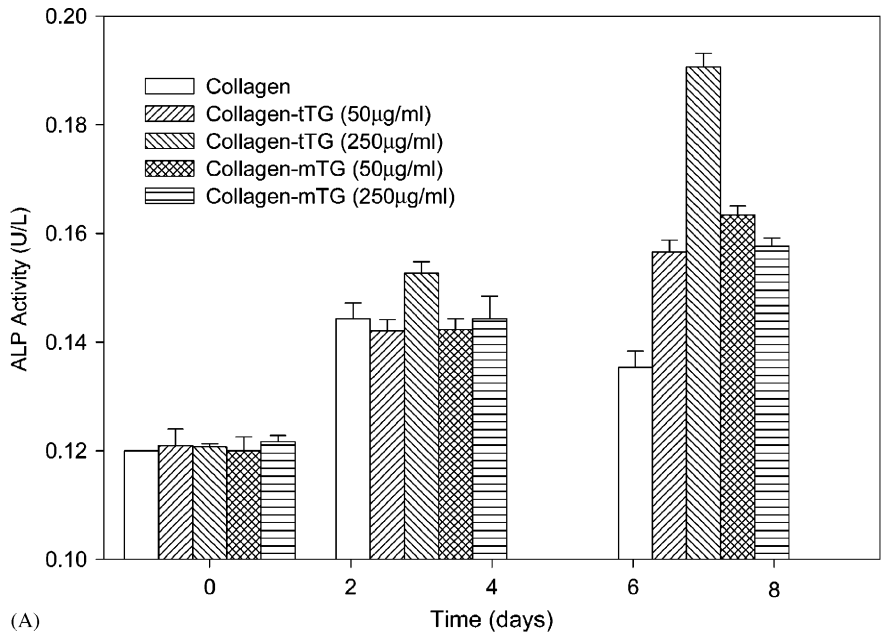


Fig. 6. Differentiation of HOB cells cultured on native and TG-treated collagen type I. Alkaline phosphatase (A) and osteopontin levels (B) were measured as standard biochemical markers of osteoblast differentiation. Results are the mean values \pm SD from three independent experiments.

The proliferation rates and the attachment and spreading characteristics of HFDF and HOB cells were increased after growth on TG-cross-linked collagen when compared to culture on native collagen; furthermore suggesting alteration of the natural collagen confirmation resulting in the exposure of cryptic cell binding sites within the cross-linked collagen [16]. Importantly, long-term growth and survival rates were also maintained. These data confirm that the cross-linked collagen is eliciting a different cellular response compared to untreated collagen. HOB cells were also found to differentiate more rapidly after culture on TG-

modified collagens as demonstrated by the corresponding increases in ALP activities and the earlier appearance of OPN. A possible explanation for this is that the TG-treated collagen matrix is in contact with the cells longer due to its increased proteolytic resistance thus providing the required integrin-mediated signal to the HOB cells necessary for differentiation [33].

The ability of tTG to act as a cell adhesion protein is well documented, promoting increased cell proliferation, spreading and attachment [34,35]. In fact, tTG, as well as Factor XIII, are critical components in the wound healing process and also in bone modelling and bone

ossification [36], where up-regulation of TG activity and enhancement of ECM cross-link formation is observed [37–41]. The cell adhesion characteristics of tTG have already been exploited to enhance the biocompatibility of medical devices [42]. Treatment of collagen type I with tTG may therefore lead to a modified collagen that is mimicking the natural remodelling/healing processes experienced in vivo. However, the finding that both the mammalian and microbial enzymes alter the biological characteristics of collagen type I in the same manner, indicates that cross-linking is essential since it is unlikely that the microbial enzyme can act as a cell adhesion protein given the large biochemical and physical differences between the enzymes [43].

5. Conclusion

In conclusion, the cellular response of HFDF and HOB cells grown on transglutaminase-cross-linked collagen is altered in such a manner that they show enhanced attachment, spreading and proliferation. Another important finding was that HOB cells differentiated faster on the cross-linked collagen. The modified collagen was also degraded at a much slower rate than native collagen further enhancing its in vivo efficacy as a biomaterial. Transglutaminases, therefore, show considerable potential as alternative cross-linking treatments for the production of novel biomaterials that do not suffer from the same drawbacks as other chemical or physical methods.

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