Title: Proving Osteoinductive Potential of a Decellularized Xenograft Bone Substitute

Running Title: Osteoinductivity in a Porcine Xenograft

BASIC RESEARCH ARTICLES

Abstract

Background: Large bone defects remain a major clinical challenge for orthopaedic surgeons. Tissue engineered bone grafts have garnered increased attention as a solution to this problem. One ideal property of any bone graft is osteoinductivity or the ability to stimulate progenitor cell differentiation into a bone forming lineage.

Questions:

a. Is the osteoinductive potential of a porcine bone xenograft maintained *in vitro* after undergoing a novel decellularization and oxidation process?
b. Are porcine bone scaffolds osteoinductive in an *in vivo* animal model?

Methods:

a. *In Vitro* – C2C12 pre-osteoblasts were seeded on the scaffold or a commercial grade demineralized bone matrix (DBM) to study osteogenic differentiation and compare osteoinductive potential. MC3T3-E1 pre-osteoblasts were seeded on the scaffold and compared to a control monolayer to identify early markers of osteogenic differentiation.
b. *In Vivo* – MC3T3-E1-seeded scaffolds were implanted subcutaneously in mice and assessed for markers of early osteogenic differentiation, new bone formation (micro-computed tomography and histological assessment), and vascular infiltration (histology).

Results:

Osteoinductive potential was demonstrated in *in vitro* experiments by similar osteogenic marker expression compared to DBM and significantly greater expression than a control monolayer.

Osteoinductivity was confirmed with *in vivo* experiments showing both new bone formation and vascular infiltration.

Conclusion:

Porcine bone maintains osteoinductive properties after decellularization and oxidation.

Clinical Relevance:

This construct could potentially serve as a bone graft substitute maintaining the osteoinductive potential of native bone. The unrestricted supply and controlled donor biology may satisfy a large clinical need for orthopaedic cases requiring bone grafting.

38 **Introduction**

39 Management of large bone defects resulting from trauma, infection, or tumor
40 resection remains a major clinical challenge for orthopaedic surgeons[1-3]. These defects
41 are considered critical bone defects if they are unlikely to heal spontaneously during a
42 patient's lifetime and are typically larger than twice the width of the diaphysis[4]. The gold
43 standard for treatment is the use of autologous bone graft; however, due to the associated
44 morbidity and lack of adequate bone stock or donor sites, alternative grafts are commonly
45 used. The ideal bone graft is osteoconductive, osteogenic, and osteoinductive[1].
46 Osteoconductivity is the ability for the bone graft to allow osseous growth on the surface,
47 or within its pores[5]. Osteogenic grafts retain living bone cells[5]. Osteoinductivity is the
48 ability to stimulate progenitor cells to differentiate into a bone forming cell lineage[5,6].

49 Alternative bone grafts include allografts and tissue engineered bone substitutes[1,4].
50 Allograft use risks disease transmission and has limited availability from young, healthy
51 donors[7,8]. Tissue engineered constructs include synthetics and xenograft-derived
52 alternatives[4]. The advantage of synthetic bone replacements is that the constructs can be
53 manufactured to custom structure[9]. Furthermore, osteogenicity can be artificially re-
54 created by pre-seeding osteogenic cells onto the material prior to implantation.
55 Osteoinductivity, however, requires the construct be able to induce cell differentiation,
56 and therefore is more difficult to re-create[6,10,11]. Xenografts are one potential way to
57 utilize the natural osteoinductive properties of native bone without using an allograft.
58 Swine may be the ideal species for xenotransplantation due to physiologic compatibility
59 with humans[12,13]. However; porcine xenotransplantation is potentially dangerous due to
60 the presence of the alpha-gal epitope which can induce a severe inflammatory response in

61 human hosts[14,15]. Our laboratory developed a novel decellularization process that
62 successfully renders porcine soft tissues sterile and removes the alpha-gal epitope[16-19].
63 We have applied this process to porcine cancellous bone and demonstrated that the
64 construct was successfully decellularized and maintained native structural properties,
65 therefore preserving the construct's osteoconductivity[19,20]. Proteomics data also showed
66 that important growth factors believed to have a critical role in cell differentiation and
67 osteoinductivity were also preserved on the scaffold. However, the clinical relevance and
68 biologic function of these proteins after chemical processing are unknown.

69 Therefore, the current research project aimed to:

70 **1)** Demonstrate osteoinductive potential of a porcine xenograft-derived bone
71 scaffold *in vitro.*

72 **2)** Prove the osteoinductive potential is maintained in an *in vivo* model.

73 **Materials and Methods**

74 *In vitro* and *in vivo* experiments were designed to determine if a novel
75 decellularization and oxidation protocol applied to porcine bone resulted in an
76 osteoinductive bone scaffold. Scaffolds were processed using methods previously
77 described[17]. Briefly, cancellous bone was harvested from the distal metaphysis of
78 porcine femurs collected from an abattoir and subjected to a chemical decellularization
79 and oxidation protocol using combinations of deionized water, trypsin, antimicrobials,
80 peracetic acid, and triton X-100. Residual peracetic acid was cleared from specimens by
81 serial water washes until PAA levels were below the limits of detection (0.5 parts per
82 million) with high sensitivity PAA test strips (Quantofix® peroxides test sticks, Sigma).

83 Scaffolds were lyophilized and frozen at -80°C until further use. Previous proteomics
84 experiments by our group have demonstrated that following this process the protein
85 composition of the scaffold is similar to that of a commercial DBM product[19] Mass
86 spectrometry demonstrated that in addition to the expected abundance of structural
87 proteins, such as collagen alpha-1 and -2 chains, there were also notable similarities in
88 the growth factors preserved on the scaffold and commercial DBM samples analyzed.
89 Proteins such as chondroadherin, lumican, fibromodulin and biglycan play critical roles
90 in cell differentiation, intra-cellular cascade signaling, and extra-cellular matrix assembly,
91 and were found on both the porcine scaffold and human DBM.

92 Two different cell lines were chosen for indirect quantification of the scaffold's
93 osteoinductive potential. C2C12 (ATCC® CRL1772™, Rockville, MD) is a mouse
94 myoblast cell line that differentiates into osteoblasts in the presence of bone
95 morphogenetic protein (BMP)-2 and is commonly used in osteoinduction studies[21-25].
96 MC3T3-E1 subclone 4 cells (ATCC® CRL2593™) were chosen as a second cell line for
97 testing of the scaffold's osteoinductive potential. These cells are an osteoblast precursor
98 derived from C57BL/6 mice and previously used to study osteoinductive potential[26,27].

99 *In Vitro*

100 Scaffolds or cancellous DBM sheets (Musculoskeletal Transplant Foundation,
101 Edison NJ) (n=77 per group) were seeded with $1x10^6$ C2C12 cells. As a negative control,
102 cells were also seeded onto gelfoam sponges (Cardinal Health) which have very limited
103 biologic activity. The C2C12 cell line was passaged in DMEM supplemented with
104 penicillin/streptomycin and 10% FBS, never exceeding 80% confluence in order to avoid
105 terminal differentiation and myoblastic depletion. Cells were harvested at passage 4 and

106 suspended in 100 μL aliquots before being seeded onto constructs. Constructs were moved
107 into Petri dishes covered with media and incubated for 24 hours to allow cell attachment
108 to the matrix.. After 24 hours of incubation Samples from each group (n=11) were taken
109 for analysis while the remaining were separated for continued incubation in 2 different
110 medias: 1) Osteogenic Media (OM)[28-31] consisting of DMEM with 10 mM β-
111 Glycerophosphate and 50 μg/mL ascorbic acid and 2) BMP-2 Enriched Media[21,22,25,32]
112 consisting of the OM supplemented with 100 ng/mL BMP-2 (recombinant human BMP-2
113 355-BM-050, R&D Systems). OM provided an environment supportive of osteogenic
114 differentiation due to the addition of β-Glycerophosphate and ascorbic acid, while BMP-2
115 enriched media served as a positive control to drive cells towards the osteoblastic lineage[33].
116 Constructs (n=11) were harvested from each group at days 1, 3, 7, and 15 for analysis of
117 cell proliferation of early and late osteogenic differentiation[34]. These time points were
118 chosen after review of previous literature studying osteogenic differentiation with the
119 C2C12 cell line[25,29,35,36] and specific *in vitro* data showing C2C12 osteogenic
120 differentiation can occur within 48hours in the presence of BMP-2[22,37].

121 At each time point, constructs (n=2) from each group (n=6) were rinsed with PBS,
122 transferred to chamber slides, and incubated with the Live/Dead® Viability/Cytotoxicity
123 Kit (Molecular Probes, Eugene, OR) according to manufacturer's instructions. Specimens
124 were imaged on a fluorescent confocal microscope (Zeiss Axiovert 100 M) to render cross-
125 sectional 2D images and projected 3D images. Live cells are labeled with the green calcein
126 AM fluorophore and dead cells are labeled with the red ethidium homodimer-1
127 fluorophore.

128 DNA was quantified from constructs (n=3) in each group to estimate cell number
129 and proliferation. Samples were flash frozen in liquid nitrogen, homogenized with a
130 sterilized tissue press, and lysed in 1 mL mammalian protein extraction reagent (M-PER®,
131 ThermoScientific, Waltham, MA). Samples were centrifuged and supernatants collected
132 for analysis using the Quant-iT™ PicoGreen® dsDNA Assay Kit (ThermoScientific).

133 Cell attachment, morphology, and surface distribution were characterized by
134 electron microscopy. Specimens were removed from dishes in each group at every time
135 point, washed with PBS, fixed in 2.5% glutaraldehyde for 3 hours, and imaged on a Hitachi
136 S-2600 scanning electron microscope (SEM).

137 For histology, specimens from each group were removed from dishes, fixed in 10%
138 formalin for 48 hours, decalcified with Immunocal® (Decal Chemical Cort, Tallman, NY)
139 for 3-5 days, processed, and embedded in paraffin. Sections were mounted and stained with
140 hematoxylin and eosin (H&E), Masson's trichrome, or 4',6-diamidino-2-phenylindole
141 (DAPI) mounting media (ProLong® Gold Antifade Mountant, ThermoScientific).

142 The alkaline phosphatase (ALP) enzyme activity was measured from constructs
143 (n=3) using methods previously described.[36,38-42] Each reaction was read in triplicate by
144 loading 150 μL from each tube into 96 well plates and measuring absorbance at 405 nm on
145 a microplate reader (Spectra Max 340 PC). Cell-specific ALP activity was determined by
146 normalizing enzyme activity to the respective sample's DNA content determined by Pico
147 Green assay.[38,43,44]

148 Immunohistochemistry (IHC) was performed with an anti-Placental ALP (Abcam
149 ab16695, Cambridge, United Kingdom) primary antibody that reacts with cell membrane-
150 bound enzyme followed by a secondary biotin-conjugated anti-rabbit antibody (BioGenex,

151 Freemont, CA) linked to horseradish peroxidase. Slides were developed with
152 diaminobenzidine substrate (Vector, Burlingame, CA) and counterstained with Meyer's
153 Hematoxylin.

154 Next, $1x10^6$ MC3T3-E1 cells suspended in 50 μL of alpha-minimum essential
155 medium (α-MEM)+10% FBS were seeded and incubated on the scaffold for 1 hour in 50
156 μL of α-MEM+10% FBS, before being submerged in 750 μL of α-MEM+10% FBS with
157 50 μM ascorbic acid and incubated at 37°C for 7 days (n=18). Control monolayers of 1
158 x 10^4 cells were also incubated at 37°C for 7 days in 250 μL α-MEM+10% FBS with 50
159 μM ascorbic acid during this time (n=9). The presence of ascorbic acid provides a
160 supportive environment for MC3T3-E1 cell differentiation.[45,46] After 7 days, RNA was
161 isolated from the scaffolds by vigorous agitation in Buffer RLT (RNeasy Mini Kit,
162 QIAGEN, Hilden, Germany) for 30 minutes, and RNA purified following manufacturer
163 instructions. RNA from monolayers was isolated following manufacturer instructions
164 using the RNeasy Mini Kit. cDNA was produced through reverse transcription using
165 High Capacity cDNA Reverse Transcription Kit (Applied Biosystems) and analyzed for
166 gene expression of osteoblast markers using quantitative PCR (ALP and BMP-7). Target
167 gene expression was normalized to the housekeeping gene 18S ribosomal RNA. Relative
168 gene expression was quantified using the $2^{-\Delta\Delta Ct}$ methodology.[47]

169 *In vivo*

170 To demonstrate cell viability and osteoinductivity *in vivo,* scaffolds (n=25) seeded
171 with MC3T3-E1 cells overnight (1 x 10^6 suspended in 50 ul α-MEM+10% FBS) were
172 subcutaneously implanted in 7-week-old male C57BL/6 mice (Jackson Labs) for 4 weeks
173 under a Wake Forest School of Medicine IACUC Protocol #A16-197. Scaffolds without

174 cells were implanted to serve as a negative control (n=15). A subset of scaffolds (n=12
175 with cells, n=7 without cells) underwent microcomputed-tomography (microCT)
176 scanning (TriFoil Imaging Triumph PET/CT, voxel size 1 mm) before cell seeding and
177 implantation. Upon explantation, constructs were placed in Buffer RLT (QIAGEN) and
178 vortexed to extract RNA or placed in 10% formalin for repeat microCT scanning to
179 assess new bone formation. RNA was extracted from explanted scaffolds and analyzed
180 for gene markers of osteogenic differentiation (ALP, receptor activator of nuclear factor κ
181 B ligand (RANKL), BMP-2, and BMP-7) using quantitative PCR (n=13 with cells, n=8
182 without cells). Target gene expression was normalized to the housekeeping gene 18S.
183 Relative gene expression was quantified using the $2^{-\Delta\Delta Ct}$ methodology. Bone formation in
184 the scaffolds by serial microCT scanning was assessed by change in bone volume/total
185 volume ratio (BV/TV) and trabecular thickness (Tb.Th) using MicroView 3D Image
186 Viewer and Analysis Tool (Parallax Innovations, Ilderton, ON, Canada). After microCT
187 scanning, samples were fixed in 10% formalin overnight and subsequently decalcified in
188 14% neutral, saturated EDTA for 7-14 days. Samples were processed and embedded in
189 paraffin. Sections were stained with Russel-Movat Pentachrome (American MasterTech
190 Scientific Inc; St. Lodi, CA) and IHC was performed using primary antibodies against
191 osteopontin (Abcam ab8448) and ALP (R&D Systems FAB1448A) to identify active
192 bone remodeling, angiogenesis, and new bone formation.

193 Multiple group comparisons were performed using one-way ANOVA, t-tests were
194 performed on independent means when comparing two groups, and paired t-tests were
195 used when comparing paired groups. Statistical significance was determined when α error
196 < 0.05.

197 **Results**

198 C2C12 pre-osteoblasts proliferated on scaffolds and deposited extracellular matrix
199 (ECM) components. 3D images demonstrated circumferential cell attachment evenly
200 around the pores. Live (green) signal increased during incubation with the strongest signal
201 noted at day 15 (Figure 1). Dead (red) signal was strongest on day 1, likely due to early
202 contact inhibition after seeding constructs at a high cell density. DNA content on DBM
203 was greater than scaffolds at every time point, indicating higher cell density. BMP had no
204 consistent effect on cell proliferation. Cells seeded on the scaffold proliferated as
205 demonstrated by increased DNA at each time point. The differences were significant
206 between day 1 and 15 ($p<0.01$) and day 3 and 15 ($p=0.01$). Similarly, DNA content on
207 DBM increased at each time point as well (Figure 2). DAPI and H&E sections (Figure 3)
208 confirmed higher cell density on DBM relative to scaffolds. SEM supported this finding
209 with denser cell distribution on DBM samples relative to scaffolds at day 7 and 15 (Figure
210 4). ECM was deposited uniformly at later time points, and BMP-2 did not change cell
211 morphology, density, or distribution on matrices. Molecular assays showed that cells
212 seeded on scaffolds had greater ALP enzyme activity at days 7 and 15 ($p<0.0001$)
213 compared to cells seeded on DBM or gelfoam constructs (Figure 5). BMP-2 increased ALP
214 activity on all constructs; this increase was significant only for scaffolds (days 3 ($p=0.005$),
215 7 ($p=0.02$), 15 ($p<0.0001$)) suggestive of an additive effect on this matrix. ALP IHC
216 staining increased at day 15 and supported the above cell-specific enzyme activity findings
217 (Figure 6). MC3T3-E1 cells pre-seeded on scaffolds demonstrated greater ALP expression
218 than cell monolayers ($p=0.0021$); however, BMP-7 expression was similar (data not

219 shown). These results indicate the scaffold construct may possess osteoinductive potential
220 *in vitro*.

221 *In vivo* expression of ALP, BMP-7, and BMP-2 increased within the pre-seeded
222 scaffolds; however, only ALP was significant (p=0.0009) (Figure 7). RANKL gene
223 expression was equal between groups. MicroCT analysis was performed on 9 seeded and
224 4 un-seeded scaffolds. These data demonstrated greater changes in BV/TV and Tb.Th in
225 the pre-seeded scaffolds; however, only Tb.Th reached significance (p=0.03). Paired t-
226 tests showed significantly increased BV/TV (p=0.0013) and Tb.Th (p=0.0002) after
227 explantation in both groups (n=13) indicating new bone formation, regardless of cell
228 seeding (Figure 8). Pentachrome staining demonstrated angiogenesis and new bone
229 formation within the scaffold (Figure 9). IHC analysis revealed positive staining for OPN
230 and ALP. These results proved that the scaffold maintains osteoinductive properties
231 following decellularization, due to its ability to recruit and stimulate cells down a bone
232 forming lineage *in vivo*.

233 **Discussion**

234 Large bone defects resulting from trauma, infection, or tumor resection often require
235 bone grafting to fill the defect[1,7]. The gold standard for bone grafting is autologous bone
236 graft; however, limited quantity and structural deficiencies preclude its use in larger
237 defects. Allograft is a suitable alternative, but this has been associated with the
238 transmission of infectious diseases[7,8]. Additionally, the quantity of donor bone is limited,
239 and donor biology cannot be controlled, resulting in considerable variability in graft
240 quality[8]. Therefore, tissue engineering plays an increased role in developing
241 alternatives[48,49]. One possibility is the use of xenografts. Our laboratory established a

242 novel decellularization and oxidation technique using peracetic acid that removes 98% of
243 DNA when applied to porcine bone[20]. Our current study demonstrates that this treatment
244 protocol preserves at least some of the native porcine bone's osteoinductive potential in
245 the decellularized scaffold. *In vitro* results were comparable to demineralized bone
246 matrix, a commercial product currently in clinical use with proven osteoinductive
247 potential.

248 There are limitations to our study. First, clinical translation of *in vitro* and animal
249 experiments is limited. However, we believe these experiments were a necessary first
250 step to determine the properties of this bone scaffold after undergoing the
251 decellularization and oxidation procedure. Second, our *in vivo* experiments involve an
252 ectopic subcutaneous implantation model, rather than an orthotopic bone void filling
253 model. However, the purpose of these experiments was solely to determine the
254 osteoinductive potential of this scaffold in an *in vivo* environment. Additionally, RNA
255 collection may have been limited due to the porous nature of the scaffold. However, we
256 attempted to minimize this by vigorous agitation of the scaffold for 30 minutes. Finally, a
257 major limitation is the use of murine rather than human cell lines for these experiments,
258 which limits immediate clinical translation. These cell lines, however, have been
259 validated for study of biomaterials osteoinductive potential previously[50,51]. The use of
260 murine cells also permitted the analysis of immune reactivity and scaffold rejection,
261 which did not occur in our study.

262 BMP-2 is one of the strongest stimulants of osteogenic differentiation in the pre-
263 osteoblast cell lines used in our experiments[22,23,37,51-53]. Concentrations as low as 100
264 ng/mL and 50 ng/mL were sufficient to promote osteogenic differentiation with increased

265 ALP activity in MC3T3-E1[53] and C2C12[22], respectively. However, few reports studied
266 osteogenic differentiation of cells seeded onto xenograft derived bone
267 scaffolds[38,40,43,44,54]. Hashimoto et al.[43] demonstrated that porcine hydroxyapatite contains
268 osteoinductive properties and that these properties are maintained after processing[43].
269 Similarly, Smith et al.[55] found that the osteoinductive properties were maintained in
270 allografts following a decellularization and washing procedure. However, Bormann et
271 al.[37] used a similar decellularization and oxidation protocol to ours with the addition of
272 peracetic acid on allograft specimens and found that the osteoinductive potential was not
273 maintained. In the present study, we applied a novel decellularization and oxidation
274 technique using peracetic acid that removed 98% of the porcine DNA from the bone
275 scaffolds[20]. Contrary to the findings by Boorman et al.[37], our results demonstrate that the
276 xenograft does indeed maintain osteoinductive potential after processing. C2C12 and
277 MC3T3-E1 cells attached to the scaffold matrix, proliferated, and underwent osteogenic
278 differentiation during the incubation period. The discrepancy between these studies
279 outlines the variability between decellularization techniques as well as allograft
280 specimens. Bormann et al.[37] reported that the donors for the samples used ranged in age
281 from 13-67 years old, and gender could be a source of variability between samples. These
282 discrepancies may affect osteoinductive capacity[56] and outline the importance of
283 controlling environmental factors that may influence the quality of the donor bone, which
284 is only possible with the use of a xenograft.

285 *In vivo* assessment of the porcine bone scaffold demonstrated spontaneous new bone
286 formation and angiogenesis. The identification of angiogenesis represents a critical
287 finding due to the lack of vascularization being one of the major limitations associated

288 with the use of tissue engineered constructs during early bone regeneration[57,58]. The
289 presence of angiogenesis signifies graft-host integration by the induction of inflammatory
290 cytokines as part of the normal healing process[59]. It is reasonable to conclude that the
291 presence of angiogenesis allowed for new bone formation due to the known importance
292 angiogenesis has in bone repair and regeneration[59]. Accordingly, Hirata et al.[60] found that
293 a BMP-2 soaked absorbable collagen sponge implanted in humans led to new bone
294 formation lined by endothelial cells. Furthermore, Bhumiratana et al.[61] implanted a
295 clinically approved decellularized bovine trabecular bone seeded with adipose-derived
296 stem cells into Yucatan minipig skull defects and concluded that angiogenesis and new
297 bone formation occurred in parallel.

298 Overall, our data demonstrate that a novel decellularization and oxidation
299 technique applied to porcine metaphyseal bone preserves the osteoinductive nature of the
300 bone. Previous literature identifies that these properties are the most difficult to
301 artificially create in synthetic scaffolds and to maintain when processing bone scaffolds,
302 therefore outlining the potential clinical impact of this construct. Future studies involving
303 this xenograft will focus on placing the construct within a bone defect, identifying
304 osseointegration, and comparing it to current standard treatments. These experiments will
305 look at the effect of supplementing the scaffold with human mesenchymal stem cells, as a
306 step towards clinical translation. Furthermore, an *in vivo* analysis of inflammatory
307 markers to confirm that the bone scaffold has no increased reactivity when compared to
308 currently used clinical implants for large bone defects should be performed.

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Legends

Figure 1. Live/Dead Stained Confocal Microscopy Images
Demineralized Bone Matrix (DBM), scaffold, and gelfoam matrices were seeded with 1 million C2C12 pre-osteoblast cells and incubated to select time points. Cross sectional images were captured at 10x magnification and overlayed to create the shown 3d projections. On day 1, matrices were switched into osteogenic media (OM) enriched with 100 ng/ml BMP-2. Representative micrographs show green fluorophore (calcein AM) staining of live cells and red fluorophore (ethidium) staining of dead cells. Constructs had notable autofluorescence with ethidium staining as shown in the "blank" images. Cell density increased with time on all 3 matrices, consistent with DNA quantification results.

Figure 2. DNA Content in Seeded Constructs
Constructs were harvested at select time points, and DNA content was measured with the PicoGreen® assay.
*<0.05, **<0.01, ***<0.001

(a) scaffold vs DBM; **(b)** scaffold vs GF; **(c)** DBM vs GF
(d) scaffold OM vs BMP; **(e)** DBM OM vs BMP; **(f)** GF OM vs BMP;
(g) DBM day 1 vs 3; **(h)** scaffold day 1 vs 3; **(i)** GF day 1 vs 3;
(j) DBM day 3 vs 7; **(k)** scaffold day 3 vs 7; **(l)** GF day 3 vs 7
(m) DBM day 7 vs 15; **(n)** scaffold day 7 vs 15; **(o)** GF day 7 vs 15
(p) scaffold day 3 vs 15; **(q)** DBM day 3 vs 15; **(r)** GF day 3 vs 15

Figure 3. Cell Density Staining on Different Constructs
DAPI (A and B) and H&E (C and D) stained sections demonstrating higher cell density on DBM (A and C) relative to scaffolds (B and D).

Figure 4. Scanning Electron Microscopy of Cell Density
Scanning electron microscopy images demonstrating a denser cell distribution on DBM samples when compared with scaffolds at days 7 and 15.

Figure 5. Alkaline Phosphatase Enzyme Activity
ALP activity is greater within the cell-seeded scaffolds in osteogenic media (A). ALP activity was significantly greater on scaffolds in a BMP-2 enriched media (B), suggesting an additive effect of the matrix.

Figure 6. **Alkaline Phosphatase Immunohistochemistry**
ALP immunohistochemical staining increased at day 15 in both constructs, confirming that there is increased alkaline phosphatase activity that is similar between constructs.

Figure 7. Gene Expression of Osteogenic Factors
Gene expression of ALP (A; Alk Phos), bone morphogenetic protein (BMP) – 2 (B), and BMP-7 (C) is increased in scaffolds pre-seeded with cells when compared to scaffolds with no cells. However, only alkaline phosphatase reached significance.

Figure 8. MicroCT Analysis of *in vivo* Constructs
Bone volume ratio and trabecular thickness both increase between pre-implantation and explantation ($p=0.0013$ and $p=0.0002$, respectively) signifying new bone formation within the xenograft.

Figure 9. Histological Staining of *in vivo* Constructs
Pentachrome staining demonstrating new vessel formation (black arrow) and new bone formation (blue arrow).

Figure 1

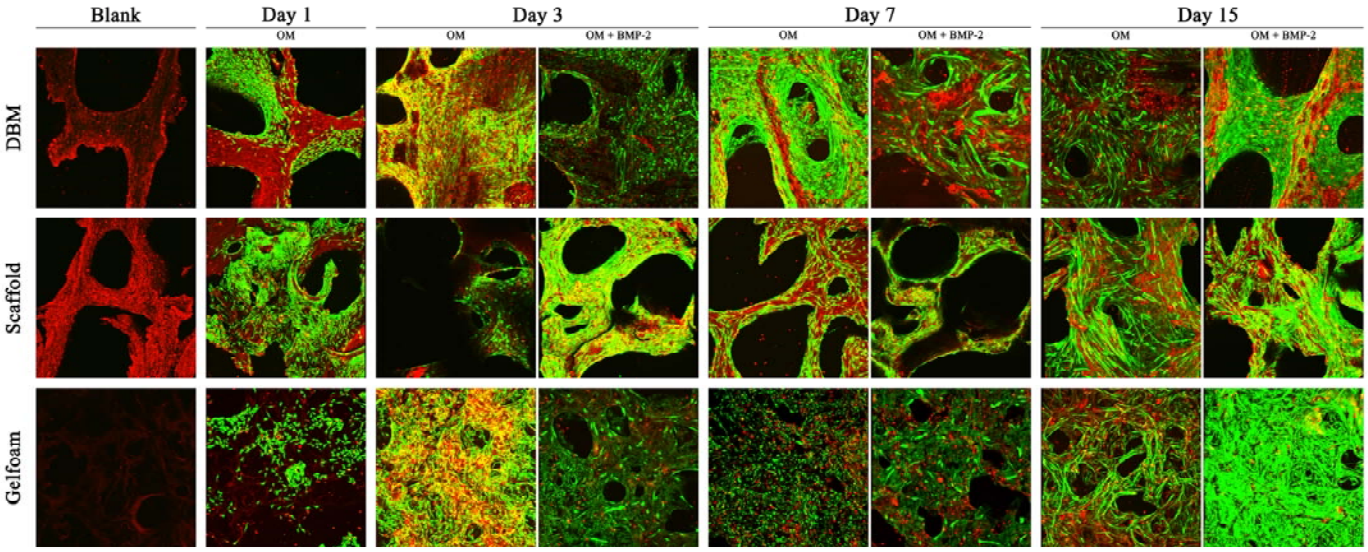

Blank
Day 1
OM
Day 3
OM
OM + BMP-2
Day 7
OM
OM + BMP-2
Day 15
OM
OM + BMP-2
DBM
Scaffold
Gelfoam

Figure 2

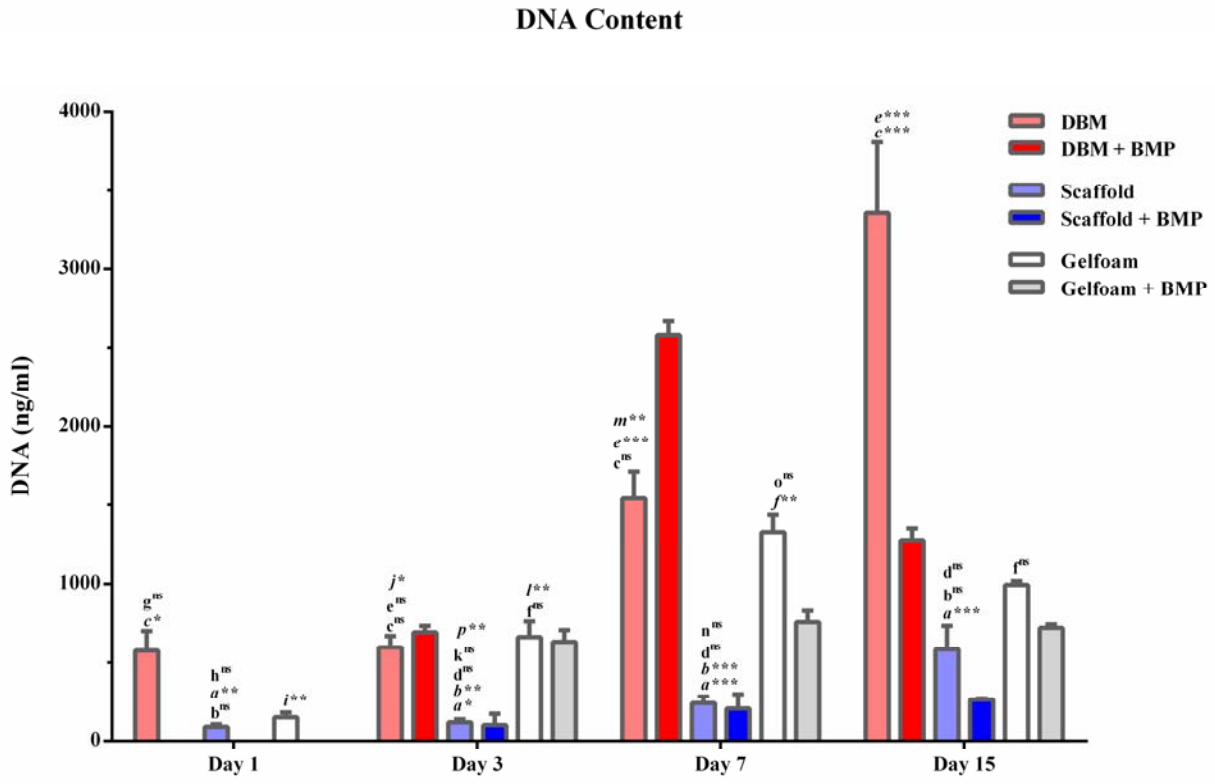

DNA Content
DNA (ng/ml)
4000
3000
2000
1000
0
Day 1
Day 3
Day 7
Day 15
DBM
DBM + BMP
Scaffold
Scaffold + BMP
Gelfoam
Gelfoam + BMP

Figure 3

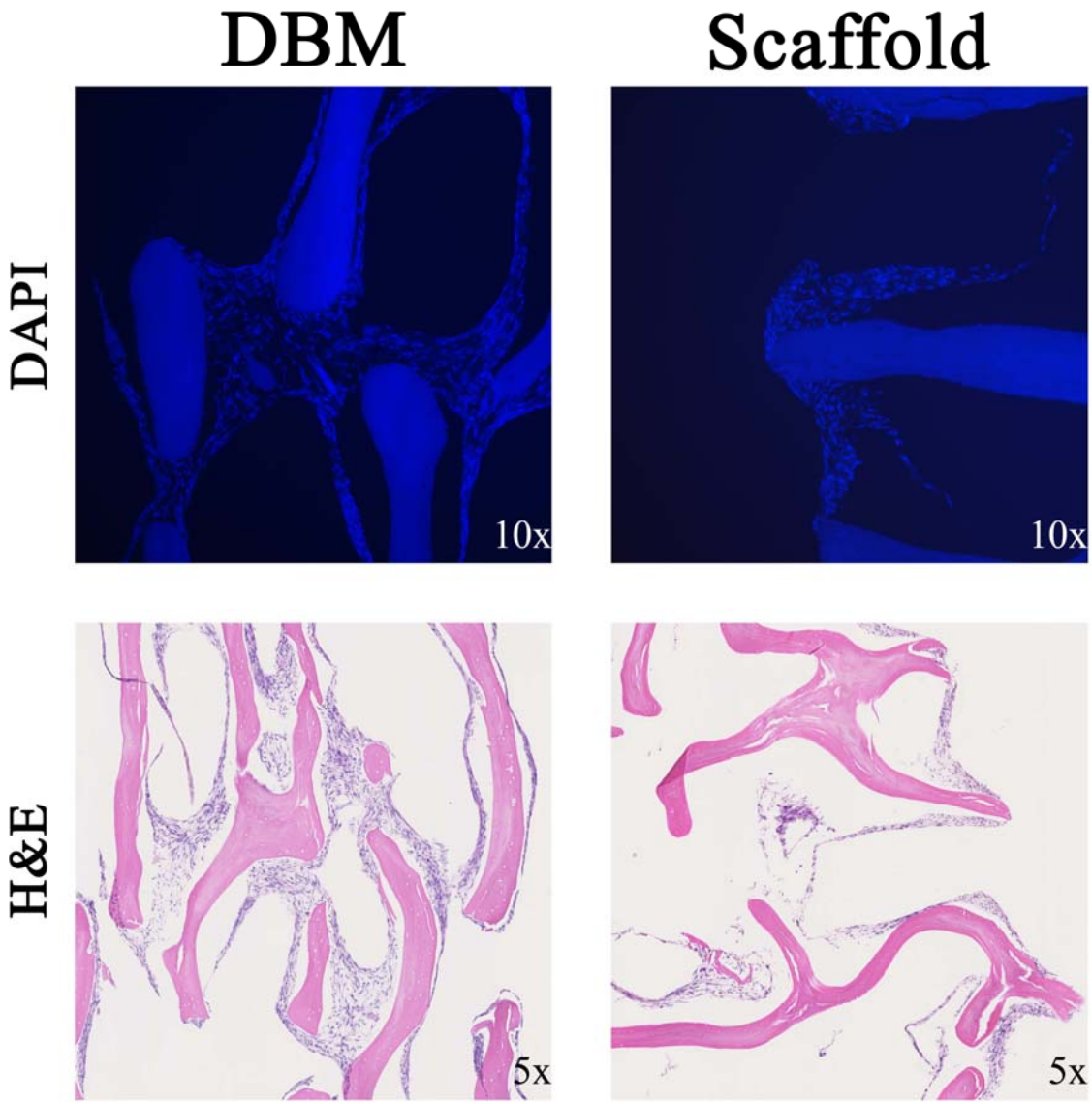


Figure 4

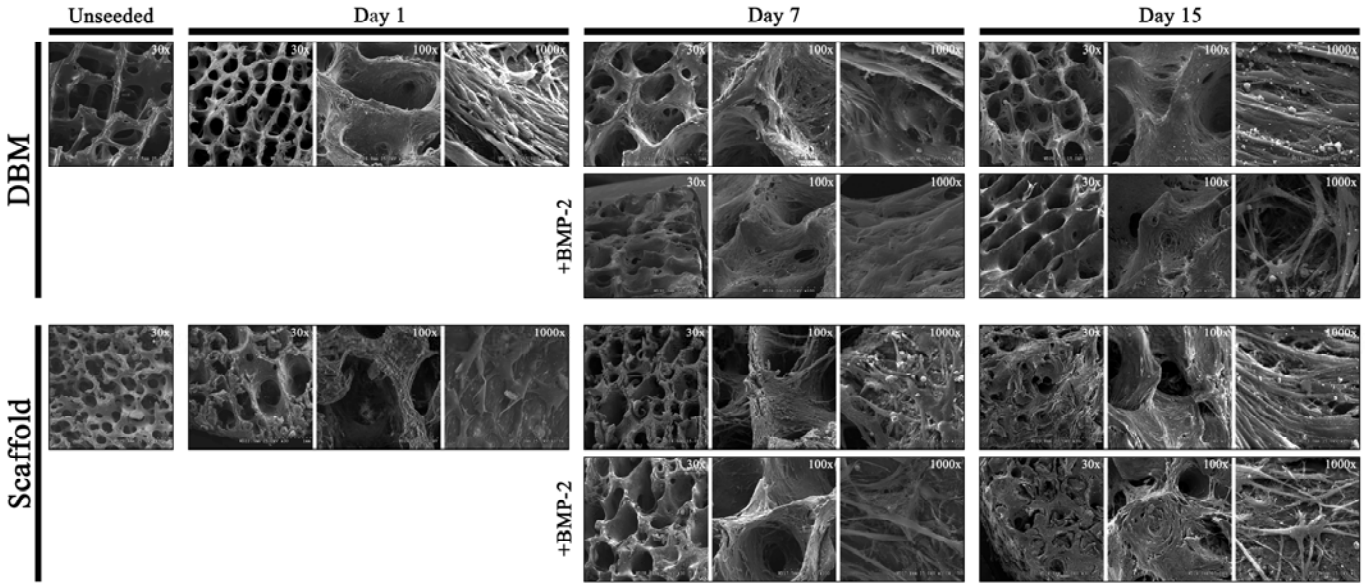

Unseeded
Day 1
Day 7
Day 15
DBM
+BMP-2
Scaffold
+BMP-2
30x
100x
1000x

Figure 5

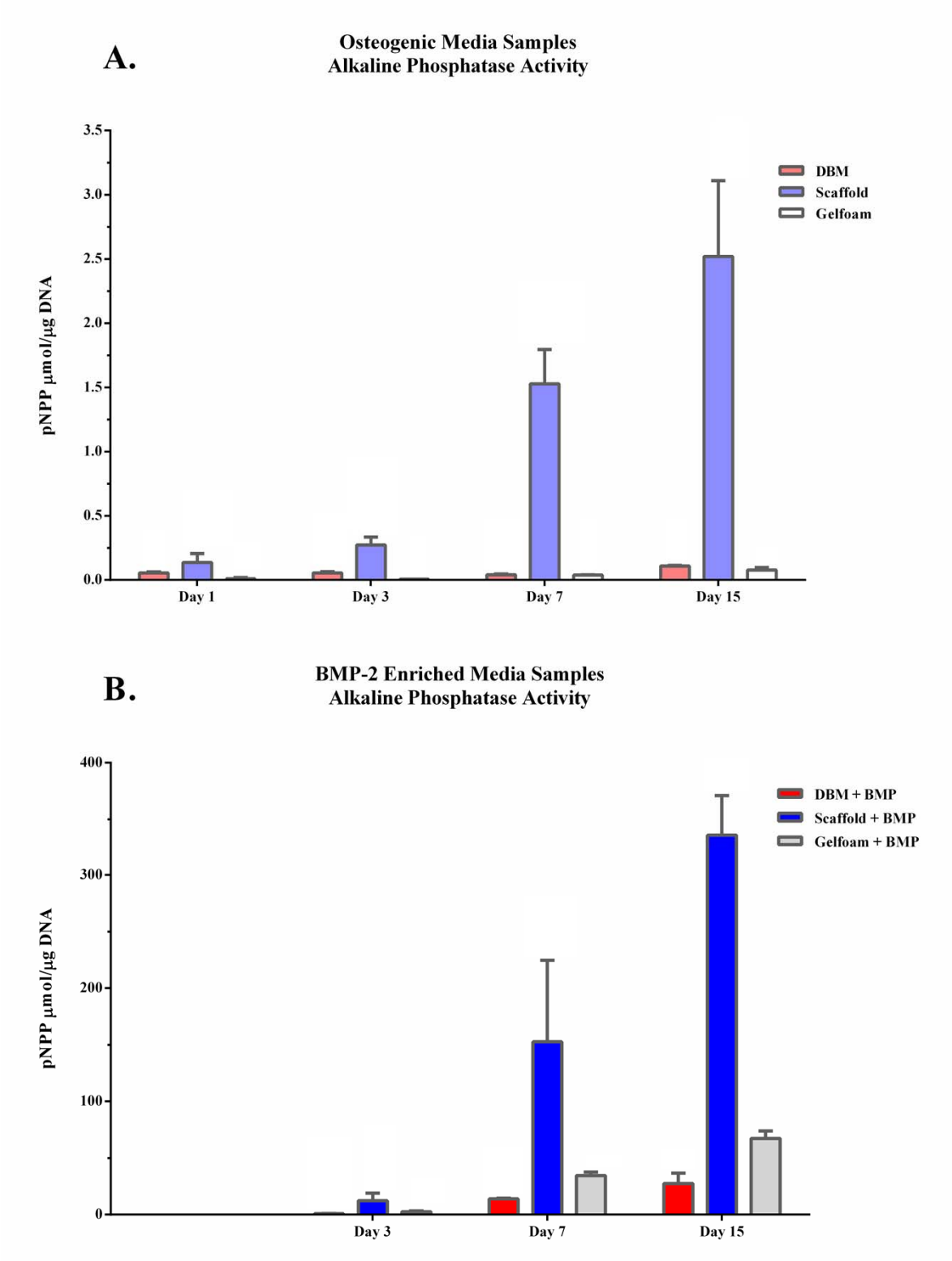

A.
Osteogenic Media Samples
Alkaline Phosphatase Activity
pNPP µmol/µg DNA
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Day 1
Day 3
Day 7
Day 15
DBM
Scaffold
Gelfoam
B.
BMP-2 Enriched Media Samples
Alkaline Phosphatase Activity
pNPP µmol/µg DNA
400
300
200
100
0
Day 3
Day 7
Day 15
DBM + BMP
Scaffold + BMP
Gelfoam + BMP

Figure 6

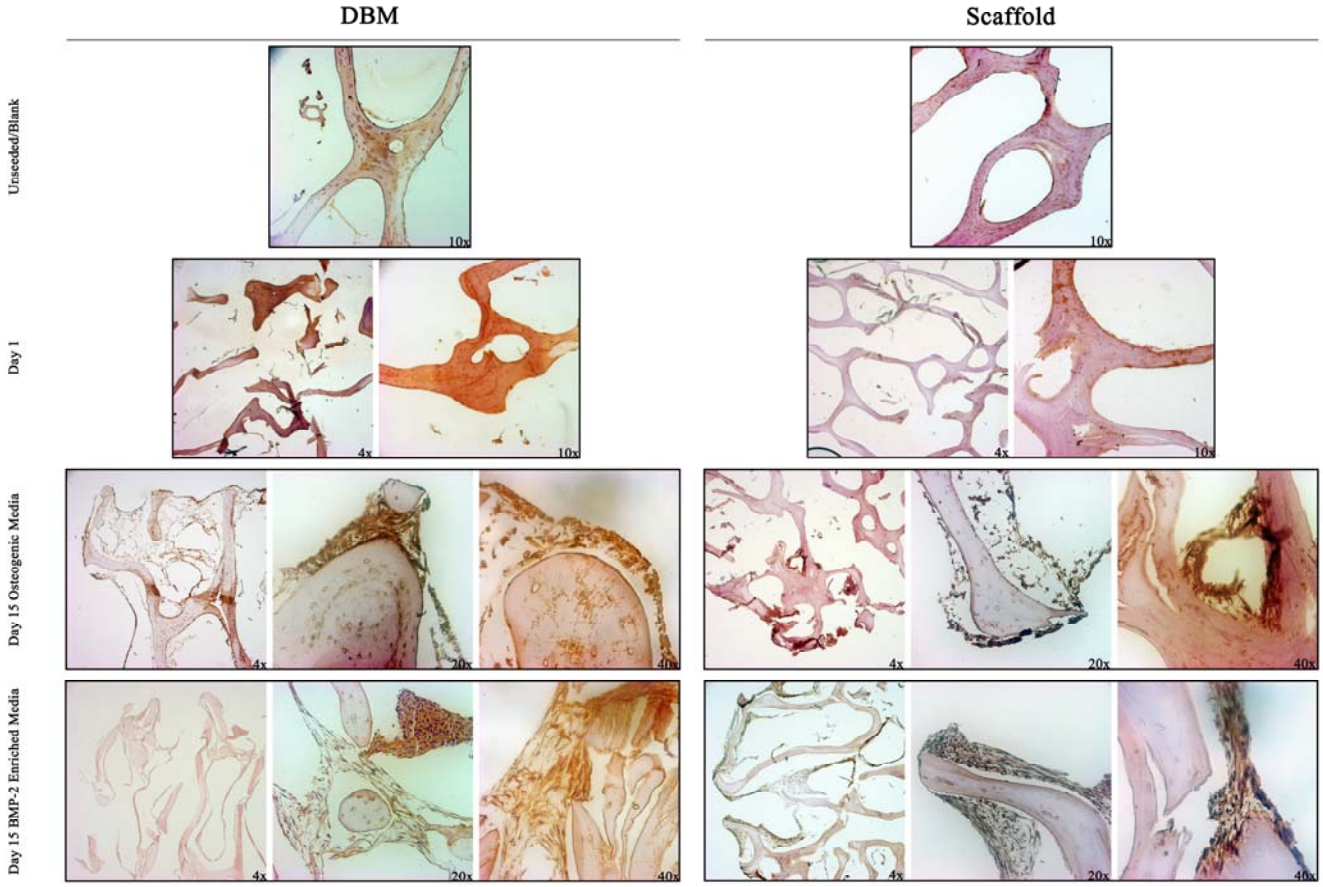
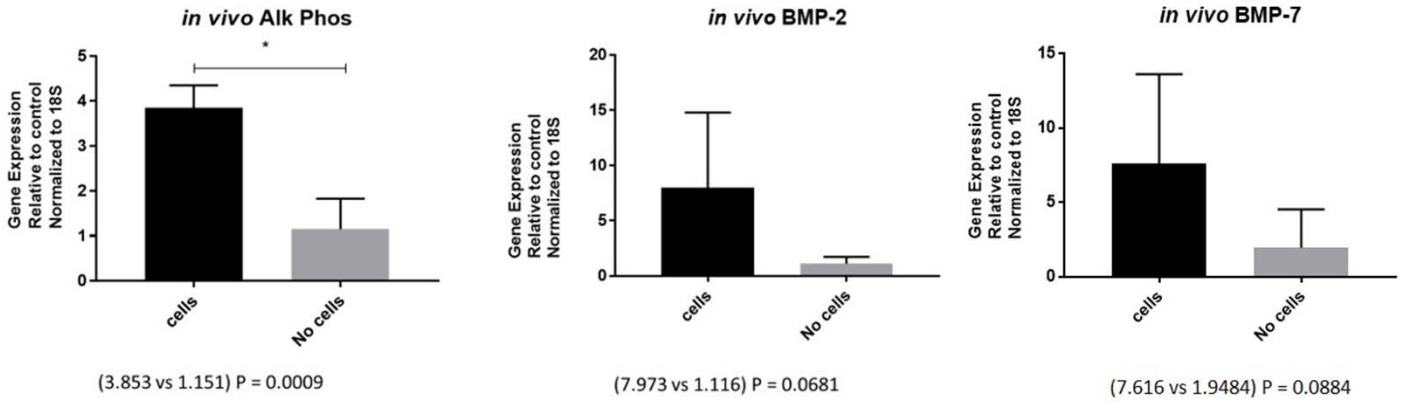

DBM
Scaffold
Unseeded/Blank
Day 1
Day 15 Osteogenic Media
Day 15 BMP-2 Enriched Media
10x
4x
20x
40x

Figure 7

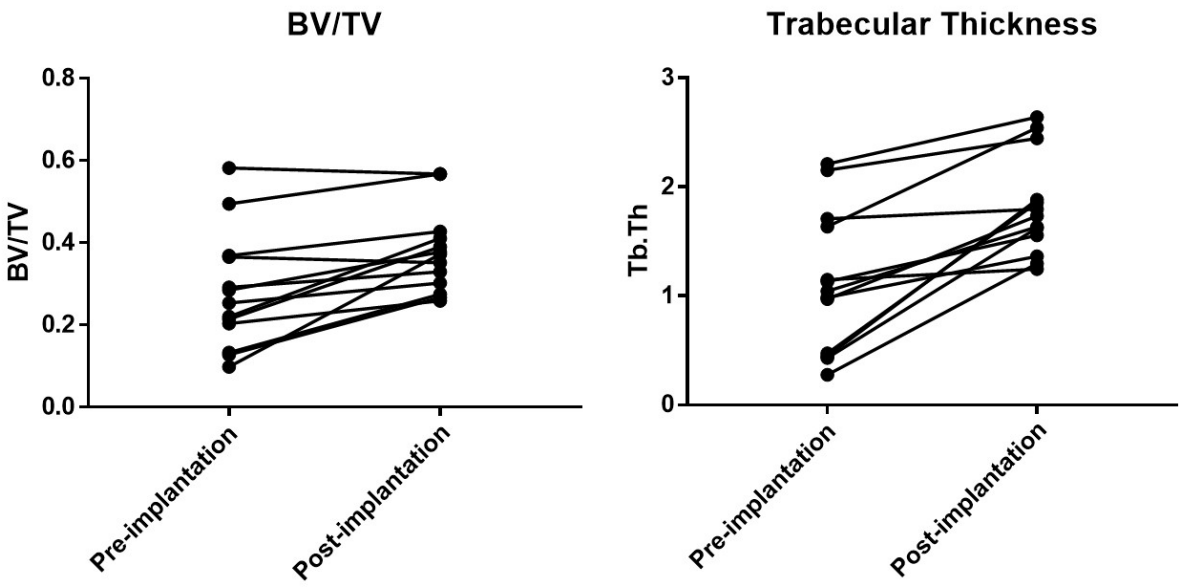


(3.853 vs 1.151) P = 0.0009

(7.973 vs 1.116) P = 0.0681

(7.616 vs 1.9484) P = 0.0884

Figure 8


BV/TV
BV/TV
0.8
0.6
0.4
0.2
0.0
Pre-implantation
Post-implantation
Trabecular Thickness
Tb.Th
3
2
1
0
Pre-implantation
Post-implantation

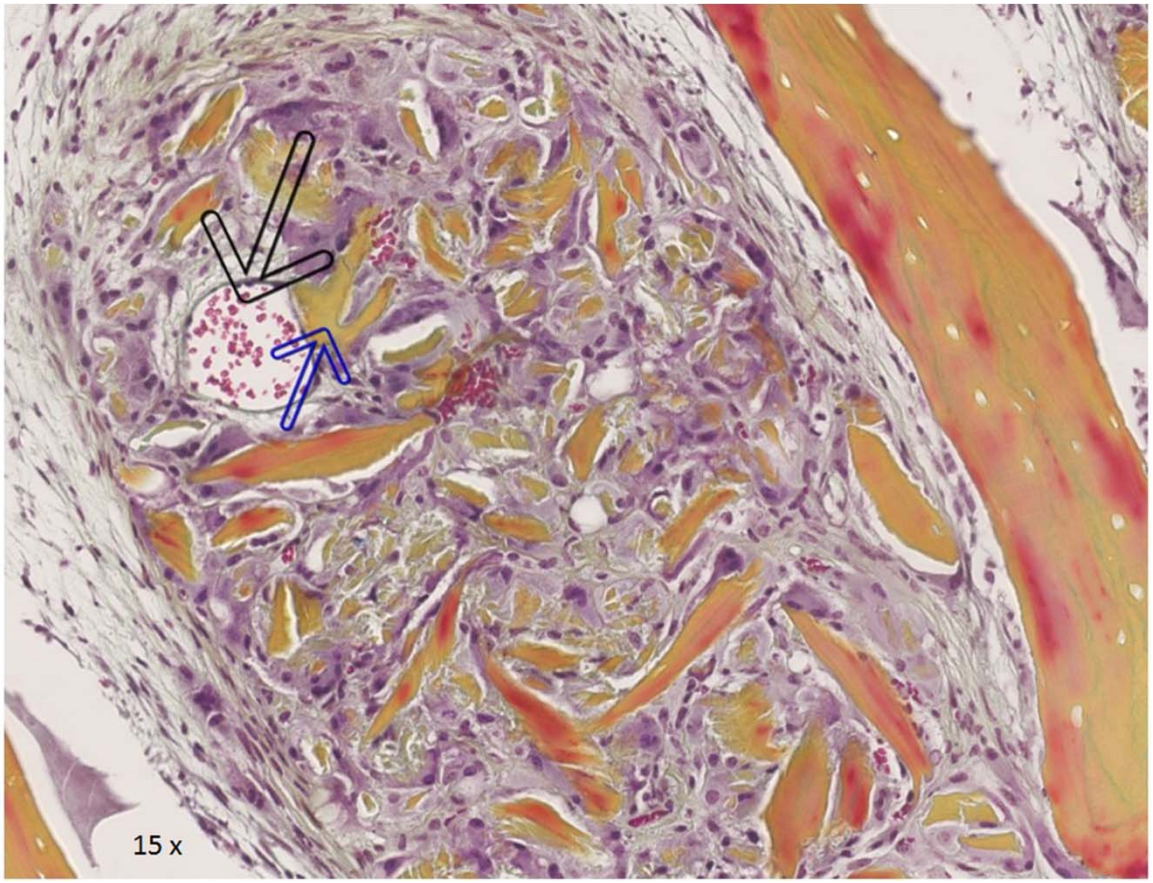



Figure 9