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Osteoblast Interactions Within a Biomimetic Apatite Microenvironment

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Abstract—Numerous reports have shown that accelerated apatites can mediate osteoblastic differentiation in vitro and bone formation in vivo. However, how cells interact within the apatite microenvironment remains largely unclear, despite the vast literature available today. In response, this study evaluates the in vitro interactions of a well-characterized osteoblast cell line (MC3T3-E1) with the apatite microenvironment. Specifically, cell attachment, spreading, and viability were evaluated in the presence and absence of serum proteins. Proteins were found to be critical in the mediation of cell–apatite interactions, as adherence of MC3T3-E1 cells to apatite surfaces without protein coatings resulted in significant levels of cell death within 24 h in serum-free media. In the absence of protein–apatite interaction, cell viability could be “rescued” upon treatment of MC3T3-E1 cells with inhibitors to phosphate (PO43−) transport, suggesting that PO43− uptake may play a role in viability. In contrast, rescue was not observed upon treatment with calcium (Ca2+) channel inhibitors. Interestingly, a rapid “pull-down” of extracellular Ca2+ and PO43− ions onto the apatite surface could be measured upon the incubation of apatites with α-MEM, suggesting that cells may be subject to changing levels of Ca2+ and PO43− within their microenvironment. Therefore, the biomimetic apatite surface may significantly alter the microenvironment of adherent osteoblasts and, as such, be capable of affecting both cell survival and differentiation.

Keywords—Biomimetic apatite, Osteoblast, Protein adsorption.

INTRODUCTION

Accelerated biomimetic apatite coatings have a history of success in both in vitro11,12 and in vivo13 studies for bone tissue engineering. Chou et al.12 previously showed that the coating of two-dimensional surfaces with accelerated apatite could support cell attachment, spreading, viability, and proliferation in standard in vitro culture conditions. The osteoinductive properties of the apatite coatings were made evident by the upregulation of several bone-specific markers such as osteopontin (OPN), osteocalcin (OCN), and bone sialoprotein (BSP) in MC3T3-E1 cells cultured on apatite compared to cells cultured on standard uncoated tissue culture polystyrene (TCPS). Furthermore, it was observed that the apatite surfaces could induce the MC3T3-E1 cells to express these osteogenic markers in the absence of commonly used osteogenic factors such as ascorbic acid and beta-glycerophosphate. On a three-dimensional substrate, MC3T3-E1 cells cultured on apatite-coated PLGA scaffolds in vitro also showed significant upregulation of OPN expression at day 3, while OCN and BSP expression was upregulated at 4 weeks relative to cells on non-coated PLGA scaffold controls.11 These apatite-coated PLGA scaffolds have also shown potential in improving bone formation in vivo, demonstrating the ability to regenerate bone in critical-size mouse calvarial defects in conjunction with adipose-derived adult stromal cells.13 Despite this success of using apatite coatings for bone tissue regeneration, little is known on the exact mechanism that induces the positive biological response of the apatite microenvironment. As a first step in elucidating the relationship between apatite surfaces and the cellular response, MC3T3-E1 pre-osteoblast cells were cultured, in this study, on apatite-coated TCPS in the presence and absence of proteins, and the effect on adhesion and viability were assessed.
MATERIALS AND METHODS

Preparation of Apatite-Coated Surfaces

Biomimetic apatite-coated surfaces were prepared using an accelerated approach using simulated body fluid solutions (5 × SBF1 and 5 × SBF2) as previously published. 10 TCPS wells were coated through an initial incubation with 5 × SBF1 for 24 h at 37 °C, followed by a 48 h incubation (at 37 °C) with 5 × SBF2. Each well was then rinsed gently with sterile distilled deionized water and dried in a laminar flow hood overnight.

Apatite Morphology

Surface morphology and elemental composition (Ca and P) of the apatite coatings were analyzed with a FEI Nova SEM 230 scanning electron microscope with attached EDS detector (FEI Co., Hillsboro, OR). Sections of apatite-coated TCPS were analyzed with FEI Nova SEM 230 scanning electron microscope with an accelerating voltage of 10 kV. Energy dispersive X-ray analysis (EDS) was performed on the samples to obtain Ca and P content of the apatite coatings.12

MC3T3-E1 Cell Culture and Viability on Apatite Surfaces

MC3T3-E1 cells were purchased from ATCC (CRL-2594). The cells were expanded under standard tissue culture conditions in MC3T3-E1 expansion medium (EM) containing α-MEM, 10% FBS, and 1% penicillin/streptomycin. For experiments performed on bare apatite surfaces, monolayers of MC3T3-E1 cells were prepared for serum-free conditions by incubating in EM containing 5% FBS for 6 h, followed by 12 h in serum-free EM. The cells were then harvested using 0.25% trypsin/2.21 mM EDTA, and resuspended at a desired density in serum-free EM. The apatite surfaces were seeded by incubating with the cell suspension overnight in a 37 °C, 5% CO₂ incubator. All tissue culture reagents were purchased from Mediatech CellGro (Manassas, VA).

To assess the effect of adsorption on viability, either FBS or BSA was absorbed to the apatite-coated surfaces. Since FBS contains a variety of proteins including albumin, BSA was also chosen in this study to eliminate possible confounding effects that multiple protein adsorption from FBS may have on influencing cell behavior or function.

For BSA-coated apatite, a 1% (w/v) stock solution was made by dissolving BSA protein (#A9418, Sigma, St. Louis, MO) in PBS (Ca²⁺ and Mg²⁺ free, Mediatech CellGro, Manassas, VA). The BSA stock solution was sterile filtered and further diluted with sterile 1XPBS to make 0.1, 0.01, and 0.001% BSA solutions. FBS solutions were created by the dilution of FBS (Omega Scientific, Tarzana, CA) in sterile 1 × PBS to make concentrations of 10, 1, 0.1, and 0.01% FBS. Apatite-coated 12-well TCPS plates were then incubated with the BSA and FBS solutions for 12 h in a 37 °C incubator. For all wells, the apatite surface area to protein solution volume ratio was 3.9 cm²/mL. Each well was then rinsed gently three times with 1 × PBS and the amount of protein adsorbed to the apatite surfaces was quantified using BCA assay (Pierce BCA Protein Assay, Thermo, Waltham, MA).

Determination of Caspase Signaling Activity by Immunofluorescence

To study apoptosis, caspase-3 activity was assessed in MC3T3-E1 cells cultured on apatite surfaces. Cells were cultured at a cell seeding density of 10,000 cells/cm² in serum-free EM for 24 h on bare apatite, 1% BSA-coated apatite, or bare apatite surfaces in the presence of 1 mM phosphonoformic acid (PFA). The cells were then fixed and probed with antibodies specific for activated caspase-3, washed three times with 1 × PBS for 5 min/wash, and then incubated with FITC-conjugated goat anti-rabbit secondary antibodies. Cell nuclei were counterstained with DAPI (Southern Biotech, Birmingham, AL). As a positive control, MC3T3-E1 cells were cultured on TCPS in the presence of 1 μM doxorubicin (Sigma) a DNA reagent, which is metabolically processed by the cells, was added directly to the MC3T3-E1 EM at select time points and the cells incubated for 1 h at 37 °C. The EM containing the metabolized Alamar Blue was then removed and measured at 535/590 nm (excitation/emission). Cell number was determined based on these absorbances according to the manufacturer. Viability assays were repeated three times (n = 3) and expressed as the average number of viable cells ±SD.
intercalator that induces apoptosis through the caspase cascade. Staining for caspase activity was observed under fluorescence microscopy (Leica DM IRB, Wetzlar, Germany).

Effect of Caspase Inhibition on MC3T3-E1 Cell Viability upon Culture on Apatite Surfaces

To further assess the role of apoptosis in cell death on apatite surfaces, MC3T3-E1 cells were cultured on bare apatite in serum-free EM in the presence of the general caspase inhibitor zVAD-fmk. MC3T3-E1 cells were prepared for serum-free conditions as described above, and treated with various concentrations of zVAD-fmk (0, 10, 50, 100 μM) prior to seeding onto apatite. The cells were then seeded at density of 10,000 cell/cm² onto apatite-coated TCPS, and again treated following seeding with zVAD-fmk at the concentrations listed above for 24 h. Cells cultured on 1% BSA-coated apatite were used as a control. After 24 h, cell viability was assessed with Live/Dead staining and Alamar Blue assay.

The Effect of Extracellular Calcium (Ca²⁺) and Phosphate (PO₄³⁻) on MC3T3-E1 Viability

The effect of Ca²⁺ and PO₄³⁻ uptake on cell viability was performed by supplementing EM with known amounts of Ca²⁺ and PO₄³⁻. For this, 10 mM stock solutions of CaCl₂ (EMD) and NaH₂PO₄ (Sigma) were prepared separately in EM. MC3T3-E1 cells were cultured on TCPS at 10,000 cells/cm² for 4 h in unsupplemented EM to allow cell attachment. After 4 h, the media from each well was replaced with EM supplemented with various concentrations of Ca²⁺ and PO₄³⁻, prepared from the 10 mM stock solutions of CaCl₂ and NaH₂PO₄. The cells were cultured in the Ca²⁺/PO₄³⁻-supplemented media for 24 h and cell viability was assessed using Live/Dead staining or Alamar Blue assay. The pH of the Ca²⁺ and PO₄³⁻-supplemented EM at each of the different concentrations was measured to verify that the pH had not altered significantly from physiological pH (data not shown).

To confirm the effect of Ca²⁺ and PO₄³⁻ uptake on cell death, MC3T3-E1 cells were incubated in EM containing cytotoxic levels of Ca²⁺ and PO₄³⁻ in the presence of Ca²⁺ blockers or PO₄³⁻ transporter inhibitor. Cells were seeded at 10,000 cells/cm² on either uncoated or apatite-coated 12-well TCPS plates and immediately treated with EM for 24 h supplemented with ion transport inhibitor. To block Ca²⁺ uptake, the L-type Ca²⁺-channel inhibitors, nifedipine (Sigma) or verapamil (Sigma), or the generalized Ca²⁺-channel inhibitor lanthanum chloride (Sigma) were added to EM at a concentration ranging from 25 to 100 μM. To block uptake of PO₄³⁻, the PO₄³⁻ transport inhibitor phosphonoformate (PFA, Sigma) was added to the culture medium at concentrations ranging from 25 μM to 1 mM. The effect of these inhibitors on MC3T3-E1 viability was assessed by Live/Dead staining and Alamar Blue assay.

Inductively Coupled Plasma-Optical Emission Spectroscopy and Radio-Labeled Calcium Phosphate Tracking

Analysis of extracellular Ca and P concentration in culture media was performed using inductively coupled plasma-optical emission spectroscopy (ICP-OES). For this, apatite-coated surfaces were incubated in the presence of serum-free α-MEM from 15 min to 24 h. Basal levels of Ca and P are reported by the manufacturer to be 1.8 and 1.0 mM, respectively. The medium from each apatite-coated well was then collected and digested with nitric acid for 2 h on a 90 °C heating block. Each digested sample was diluted with glass distilled water until the final concentration of nitric acid reached 5% to match that of the calibration standards, which contained a known amount of Ca and P. The samples were then analyzed for elemental Ca and P with a TJA Radial Iris 1000 ICP-OES machine (Thermo, Waltham, MA).

To confirm that Ca²⁺ and PO₄³⁻ ions from culture medium were adsorbing to the apatite surface, α-MEM was supplemented with radioactive Ca-45 or P-32 isotopes (MP Biomedicals, Santa Ana, CA) at a concentration of 1μCi/mL, and incubated over apatite-coated surfaces up to 24 h. The media was collected and radioactivity measured with a Beckman Coulter LS6500 multi-purpose scintillation counter (Beckman Coulter, Brea, CA). In addition, the apatite coatings were digested with 1 mM HCl from the bottom of each well and their radioactivity also measured to determine the amount of radioactive Ca²⁺ and PO₄³⁻ adsorbed to the apatite.

RESULTS

Apatite Morphology

Apatite surfaces prepared through an accelerated approach showed a plate-like structure, with plate length ranging from approximately 1–5 μm (Fig. 1). EDS analysis confirmed that the apatite consisted primarily of Ca and P, in a Ca/P atomic ratio of 1.48, which is slightly below the reported 1.67 stoichiometric ratio of pure hydroxyapatite, but is consistent with other apatite coatings prepared from this biomimetic approach.
**Protein Adsorption on Apatite Surfaces is Required for Cell Viability**

Previous studies have shown that adsorption of serum proteins onto biomaterial surfaces can mitigate cell death. Consistent with this data, the bare apatite surfaces created in this study rapidly induced the death of MC3T3-E1 cells. Using a Live/Dead immunofluorescent (IF) assay, short-term adhesion to bare apatite (i.e., 1 h) did not appear to affect MC3T3-E1 viability, with the majority of the adherent cells capable of metabolically cleaving the calcein AM viability marker. However, adhesion of cells to bare apatite for only 3 h began to produce significant levels of cell death (Fig. 2a). Increasing adhesion time to 24 h resulted in a dramatic increase in cell death with the majority of cells incorporating EthD-1 as a fluorescent marker of dead cells. Quantitatively, a similar time course of increasing cell death was observed using an Alamar Blue assay—an assay that quantifies viable cells through metabolic processing of the Alamar Blue reagent. As with the Live/Dead assay, the Alamar Blue assay confirmed that the majority of MC3T3-E1

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**FIGURE 1.** Plate-like morphology of biomimetically prepared apatite surfaces. Apatite surfaces were created in tissue culture polystyrene (TCPS) wells using an accelerated biomimetic approach. ×1000 (a) and ×5000 (b) scanning electron micrographs confirm the plate-like morphology of the resulting apatite surface. EDS analysis (a, inset) confirmed the content of calcium and phosphorus with a stoichiometric Ca/P ratio of 1.48.

**FIGURE 2.** Bare apatite surfaces do not support cell viability. (a) MC3T3-E1 cells were seeded on uncoated apatite surfaces (i.e., bare apatite) and viability assessed after 1, 3, and 24 h using a Live/Dead stain. The majority of cells remain viable (green fluorescence) after 1 h. However, increased cell death (red fluorescence) is observed between 3 and 24 h. MC3T3-E1 cells cultured on 1% BSA-coated apatite surfaces retained viability at all time points assessed. (b) MC3T3-E1 viability was quantified over 24 h culture on bare apatite at the indicated times using an Alamar Blue fluorometric assay. The total number of metabolically active (i.e., viable) cells on the apatite surface was determined (cell number — metabolically active (×1000)) and expressed with respect to time (hours cultured on apatite).
cells, after 1 h adherence to bare apatite, were still metabolically active (i.e., viable). However, a significant drop in the number of viable cells (i.e., a 79.6% decrease in viability) was observed after 3 h (Fig. 2b). Unlike the Live/Dead IF assay, Alamar Blue failed to measure any further decrease in cell viability between 3 and 24 h, whereas there was an obvious drop in viability using the Live/Dead assay. This discrepancy may be due to inherent differences in the sensitivity of these two assays. However, both assays confirm that cellular adhesion to bare apatite layers induces their death.

To mitigate cell death, apatite surfaces, prior to cell seeding, were pre-absorbed with increasing concentrations of BSA or FBS as a source of protein. A simple BCA protein assay confirmed the adsorption of these proteins to the apatite surface (Fig. 3a). For FBS a linear relationship between adsorbed protein and FBS concentration was observed between the ranges of 0.1–10%. After 12 h incubation with a 0.01% FBS solution, the surface coverage of FBS protein on apatite was measured to be approximately 1.1 µg/cm². Increasing the FBS concentration 100-fold to 1.0% FBS resulted in almost a 1.5-fold increase in adsorbed FBS protein (1.54 µg/cm²), while a 1000-fold increase to 10% FBS resulted in almost a 1.75-fold increase (1.84 µg/cm²). While not shown, there was no appreciable increase in protein absorption if the FBS concentration was increased beyond 10% (data not shown). Linearity in the adsorption of BSA to apatite surfaces was not as apparent. However, a moderate linear relationship was observed between the ranges of 0.1 and 0.001% BSA. For adsorbed BSA on apatite, incubation for 12 h with a 0.001% BSA solution resulted in approximately 0.5 µg/cm² surface coverage.

![FIGURE 3](image-url)
A tenfold increase in the BSA concentration to 0.01% led to a twofold increase in adsorbed BSA at 1.1 μg/cm². Only a slight increase in BSA adsorption was observed after increasing the BSA solution 100- and 1000-fold, with protein surface coverage of 1.22 and 1.28 μg/cm², being measured, respectively.

Live/Dead staining of MC3T3-E1 cells cultured in serum-free EM on protein-coated apatite surfaces showed that “rescuing” cell viability was related to the amount of pre-adsorbed protein on the apatite surface prior to cell seeding (Fig. 3b). As shown in Fig. 3b, the viability of cells maintained in serum-free media for 24 h on apatite surfaces with increasing amounts of adsorbed BSA or FBS, increased in a qualitative manner. For example, approximately 50% of the seeded cells maintained on apatite surfaces pre-treated with a 0.1% FBS solution remained viable, while nearly all cells remained viable on apatite surfaces pre-treated with 10% FBS. Similarly, MC3T3-E1 cells cultured for 24 h on apatite surfaces pre-exposed to 0.01% BSA (i.e., the approximate concentration of albumin found in 0.1% FBS) showed close to 50% viability, while protein pre-adsorption with a 1% BSA solution (i.e., the approximate amount of albumin found in 10% FBS) rescued viability in nearly 100% of the adherent cells. Quantifying cell metabolic activity as a means of measuring viability confirmed the Live/Dead studies (Fig. 3c). As with the protein adsorption studies of Fig. 3a, a definitive dose-dependent relationship appeared to exist between FBS concentration and cell viability. In contrast, the effect of BSA on MC3T3-E1 viability was not as linear, but appeared to plateau out at 0.01% BSA. Increasing the concentration of BSA beyond 0.01% did not enhance viability in a statistically significant manner.

**Apatite-Induced Cell Death Is Not Through Caspase-Mediated Apoptosis**

To determine whether apatite-induced cell death was mediated by an apoptotic mechanism, MC3T3-E1 cells were cultured on bare apatite surfaces at various time points and probed for caspase-mediated activation of apoptosis using an antibody specific to cleaved caspase-3. As shown in the Live/Dead and Alamar Blue assays, MC3T3-E1 cells cultured on bare apatite for only 1 h did not show any evidence of caspase-3 cleavage, consistent with the viable state of these cells at this juncture (Fig. 4a). However, cleaved caspase-3 was still not observed when the culture time was increased to 3 or 24 h—times in which MC3T3-E1 cell death has been detected (data not shown). In contrast to these results, strong immunofluorescence for cleaved caspase-3 was observed in positive controls in which cells were treated with 1 μM doxorubicin to induce apoptosis.

To determine if other effector caspases known to induce apoptosis (i.e., caspase-6, caspase-7) were mediating MC3T3-E1 cell death, cells were cultured on bare apatite surfaces in the presence of the general caspase inhibitor zVAD-fmk. Over the range of zVAD-fmk concentrations tested (0, 10, 50, 100 μM), Live/Dead staining (Fig. 4b) and Alamar Blue viability quantification (Fig. 4c) showed that general inhibition of caspase activity was not sufficient for preventing MC3T3-E1 cell death when cultured on bare apatite. Adsorbed BSA on apatite, however, still demonstrated the ability to mitigate the cytotoxic effects of the apatite surface, with or without the presence of zVAD-fmk in the medium. Taken together, the lack of caspase-3 activation and the inability to rescue cell viability through the inhibition of caspase activity, suggest that the mechanism of apatite-induced cell death over 24 h of culture is not due to caspase-mediated apoptosis.

**Elevated Levels of Ca²⁺ in Combination with PO₄³⁻ Can Decrease MC3T3-E1 Cell Viability**

Previous work by Adams et al.² has shown that extracellular Ca²⁺ and PO₄³⁻ can decrease the viability of human osteoblast-like cells and MC3T3-E1 murine pre-osteoblast cells in a dose-dependent manner. Since biomimetic apatite surfaces are composed primarily of Ca²⁺ and PO₄³⁻, it is possible that the release of these ions into the medium upon culture onto apatites could expose MC3T3-E1 cells to elevated levels of these ions. To confirm the effects of elevated extracellular Ca²⁺ and PO₄³⁻ on MC3T3-E1 viability, MC3T3-E1 cells were cultured on TCPS in basal EM, containing 1.8 mM total Ca²⁺ and 1.0 mM total PO₄³⁻ and in EM supplemented with increasing concentrations of these two ions. Using Alamar Blue to quantify cell viability (Fig. 5a), it was confirmed that exposure of cells to elevated extracellular Ca²⁺ and PO₄³⁻ resulted in a decrease in MC3T3-E1 viability. Cell death by Ca²⁺ and PO₄³⁻ ions was concentration-dependent and required the presence of both ions for maximal effect. For example, when the concentration of extracellular Ca²⁺ was held constant at its basal level of 1.8 mM, increasing extracellular PO₄³⁻ levels (e.g., 2.5–10 mM) did not significantly alter cell viability. Likewise, when cells were cultured at basal PO₄³⁻ levels (i.e., 1.0 mM), increasing extracellular Ca²⁺ concentrations (i.e., 2.5–10 mM) had no significant effect on cell death. However, when both the concentrations of Ca²⁺ and PO₄³⁻ were increased, MC3T3-E1 cell death levels also increased. Increasing extracellular PO₄³⁻ to 5.0 mM, combined with increasing Ca²⁺ levels to 5.0 mM led to nearly a 33% decrease in the number of viable cells, while increasing
FIGURE 4. MC3T3-E1 cell death on bare apatite surfaces is not mediated through a caspase-dependent apoptotic pathway. (a) MC3T3-E1 cells were cultured on bare apatite (left panel), 1% BSA-coated apatite (center panel), or bare apatite with 1 mM PFA (right panel) for 1 h and then analyzed for immunofluorescent staining of activated caspase-3 (cleaved caspase 3—green fluorescence). Cell nuclei were counterstained with DAPI (blue) and the images merged. (b) MC3T3-E1 cells cultured on bare apatite (black bars) or 1% BSA-coated apatite surfaces (white bars) for 24 h in the presence of the general caspase inhibitor zVAD-fmk. Cell viability was assessed with Live (green)/Dead (red) staining. (c) Quantification of cell viability on bare apatite vs. 1% BSA-coated apatite in the presence of zVAD-fmk was assessed using fluorescent Alamar Blue assay. The number of viable cells (cell number − metabolically active (×1000)) was expressed with respect to the μM concentration of zVAD-fmk.
Ca^{2+} further to 10 mM decreased cell viability 98%. Similarly, when PO_4^{3-} levels were increased to their maximal level of 10 mM, a Ca^{2+} concentration of 5.0 mM resulted in a 50% drop in viable cells, while a Ca^{2+} concentration of 10 mM decreased cell viability 95%. Taken together, the results confirmed previous studies showing that the ion-pairing of extracellular Ca^{2+} and PO_4^{3-} at specific concentrations can be cytotoxic to MC3T3-E1 cells. Moreover, the data indicates that at higher levels of PO_4^{3-} (i.e., 5, 10 mM), elevating extracellular Ca^{2+} levels can dramatically decrease cell viability.

To further confirm the cytotoxic effects of Ca^{2+} and PO_4^{3-} on MC3T3-E1 viability, cells, incubated on TCPS in the presence of cytotoxic levels of extracellular Ca^{2+} and PO_4^{3-}, were treated with the Na–Pi co-transporter inhibitor PFA, to block PO_4^{3-} entry into the cell, followed by an assessment of their viability. Results from the Alamar Blue assay confirmed previous studies showing that administering PFA results in the “rescue” of MC3T3-E1 viability (Fig. 5b). At the higher levels of extracellular PO_4^{3-} (i.e., 5, 10 mM), which were shown to be cytotoxic in this study with a slight increase in extracellular Ca^{2+}, a delivered dose of 1 mM PFA was sufficient to significantly reduce the amount of cell death that was observed above. In contrast, as has been shown previously, although the blockage of PO_4^{3-} transporters was sufficient to inhibit the Ca^{2+}/PO_4^{3-}-induced cell death, treatment of cells with L-type Ca^{2+} channel blockers (nifedipine or verapamil) and a general Ca^{2+} channel blocker (lanthanum chloride) did little to mitigate cell death in the presence of elevated extracellular Ca^{2+} and PO_4^{3-} (data not shown).

Apatite Surfaces in Culture Medium Induce the “Pull-Down” of Extracellular Ca^{2+} and PO_4^{3-}”

As shown above, increasing levels of extracellular Ca^{2+} and PO_4^{3-} can be cytotoxic to adherent MC3T3-E1 cells. Since biomimetic apatite surfaces are composed primarily of Ca^{2+} and PO_4^{3-}, the observed cell death upon adherence of MC3T3-E1 cells to bare apatite may be the result of localized degradation of the apatite in culture conditions, thus elevating extracellular levels of these ions. Therefore, the stability of the apatite surface in culture was measured using ICP-OES. For this, acellular, bare apatite surfaces were incubated in serum-free α-MEM (as a component of EM) for up to 24 h and extracellular levels of calcium and phosphorus (as a component of phosphate) were measured by ICP-OES (Fig. 6a). Consistent with reported values, basal levels of calcium and phosphorus within serum-free α-MEM was measured at 1.8 and 1.0 mM, respectively. During the first 3 h of incubation on apatite surfaces, the concentration of calcium and phosphorus within the α-MEM decreased to approximately 53 ± 0.041% and 63 ± 0.032% of their original concentrations, respectively, suggesting that the apatite layer may “pull-down” these ions from the...
overlying medium. After 12 h, this calcium and phosphorus ion "pull-down" reached equilibrium, stabilizing at a concentration of approximately 0.58 ± 0.14 mM Ca and 0.42 ± 0.04 mM P, decreasing to 32 ± 0.072% and 44 ± 0.053% of the basal levels, respectively. ICP-OES analysis of medium incubated over apatite surfaces for an additional 48 h (i.e., 72 h total) did not detect any further change in the levels of extracellular calcium and phosphorus. Taken together, the ICP-OES data suggests that the apatite surface does not significantly release Ca²⁺ and PO₄³⁻ ions into the extracellular environment but may induce a "pull-down" of these ions from the culture medium.

To confirm this data, apatite surfaces were cultured with serum-free α-MEM containing radioactive Ca-45 and P-32. After 3 h incubation over apatite surfaces, the radioactivity of Ca-45 and P-32 in the serum-free α-MEM fell to levels nearly identical to that obtained from ICP-OES. (Figs. 6b, 6c, dashed lines). The amount of radioactive Ca-45 and P-32 in the medium fell to 53 ± 0.017% and 62 ± 0.0067%, respectively. Similar to the results obtained by ICP-OES, the decrease in Ca-45 and P-32 in the medium began to level off after 12 h incubation over apatite at approximately 36 ± 0.017% of the starting Ca-45 levels and 49 ± 0.011% of the P-32 initially added to the serum-free medium.

After removal of the Ca-45 and P-32-supplemented α-MEM from the apatite-coated wells at each time point, the apatite coatings were dissolved with dilute HCl and the amount of Ca-45 and P-32 that had deposited on the surfaces were measured. The radioactivity of deposited Ca-45 and P-32 onto the apatite surface correlated almost identically to the amount of radioactive material that had been depleted from the Ca-45 and P-32-supplemented medium collected at each time point (Figs. 6b, 6c, solid lines). Along with the ICP-OES data, these results suggest that the apatite surfaces are capable of altering local extracellular ionic Ca²⁺ and PO₄³⁻ concentrations that are presented to the cultured MC3T3-E1 cells.

Inhibition of PO₄³⁻ Uptake Can "Rescue" MC3T3-E1 Viability upon Culture on Apatite Surfaces

The results from this study, as well as those obtained by others, suggest that the inhibition specifically of Na–Pi co-transporters can rescue viability...
of MC3T3-E1 cells cultured on TCPS in the presence of cytotoxic levels of Ca\(^{2+}\) and PO\(_4^{3-}\). Therefore, the viability of MC3T3-E1 cells cultured on bare apatite was assessed in the presence of PFA. Consistent with our studies on TCPS, live-dead staining (Fig. 7a) and Alamar Blue quantitation (Fig. 7b) showed a concentration-dependent effect of the ability of PFA to rescue MC3T3-E1 viability, with the minimum concentration required for significant rescue at 500 \(\mu\text{M}\). As expected, pre-coating apatite surfaces with 1% BSA negated the cytotoxic effect of the apatite surface. To assess if increasing levels of PFA could compound the toxicity of the apatite surface, cells were cultured on apatite surfaces coated with 1% BSA as a control and treated with increasing amounts of PFA. Viability levels were unchanged on these BSA-coated surfaces in the presence of increasing PFA, indicating a lack of toxicity by PFA. The observed rescue was specific to PO\(_4^{3-}\) uptake as MC3T3-E1 cells cultured on apatite and treated with the Ca\(^{2+}\) channel inhibitors nifedipine, verapamil, or lanthanum chloride, showed similar levels of cell death when compared to samples cultured on apatite in the absence of these inhibitors (Fig. 8). Viability levels were unchanged as concentrations of lanthanum chloride were increased on BSA-coated surfaces, indicating a lack of toxicity attributable to this inhibitor. However, a possible toxic effect was observed for nifedipine, with levels above 5 \(\mu\text{M}\) decreasing the viability of cells cultured on BSA-coated apatite controls. However, even at subtoxic nifedipine levels (i.e., 1 and 5 \(\mu\text{M}\)), this inhibitor was still unable to rescue MC3T3-E1 viability on bare apatite surfaces. Based on these results, it is possible that the observed death of MC3T3-E1 cells cultured

![FIGURE 7](image_url)

**FIGURE 7.** Blocking the uptake of phosphate ions can rescue the viability of MC3T3-E1 cells cultured on bare apatite. MC3T3-E1 cells were cultured for 24 h on bare apatite in EM supplemented with the Na–Pi co-transport inhibitor phosphonoformate (PFA) at the indicated concentrations to block entry of phosphate into the cells. Viable cells (green fluorescence) and dead cells (red fluorescence) were detected using a Live/Dead viability cytotoxicity stain. MC3T3-E1 cells were also cultured with PFA on apatite surfaces coated with 1% BSA (1% BSA-coated apatite) as a control for the effects of this inhibitor. Increasing levels of viable cells on bare apatite treated with increasing levels of PFA suggests that blocking phosphate uptake can "rescue" MC3T3-E1 cells from apatite-induced cell death. (b) MC3T3-E1 cells were cultured on either bare apatite (black bars) or 1% BSA-coated apatite (white bars) as a control, and the number of viable cells was determined via Alamar Blue assay (cell number - metabolically active \(\times 1000\)). Increasing amounts of PFA appears to increase MC3T3-E1 viability on bare apatite with a concentration of 500 \(\mu\text{M}\) rescuing the majority of cells.
on bare apatite is due to the specific uptake of $\text{PO}_4^{3-}$ ions into the cell.

**DISCUSSION**

Despite the evidence suggesting that accelerated biomimetic apatite coatings are capable of mediating osteoblastic differentiation in vitro and new bone formation in vivo, the exact mechanisms by which cells interact with biomimetic apatite coatings to elicit these osteogenic responses remains largely unknown, and few studies in the literature have studied the direct cell-apatite relationship closely. As such, this study attempts to more closely examine the relationship between the apatite layer and the cellular response. In the in vivo environment, apatite materials are very biocompatible. However, performing the in vitro experiments in this study allows us to dissect the apatite microenvironment and evaluate the relative contribution of each component in this highly complex, dynamic system. To accomplish this, MC3T3-E1 pre-osteoblasts were cultured on apatite surfaces and the effect of this surface on the adhesion and viability of these cells was assessed.

As was previously shown, apatite coatings prepared from an accelerated biomimetic approach resulted in a uniform coating consisting of $\text{Ca}^{2+}$ and $\text{PO}_4^{3-}$ ions in a calcium/phosphorus atomic ratio of 1.48, which is below the stoichiometric ratio of 1.67 for hydroxyapatite. The coating consists of distinct plate-like apatite crystals around amorphous calcium phosphates. Electron diffraction of the calcium-deficient, plate-like apatite crystal revealed diffraction patterns at $d_1 = 2.81$ Å, $d_2 = 3.44$ Å, and $d_3 = 2.72$ Å which correspond to (2 1 1), (0 0 2), and (1 1 2) planes of hydroxyapatite, respectively. Although the direct effect of apatite crystal structure on cell viability remains largely undiscovered, it is known, however, that the crystalline phase of the apatite contributes to

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**FIGURE 8.** Blocking the uptake of calcium ions has no effect on the viability of MC3T3-E1 cells cultured on bare apatite. MC3T3-E1 cells were cultured for 24 h on bare apatite in EM supplemented with the L-type calcium channel inhibitors (a) nifedipine, and (b) verapamil and the general calcium channel blocker (c) lanthanum chloride at the concentrations shown (black bars). MC3T3 cells were also cultured with these inhibitors on apatite surfaces coated with 1% BSA (1% BSA on apatite) as a control for the effects of this inhibitor (white bars). The number of viable cells (cell number — metabolically active ($\times$1000)) was measured via Alamar Blue assay. At the given concentrations indicated below, treatment with calcium channel blockers was not able to "rescue" viability of MC3T3-E1 cells cultured on bare apatite surfaces. Treatment with higher concentrations of nifedipine (i.e., 10–100 µM) indicated a possible toxic effect of this calcium channel blocker to control cells cultured on 1% BSA-coated apatite, while lack of toxicity was observed for the given concentrations of verapamil and lanthanum chloride.
its stability and consequently its dissolution rate.\textsuperscript{14,29} It is known that both the amorphous and crystalline phases undergo continuous phase transformation, and fluctuations in $\text{Ca}^{2+}$ and $\text{P}O_4^{3-}$ levels may contribute significantly to changes in the overall microenvironment and subsequent \textit{in vitro} cellular response.

Consistent with previous studies,\textsuperscript{36} MC3T3-E1 cells rapidly adhered to uncoated apatite materials (i.e., bare apatite). However, cell death began to appear within the first 3 h post-seeding with increasing levels of cell death becoming apparent as culture time increased. The reason for this rapid cell death was found not to be due to canonical apoptotic mechanisms. Cells undergoing apoptosis, or “programmed cell death,” typically commit to one of two distinct pathways (extrinsic or intrinsic) that converge upon one or more effector caspases (caspase-3, -6, -7), whose activation results in cell death.\textsuperscript{22} Our results, however, showed that the bare apatite surface did not induce activation of caspase-3 within adherent MC3T3-E1 cells, nor did inhibition of caspase activation by the general caspase inhibitor zVAD-fmk prevent cell death. Although our experiments preclude activation of the caspase cascade as the mechanism of death in MC3T3-E1 cells cultured on bare apatite, it is still possible that cell death via apoptosis may be occurring through caspase-independent pathways.\textsuperscript{9}

Morphologically, apoptosis is generally marked by membrane blebbing, chromatin condensation, and DNA fragmentation.\textsuperscript{34,38} In this study, DAPI staining as well as EthD-1 (dead) staining of cell nuclei clearly show that cells cultured on bare apatite exhibit significant alteration of nuclear morphology. However, instead of DNA condensation both DAPI and EthD-1 show a very diffuse staining pattern, suggesting that DNA dispersion outside the nuclear envelope may be occurring when cells are cultured on bare apatite. This result may further suggest that when cultured on bare apatite surfaces, the mechanism of apoptosis is also known to cause the net surface charge to become more negative.\textsuperscript{31} As such, the adsorption of BSA or FBS to the apatite layers in this study may alter surface charge sufficiently to improve cell adhesion and viability.

Adsorbed protein layers, alternatively, may increase the surface stability of the apatite through the modulation of phase transformation.\textsuperscript{3,23} Fibroblasts cultured on biphasic tricalcium phosphate–hydroxapatite (TCP–HA) ceramics in the absence of proteins are thought to rupture due to adhesion to the unstable TCP–HA surface,\textsuperscript{36} while the addition of serum components to their culture media is capable of mitigating this response. The adsorption of serum protein to these TCP–HA surfaces and the increased stability of this surface are proposed as the mechanism behind the increased survival of these fibroblasts. Additional studies on the surface charge and stability of the apatite surfaces created in this study are certainly warranted.

Previous \textit{in vitro} work on MC3T3-E1 pre-osteoblasts has shown that elevated levels of both extracellular $\text{Ca}^{2+}$ and $\text{P}O_4^{3-}$ decrease cell viability, possibly through their complexing as an ion pair or cluster, thus triggering receptor-mediated induction of apoptosis, or endocytic activation of cell death.\textsuperscript{22} Consistent with these studies, we confirmed that MC3T3-E1 cells, cultured on TCP showed increasing levels of cell death upon supplementation with both extracellular $\text{Ca}^{2+}$ and $\text{P}O_4^{3-}$. $\text{Ca}^{2+}$ uptake into osteoblasts is
thought to be mediated through several types of calcium channels including conventional L- and T-type channels and G-protein coupled receptors termed “Ca²⁺-sensing receptors” that respond to extracellular Ca²⁺ levels. Phosphate uptake by these cells has been attributed to the type III Na–Pi transporters, Pit-1 and Pit-2. While both Ca²⁺ and PO₄³⁻ ions were needed to induce MC3T3-E1 cell death in this study, only specific inhibition of PO₄³⁻ uptake was able to mitigate this response, indicating that cell death is sensitive to PO₄³⁻ transport, and that this sensitivity has been shown to be Ca²⁺-dependent. In contrast, treatment with several Ca²⁺ channel blockers (i.e., nifedipine, verapamil, lanthanum chloride) was unable to change levels of cell death. Although the inhibition of the Ca²⁺ channels specific to the blockers used in this study failed to rescue cell viability, there may be other Ca²⁺ channels that play a more significant role in mediating cell viability and function, and efforts to determine intracellular Ca²⁺ levels will provide additional insight into this mechanism. Inhibition of extracellular PO₄³⁻ transport into human osteoblasts and MC3T3-E1 cells by the Pit-1 inhibitor phosphonoformate (PFA) has been shown to reduce Ca²⁺/PO₄³⁻-induced cell death through its ability to modulate the mitochondrial membrane permeability transition as well as caspase-mediated apoptosis. The precise reason for why both extracellular Ca²⁺ and PO₄³⁻ ions are needed to induce cell death in MC3T3-E1 cells, and why specifically inhibiting PO₄³⁻ uptake is able to rescue these cells remains unclear. In vascular smooth muscle cells, Pit-1 expression levels can be regulated by calcium concentration. As such, it is possible that increasing extracellular Ca²⁺ levels may increase PO₄³⁻ uptake into MC3T3-E1 cells through its ability to regulate expression levels of the Pit-1 transporter. Further studies examining this possibility are certainly warranted.

As a rich source of Ca²⁺ and PO₄³⁻, biomimetic apatite coatings may be able to induce cell death in a manner similar to extracellular Ca²⁺/PO₄³⁻. In vitro, slightly acidic conditions can induce the dissolution of calcium phosphate ceramic materials and the release of Ca²⁺ and PO₄³⁻ ions into the extracellular environment. The release of these ions may create a microenvironment surrounding the cell in which the levels of Ca²⁺ and PO₄³⁻ are toxic. Subsequent PO₄³⁻ uptake by the adherent MC3T3-E1 cell would then lead to PO₄³⁻-induced cell death. In support of this theory, the rescue of MC3T3-E1 viability on bare apatite was induced in the current study upon treatment of the cells with PFA, whereas blocking Ca²⁺ uptake had no effect. Furthermore, the presence of an adsorbed protein layer may be sufficient for mitigating PO₄³⁻ uptake by MC3T3-E1 cells in a similar manner as PFA. However, the ICP-OES analysis of our study confirmed that the culture conditions used did not cause a noticeable release of ions from the apatite into solution. Rather, levels of extracellular calcium and phosphorus (as a component of PO₄³⁻) were found to decrease upon incubation of apatite surfaces with α-MEM, suggesting that the apatite surface may act to “pull-down” or “attract” Ca²⁺ and PO₄³⁻ ions from the overlying medium towards the apatite surface. Similar decreases in the concentrations of Ca²⁺ and PO₄³⁻ ions in culture medium have been reported with TCP–HA ceramics. How this “pull-down” might relate to MC3T3-E1 death on bare apatite layers remains unknown but it is tempting to speculate that an apatite-induced “flux” of PO₄³⁻ ions through the microenvironment of the adherent cell could result in increased uptake of these ions, thus resulting in the induction of cell death.

CONCLUSIONS

In the absence of an adsorbed protein layer, bare apatites surfaces induce cell death of MC3T3-E1 pre-osteoblasts in serum-free media. However, it was determined that the mechanism of cell death was not mediated by caspase-dependent activation of apoptosis. Cell death could be prevented by pre-coating apatite surfaces with BSA or FBS proteins, or by pre-treating the cells with PFA to inhibit Na–Pi transport into the cell. These results suggest that adsorbed proteins may be capable of altering the bare apatite microenvironment to make it less detrimental to cell viability, possibly through the modulation of phosphate-mediated cell death.

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