Bioactive Silica Nanoparticles Promote Osteoblast Differentiation through Stimulation of Autophagy and Direct Association with LC3 and p62

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ABSTRACT We recently identified an engineered bioactive silica-based nanoparticle formulation (designated herein as NP1) that stimulates in vitro differentiation and mineralization of osteoblasts, the cells responsible for bone formation, and increases bone mineral density in young mice in vivo. The results demonstrate that these nanoparticles have intrinsic biological activity; however, the intracellular fate and a complete understanding of the mechanism(s) involved remains to be elucidated. Here we investigated the cellular mechanism(s) by which NP1 stimulates differentiation and mineralization of osteoblasts. We show that NP1 enters the cells through a caveolae-mediated endocytosis followed by stimulation of the mitogen activated protein kinase ERK1/2 (p44/p42). Our findings further revealed that NP1 stimulates autophagy including the processing of LC3β-I to LC3β-II, a key protein involved in autophagosome formation, which is dependent on ERK1/2 signaling. Using a variant of NP1 with cobalt ferrite magnetic metal core (NP1-MNP) to pull down associated proteins, we found direct binding of LC3β and p62, two key proteins involved in autophagosome formation, with silica nanoparticles. Interestingly, NP1 specifically interacts with the active and autophagosome associated form of LC3β (LC3β-II). Taken together, the stimulation of autophagy and associated signaling suggests a cellular mechanism for the stimulatory effects of silica nanoparticles on osteoblast differentiation and mineralization.

KEYWORDS: silica nanoparticles · endocytosis · ERK1/2 · autophagy · LC3β · p62 · osteoblast differentiation
entry. Clathrin-mediated endocytosis involves membrane invagination (~200 nm) regulated by coating proteins such as caveolin and is most often associated with internalization of pathogens, nutrients, antigens, and receptors, and caveolin/lipid raft-mediated endocytosis (~60–80 nm) occurs in cholesterol-rich regions of the membrane and has been associated with the regulation of cell signaling. Cellular recognition of extracellular factors can also trigger various signal transduction events. Many signaling events are funneled through one of three mitogen-activated protein kinases (MAPKs): extracellular signal-regulated kinases (ERK1/2, p44/42) most often associated with cell growth and proliferation, c-Jun amino (N)-terminal kinases (JNK1/2/3) often linked with both environmental as well as internal cell stress, and p38 associated with environmental stresses and inflammatory cytokines (reviewed in the literature). Once an extracellular factor is internalized there are a number of different mechanisms by which a cell will process the material such as targeting to the lysosome, phagosome, and autophagosome. Although the mechanism(s) by which cells process internalized nanomaterials is currently poorly understood, recent studies have suggested autophagy as a possible cellular intermediate.

The cellular process of macroautophagy (referred to herein as autophagy) is a highly regulated catabolic cellular process that degrades unnecessary or dysfunctional proteins and organelles through delivery to the lysosome. Autophagy can be induced by various stimuli, such as stress, cytokines, pathogens, aggregated proteins, and damaged or surplus organelles. Autophagy is characterized by sequestration of targeted proteins or organelles into double membrane vesicles called autophagosomes, which fuse with the lysosome causing degradation of the contents. Formation of the autophagosome is controlled by at least 32 different autophagy related genes (Atgs) mostly identified in yeast but conserved in mammalian cells. A key protein involved in "cargo" delivery and development of the double membrane is the microtubule-associated protein 1 light chain 3 (LC3β or Atg8), referred to herein as LC3β. Upon autophagosome formation inactive LC3β (LC3β-I) is proteolytically processed and lipidated to form active LC3β-II. An important protein involved in cargo delivery to the autophagosome is p62/Sequestosome 1 (SQSTM1) which binds ubiquitinated proteins and LC3β-II and results in targeting of substrates to the autophagosome. p62 (also known as a signaling adaptor/scaffold protein) has been proposed to regulate the packing and delivery of poly-ubiquitinated, misfolded, aggregated proteins and dysfunctional organelles for clearance through autophagy in mammalian cells and Drosophila. A recent study has linked the requirement of autophagy for osteoblast differentiation in vitro and a second has demonstrated that suppression of autophagy in mice leads to decreased bone quality similar to aging. These results suggest an important role of autophagy in osteoblast mineralization and maintenance of bone quality in vivo, although the details remain to be fully elucidated (reviewed in the literature).

To date, spherical silica-based nanoparticles greater than 30 nm and less than 100 nm in diameter have been generally considered to be compatible with cell viability in vitro, although further studies are needed to fully understand the complex physicochemical interactions in vivo. Our recent studies suggest that certain silica nanoparticle formulations are not inert but have intrinsic beneficial biological activity on osteoblasts and osteoclasts. These nanoparticles are spherical 50 nm silica-based and have been synthesized by the Stöber method with or without a cobalt ferrite core, which possess magnetic properties, as well as fluorescent rhodamine B incorporated into the silica shell and with or without a surface modification of poly(ethylene glycol) (PEG). Although there are numerous antiresorptive drugs that target the osteoclast and limit further bone breakdown, these agents are inefficient at rebuilding lost bone mass. To date, agents capable of actively stimulating osteoblastic bone formation are rare, and currently only one FDA approved bone anabolic agent exists. There is consequently significant interest in the identification of new bone anabolic agents for amelioration of bone disease.

In the present study we investigated the cellular events necessary for nanoparticle-stimulated osteoblast differentiation using the murine preosteoblast cell line (MC3T3-E1). We report involvement of caveolae-mediated endocytosis in the mechanism of internalization and activation of the signaling intermediate ERK1/2 as a key intracellular signaling protein for the processing of LC3β. Finally, we show involvement of autophagy in the intracellular process by which silica nanoparticles stimulate osteoblast differentiation and mineralization. On the basis of our previous findings of increased bone mineral density in nanoparticle-treated mice the current findings have therapeutic relevance and suggest the process of autophagy as a novel potential target for the regulation of bone density. Furthermore, these studies represent one of the first comprehensive investigations of the intrinsic biological properties of a nanoparticle, and their cellular processing provides additional insight into the mechanisms by which they achieve their biological effect in addition to suppression of NF-κB.

RESULTS

Internalization of NP1 by Caveolae-Mediated Endocytosis. Extracellular factors can be internalized (endocytosed) by a number of membrane-mediated mechanisms, which are influenced by size and surface properties of the factor. Using the stable fluorescent properties of NP1 we have previously observed a robust internalization
into mesenchymal-derived cells such as osteoblast, however, a much weaker internalization into cells from other lineages such as epithelial. To investigate the mechanism by which osteoblasts internalize NP1 we used known inhibitors of the different endocytic mechanisms and the strong photostable fluorescent properties of NP1 to track entry into the cell. We used two different inhibitors for each endocytic mechanism. We used the osteoblast precursor cell line MC3T3-E1, which has been used extensively to study multiple aspects of osteoblast differentiation and activity. MC3T3-E1 cells were pretreated with the following inhibitors: (1) Caveolae/lipid raft-mediated: Methyl-beta-cyclodextrin (MβCD) 3 mM and Nystatin 1 ng/mL. (2) Macrophagocytosis: Amiloride 100 μM and Cytochalasin D 10 μM. (3) Clathrin-mediated: Phenylarsine oxide 30 nM and Chlorpromazine 3 μM for 2 h (reviewed in the literature), followed by addition of NP1 (60 μg/mL) and cells were analyzed for cytoplasmic fluorescence using fluorescent microscopy after 20 h. Inhibition of caveolae/ lipid rafts completely blocked internalization of NP1 in osteoblasts (Figure 1A), while the other compounds had little effect on cell entry (Figure 1B). These results suggest that NP1 is internalized by a caveolae/lipid raft-mediated process.

NP1 Colocalizes with Endosomes. We next investigated the subsequent cellular localization of NP1 following internalization, by colocalizing NP1 fluorescence with that of fluorescent markers of target organelles. MC3T3-E1 cells were treated with NP1 (red) followed by addition of an endosome marker (transferin GFP-green) and a lysosome marker (lysotracker-blue) for 1 h, and images were captured by confocal fluorescent microscopy (Figure 1C). The results revealed a colocalization of the particles with the endosome marker at this early time point. Taken together with the endocytosis...
studies above, our data suggest that NP1 is initially internalized by caveolae followed by delivery to the endosome.

**NP1-MNP Sequesters in Autophagosome-like Structures in Preosteoblasts.** To determine the intracellular fate of NP1 following endosomal sequestration we took advantage of the electron dense core of NP1-MNP to investigate intracellular localization using transmission electron microscopy (TEM). Nondifferentiated MC3T3-E1 cells were treated with NP1-MNP for 18 h, and cells were fixed for TEM. Images at 1 μm resolution reveal numerous nanoparticles both within membrane bound structures as well as free in the cytoplasm (Figure 2A). Higher magnification images (100 and 200 nm resolution) revealed particles in discrete double membrane vesicles, a unique signature of autophagosomes\(^3^0\) (Figure 2B) and autolysosomes (Figure 2C). Dispersed NP1-MNP alone is shown for comparison (Figure 2D). Collectively, our TEM signatures showing autophagosome and autolysosome localization, combined with our intracellular fluorescent colocalization data showing endosomal but not lysosomal internalization, suggest that after endocytosis NP1-MNP is targeted to autophagosomes and ultimately sequestered in autolysosomes.

**NP1 Stimulates Autophagy.** Our TEM images suggested the presence of NP1 in autophagosomes. To determine whether NP1 is simply targeted to autophagosomes or is also involved in promoting autophagosome formation we next examined a key event in the formation of the autophagosome, and a diagnostic marker of autophagy, the shift in forms of LC3\(^\beta\) from the mature form (LC3\(^\beta\)-I) to the cleaved/lipidated-autophagosome associated form (LC3\(^\beta\)-II), which migrates as a lower molecular weight on SDS PAGE gels because of increased hydrophobicity.\(^3^1\) Treatment of preosteoblasts with NP1-MNP for times up to 60 min resulted in a strong increase in LC3\(^\beta\)-II (Figure 3A). We further detected an increase in p62 protein levels, indicative of autophagosome formation using Western blotting and corresponding to the increase in LC3\(^\beta\)-II protein levels (Figure 3A). In addition to evidence of LC3\(^\beta\) processing, we further employed a commonly used assay for monitoring autophagosome formation involving the use of a GFP tagged LC3\(^\beta\) expression construct. Upon activation of autophagy LC3\(^\beta\) translocates to punctate structures (autophagosomes) as visualized by fluorescent microscopy. We transiently transfected MC3T3-E1 cells with the LC3\(^\beta\)-GFP construct followed by treatment with NP1 for 24 h. Fluorescent microscopy revealed a dramatic increase in punctate structures, considered reflective of autophagosome formation\(^3^0,3^2\) (Figure 3B right panel), which we quantified by counting (Figure 3C). These studies suggest that not only does NP1 likely localize to the autophagosome, but also they may actively stimulate autophagosome formation.

**NP1 Directly Associates with the Key Autophagosome Proteins LC3\(^\beta\)-II and p62.** To investigate the potential for direct interactions of NP1 with autophagosome related
proteins we leveraged the magnetic properties of our cobalt-ferrite core nanoparticles to perform a "pull-down" using a magnet (Figure 4A). We used two different nanoparticles to determine the effect of altering surface properties; NP1-MNP contain abundant Si-OH silanol groups and are strongly negatively charged, whereas NP1-MNP-PEG are surface modified with PEG and are less negatively charged. Poly(ethylene glycol) (PEG) is often used for in vivo applications to increase circulating time by evading the reticuloendothelial system. Preosteoblast cells were incubated with NP1-MNP or NP1-MNP-PEG (100 μg/mL) for 3 days, lysed, and collected by magnetic separation. NP1-MNP was washed three times using the same approach, and bound proteins are analyzed by SDS-PAGE separation and Western blotting. (B) MC3T3-E1 cells were treated as described in (A), and the resulting blot probed for p62 and LC3β. NP1-MNP "OH" and NP1-MNP-PEG "PEG" were also incubated with fetal bovine serum "FBS" as a control for nonspecific binding. Whole cell lysate "WCL" was also run for comparison. LC3-II protein was dose-dependently, surface-independently separated by the magnetic pulldown method. (C) The pulldown assay was performed as in (A) with cell incubated with increasing concentrations of NP1-MNP and NP1-MNP-PEG, as indicated. (D) The pulldown assay was performed as in (A) with NP1-MNP-PEG, and the stringency of the wash conditions was increased by increasing salt concentrations. Representative of three independent experiments.

Furthermore, a second key protein needed for autophagosome formation, p62, was also coassociated with the nanoparticles using the same pulldown assay (Figure 4B). As expected, the amount of LC3β-II and p62 protein associated with the nanoparticles was dose-dependently related to the concentration added to the cells (Figure 4C).

To further investigate specificity we increased the stringency (ionic strength) of the wash steps by increasing salt concentration. Both LC3β and p62 were found bound to the nanoparticles even at the most stringent conditions (1000 mM NaCl) suggesting an extremely strong and specific interaction (Figure 4D).

**Inhibition of Autophagy Blocks NP1 Interaction with LC3β and P62.** To further investigate the mechanism by which NP1-stimulates autophagy we utilized inhibitors of different stages of autophagy, including 3-Methyladenine (3-MA) (0.5 mM), which blocks the very early stages of autophagosome formation,33 Bafilomycin A1 (BA1) (0.1 μM), which blocks fusion of the autophagosome with the lysosome and subsequent acidification,34,35 and Chloroquine (CQ) (10 μM), which blocks the final step
of degradation in the autolysosome (reviewed in the literature30) (Figure 5A). We used these inhibitors to investigate the interaction of NP1 with LC3\(\beta\) at the different stages of autophagic flux. MC3T3-E1 cells were pretreated for 1 h with inhibitors followed by addition of NP1-MNP-PEG (60 \(\mu\)g/mL) for 72 h. Cells were harvested, and nanoparticles were purified using the magnetic pulldown assay (Figure 4A) and analyzed by Western blotting. Results revealed that treatment with 3-MA greatly reduced the interaction of NP1-MNP-PEG with LC3\(\beta\)-II (Figure 5B). Treatment with CQ, which should increase autophagosome number, dramatically increased the interaction of NP1 with LC3\(\beta\)-II (Figure 5B). The results provide evidence that our nanoparticles are directly involved in initiation of the earliest stages of autophagosome formation.

**Internalization of NP1 Stimulates Activation of ERK1/2 Signaling.** Given the rapid sequestration of nanoparticles to the autophagosome, an organelle designed to sequester and dispose of potentially toxic agents, we postulated that NP1 internalization might generate a stress response that would in turn stimulate one or more of the common mitogen-activated protein kinases (MAPKs) signaling pathway cascades represented by p38, JNK, and ERK1/2. Although we did not identify a change in the stress responsive JNK pathway, a time-dependent phosphorylation of the growth-associated ERK1/2 was elicited by NP1 within 15 min of cell exposure (Figure 6A). To confirm the specificity of NP1 stimulated phosphorylation of ERK1/2 we used inhibitors of the three MAPK pathways. In agreement with the time course data, U0126, an inhibitor of MEK the upstream kinase of ERK1/2 blocked phosphorylation of ERK1/2 in response to NP1 treatment (Figure 6B). To determine if the process of endocytosis was the trigger for the stimulation of ERK1/2 phosphorylation we used M\(\beta\)CD to inhibit endocytosis. M\(\beta\)CD also blocked NP1-induced ERK1/2 phosphorylation (Figure 6C) suggesting the endocytosis stimulated by membrane exposure of NP1 initiates the ERK1/2 signal transduction pathway. Importantly, pharmacological inhibition of ERK1/2 signaling blocked the shift in LC3\(\beta\)-I to LC3\(\beta\)-II (Figure 6D) identifying ERK1/2 signaling as a required upstream event in NP1-stimulated autophagy. To rule out the possibility that ERK1/2 phosphorylation was required for NP1 endocytosis we analyzed cytoplasmic fluorescence in the presence or absence of U0126. Results revealed no inhibition of endocytosis in the presence of the ERK1/2 inhibitor (Figure 6E) confirming that stimulation

![Figure 5. Inhibiting autophagosome formation blocks interaction of NP1-MNP with LC3. (A) Schematic of autophagosome and autolysosome formation and sites of inhibitor (3-Methyladenine (3MA), Bafilomycin A1 (BA1), and Chloroquine (CQ)) action. (B) MC3T3-E1 cells were pretreated with the 3MA (0.5 mM), BA1 (0.1 \(\mu\)M), and CQ (10 \(\mu\)M) for 1 h prior to addition of NP1-MNP-PEG for 72 h. The magnetic pulldown assay was used to analyze bound proteins by Western blotting as indicated.](image-url)
Autophagy is Stimulated during Osteoblast Differentiation. Osteoblast differentiation is a complex process that occurs in vitro on the order of weeks. A number of cell culture models have been developed that reasonably mimic the changes that occur in vivo, including the murine preosteoblast cell line MC3T3-E1. These cells, when treated with ascorbic acid and provided a source of organic phosphate such as β-glycerophosphate (βGP), will differentiate and mineralize between 14 and 21 days of culture. Two key markers used to track osteoblast differentiation are the rise in alkaline phosphatase enzyme activity (an early marker of osteoblast differentiation) and increased gene expression of osteocalcin (a late marker synonymous with mineralizing osteoblasts). The result of the differentiation process is the formation and deposition of hydroxyapatite mineral. To determine if NP1 stimulates autophagy in differentiating osteoblasts, MC3T3-E1 cells were pretreated with NP1-MNP (30 μg/mL) or control followed by addition of NP1 for 45 min, and the resulting samples were analyzed for the conversion of LC3-I to LC3-II, p62, and actin by Western blotting. (E) MC3T3-E1 cells were pretreated with U0126 (30 μM) for 20 h, and fluorescent and light microscopy were used for detection of nanoparticle internalization.

Figure 6. NP1 and NP1-MNP rapidly stimulate phosphorylation of ERK1/2 (pERK1/2). (A) MC3T3-E1 cells were serum starved overnight and treated with NP1 for the indicated time (minutes). Anisomycin (ani) (2.5 μg/mL, 30 min) was used as a positive control for p38 and pJNK. Cells were harvested and analyzed by Western blotting. (B) MC3T3-E1 cells were pretreated with inhibitors for ERK1/2 (U0126 – 30 μM), JNK (SP600125 – 10 μM), and p38 (SB203580 – 10 μM) followed by treatment with NP1 for 15 min and analyzed by Western blotting. (C) MC3T3-E1 cells were pretreated with the caveolae/lipid raft inhibitor MβCD for 2 h followed by addition of NP1-MNP (100 μg/mL) for 15 min, and the resulting samples were analyzed by Western blotting. (D) MC3T3-E1 cells were pretreated with U0126 (30 μM) or control followed by addition of NP1 for 45 min, and the resulting samples were analyzed for the conversion of LC3-I to LC3-II, p62, and actin by Western blotting. (E) MC3T3-E1 cells were pretreated with U0126 (30 μM) or control followed by NP1 (60 μg/mL) for 20 h, and fluorescent and light microscopy were used for detection of nanoparticle internalization.
harvested in parallel and analyzed for markers of autophagy. The data demonstrate a time-dependent increase in LC3β-II (Figure 7D), peaking at day 11 just prior to mineralization and corresponding with the key differentiation marker osteocalcin. Interestingly, gene expression of LC3β and p62 were also time-dependently increased also peaking at 11 days corresponding to expression of osteocalcin a marker of mature differentiated osteoblasts (Figure 7E).

**NP1-MNP Is Found in Autophagosomes in Differentiated Osteoblasts.** To confirm that NP1 also localizes to autophagosomes in differentiating cells we treated MC3T3-E1 cells with differentiation medium supplemented with NP1-MNP (60 μg/mL) for 28 days, and the resulting mineralized cell layers were analyzed by TEM. Results identified nanoparticles in autolysosome structures in these mature and mineralizing osteoblasts (compare Figure 8a (untreated) and Figure 8B (NP1-MNP treated)). Higher magnification (500 nm) confirmed the autolysosome localization (Figure 8C).

**DISCUSSION**

Our previous studies identified 50 nm silica nanoparticles as having significant stimulatory effects on osteoblast mineralization, and here we investigated the potential cellular mechanisms by which NP1 might influence cell behavior. Our data suggest that NP1 not only is sequestered to autophagic vesicles, but also stimulates autophagosome formation via an ERK1/2 dependent mechanism. Autophagy is a highly controlled intracellular process currently known to be stimulated by stresses including nutrient deprivation, misfolded or aggregated proteins, or damaged organelles. It has recently been reported that 10–50 nm gold, 22 nm TiO2, quantum dots (<10 nm), and 50 nm iron oxide nanoparticles can induce autophagy, and our results presented herein add 50 nm silica nanoparticles to this list. Collectively these studies suggest that it is not the material per se that stimulates autophagy but rather size or shape. Although there are a number of potential explanations for the stimulation of autophagy we hypothesize that the nanoparticle surface is coated with protein(s), and the cell views this as a misfolded or aggregated/agglomerated protein and processes it accordingly. When nanoparticles are exposed to a biological fluid they are gradually bound with proteins, which ultimately cover the surface. This de novo protein layer creates a bio–nano interface between nanoparticles and the fluid and has been referred to as a “protein

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**Figure 7.** NP1-MNP stimulates osteoblast differentiation and expression of autophagy-related genes. (A) MC3T3-E1 cells were differentiated to osteoblasts in the presence of 30 μg/mL NP1-MNP or not (control), and samples were harvested for alkaline phosphatase enzyme activity at the indicated times (n = 3). (B) MC3T3-E1 cells were treated as in (A), and cells were stained for mineralization with Alizarin red S after 14 days. (C) Cells were treated and harvested as in (A) and analyzed for mRNA expression of osteocalcin (OSC) by qRT-PCR. (D) Cells treated as in (A) were analyzed by Western blotting and probed with antibodies specific for the indicated proteins. Ubiquitin (Ub) was used as a loading control. (E) Cells were treated as in (A) and analyzed for mRNA levels of autophagy genes using qRT-PCR. qRT-PCR results were normalized to Ubiquitin C and fold change calculated using the $2^{-\Delta\DeltaCT}$ method. *P < 0.05, **P < 0.01 (students-t test).
autophagic proteins, LC3/β-II and p62 were both identified at all salt concentrations, whereas ubiquitin (used as a nonspecific control) was not detected in any pulldown lanes demonstrating both specificity and a stronger interaction of the particles with LC3/β-II and p62. The results suggest the nanoparticles recognize both p62 and LC3/β-II directly and with high affinity. Collectively, the results suggest for the first time that endocytosed silica nanoparticles strongly interact with specific autophagy-related proteins.

Somewhat surprisingly, we found that LC3/β-II and p62 bound with similarly affinity to both the PEGylated and nontreated (OH) nanoparticles. The binding of proteins to the surface of nanoparticles could be influenced by surface properties such as charge and hydrophobicity/hydrophilicity.43 We expected that the PEGylated particles would be less interactive because the PEG moiety, which is used for in vivo applications to evade attack by the reticuloendothelial system, could physically interfere with proteins binding to the surface.49 Further, the PEGylated particle is much less negative in charge, as measured by zeta potential,4 and therefore would be less interactive with certain positively charged proteins than the more negatively charged NP1-MNP. Contrary to our expectation, there was no significant difference between NP1-MNP and NP1-MNP-PEG (Figure 5) in the interaction with LC3 or p62. There are a number of possible explanations for the findings. First, it is possible that because both NPs have negative charges favoring the interaction of similar proteins based on charge. Second, it is possible that the PEG is degraded from the nanoparticle surface once they are internalized thereby returning the surface to the base NP1 particle. Previous studies have suggested that PEG can be degraded through the oxidation of the alcohol groups (reviewed in the literature50), which can occur in mammalian cells and systems (reviewed in the literature51). The degradation is suggested to be mediated by enzymatic reactions such as alcohol dehydrogenase and sulfotransferases. Additionally, reactive oxygen species have been demonstrated to accelerate the degradation of PEG with molecular weights of 6000–20,000 to acids such as formic acetic within 120 min.52 Our PEG molecule was 260–400, and therefore, degradation should be possible in a relatively short period of time. Further, we utilized a PEG molecule having 6–9 repeating units (–CH2CH2O–, 0.35 nm) and it is possible that a longer molecule would produce a different result as suggested for those less than 3 nm.49 Finally, it is also possible that the nanoparticles are initially bound by different proteins as a result of the different surface properties; however, the cell recognizes both protein coated particles as misfolded or aggregated proteins, targeting them both for the autophagosome.

We also identified caveolae-mediated endocytosis as the mechanism of cellular entry of our silica
Figure 9. Schematic representing the intrinsic biological effects of silica-based nanoparticles on osteoblast differentiation. NP1 is internalized by caveolae-mediated endocytosis, which triggers a signal transduction pathway dependent on ERK1/2. This stimulation of ERK1/2 is necessary for the processing of LC3β form I to the activated form II. NP1 is bound by both LC3 and p62, resulting in the formation of autophagosomes. The stimulation of autophagy is necessary for osteoblast differentiation and mineralization.

Our results identified ERK1/2 as a signaling intermediate between NP1-stimulated endocytosis and autophagosome formation. Autophagy in general has been recently linked to ERK1/2. Nutrient starvation activates ERK1 and 2, and in agreement with our studies, inhibition of ERK1/2 blocks induction of autophagy.69 Amino acids have also been demonstrated to suppress autophagosome formation through inhibition of ERK1/2.69 It should be noted that the other MAPKs, JNK and p38, have also been linked to regulation of autophagy (reviewed in the literature61). The failure to detect any role of these pathways in our system suggests the possibility of either cell type specificity and/or stimulation specific effects. To our knowledge, the results presented herein are the first to link the stimulation and requirement of ERK1/2 with nanoparticle stimulated autophagy. It will be interesting to determine if this is a common property of nanomaterials or if this is influenced by size, shape and charge as with many other cellular effects of nanomaterials.

**CONCLUSIONS**

In conclusion, results presented herein suggest specific and coordinated mechanisms for the internalization and cellular processing of 50 nm silica nanoparticles (Figure 9). Our data revealed that NP1 and NP1-PEG are initially internalized by caveolae-mediated endocytosis, which triggers the stimulation of an ERK1/2 signaling pathway necessary for the processing of LC3β-I to LC3β-II and stimulating autophagosome assembly. The nanoparticles are likely released from the endosome both stimulating autophagy and being targeted to the autophagosome by p62 and LC3β-II. Although still not completely understood, this process is stimulatory to osteoblast differentiation and mineralization. This conclusion is supported by a recent study, which found that inhibiting autophagosome formation blocked mineralization in bone marrow and primary calvaria cells.23 Further, conditional knockout of Atg7, a protein necessary for autophagy, in terminally differentiated osteoblasts (osteocytes) in aged mice resulted in a decrease in cancellous bone, osteoblast number, and bone formation rate.24 Autophagy therefore represents a putative novel mechanism by which bone metabolism might be manipulated for stimulation of bone accrual. Our study adds to the understanding of the specific biological effects of nanomaterials on cell functions that will allow for future manipulation of bioactive nanomaterials with increased target specificity and efficacy.

**MATERIALS AND METHODS**

**Synthesis and Characterization of Silica Nanoparticles.** The 50 nm fluorescent silica-based nanoparticles (NP1) were synthesized by the Stöber method, which comprises a solid silica shell (SiO2) doped with rhodamine B fluorescent tracking dye as described previously.2 These nanoparticles have been characterized for shape and size distribution using scanning electron microscopy (SEM) and transmission electron microscopy (TEM).2–4 For in vivo biocompatibility we have further developed a polyethylene glycol (PEG)52 decorated variant (NP1-PEG), and the successful functionalization with PEG was confirmed by changes in zeta potential.5 We have additionally synthesized a...
A polyvinylpyrrolidone solution (PVP; 17 mg/mL in water) was added to the cobalt ferrite solution (34.7 mL, 20 mg/mL MNP solution). This mixture was added to a PEGylation solution (125 mg, 0.02 mmol), CH$_3$O(CH$_2$CH$_2$O)$_6$ (OCH$_3$)$_3$, at pH 12 (adjusted with NH$_4$OH). The resulting NP1-PEG was washed and centrifuged in ethanol three times and sterile water once. Zeta potential was measured using a Beckman Coulter Nephelometer.

General Method for Synthesis of Fluorescent Silica Core–Silica Shell Nanoparticles (NP1-Peg and NP1-MNP-Peg). Cobalt ferrite nanoparticles were separated by addition of 0.65 mL ethanol, washed with 30 mL acetone, and the precipitated particles were redispersed in ethanol (10 mL). Multigran-scale preparation of PVP-stabilized cobalt ferrite nanoparticles was easily reproduced in this modified synthetic method. A mixture of TEOs and TMSP-Rhb (molar ratio = 0.3/0.04) was injected into the ethanol solution of cobalt ferrite. Polymerization initiated by adding ammonia solution (0.86 mL; 30 wt % by NH$_3$) as a catalyst. The nanoparticle solution was centrifuged, washed three times, and dispersed in ethanol for subsequent surface-modification or PBS for cell culture.

Effect of Synthesis of Silica Shell Nanoparticles (NP1-MNP). Cobalt ferrite solution (3.47 mL, 20 mg/mL MNP solution in water) was added to polyvinylpyrrolidone solution (PVP; 0.65 mL; Mw average ~55 k, 25.6 mg/mL in H$_2$O), and the mixture was stirred for 1 day at room temperature. The PVP-stabilized cobalt ferrite nanoparticles were separated by addition of aqueous acetone (H$_2$O/acetone = 1/10, v/v) and centrifugation at 4000 rpm for 10 min. The supernatant solution was removed, and the precipitated particles were redispersed in ethanol (10 mL). Multigran-scale preparation of PVP-stabilized cobalt ferrite nanoparticles was easily reproduced in this modified synthetic method. A mixture of TEOs and TMSP-Rhb (molar ratio = 0.3/0.04) was injected into the ethanol solution of PVP-stabilized cobalt ferrite. Polymerization initiated by adding ammonia solution (0.86 mL; 30 wt % by NH$_3$) as a catalyst. The nanoparticle solution was centrifuged, washed three times, and dispersed in ethanol for subsequent surface-modification or PBS for cell culture.

PEGylation of Nanoparticles (NP1-Peg and NP1-MNP-Peg). Purified NP1 core–shell nanoparticles NP1-MNP (45 mg) were dispersed in absolute ethanol (10 mL) and then treated with 2-(methoxy(polyethylene)oxy)propyl trimethoxysilane (PEG-Si(OEt)$_3$; 125 mg, 0.02 mmol), CH$_2$O(CH$_2$CH$_2$O)$_6$OCH$_2$CH$_2$Si(OH)$_2$, at pH 12 (adjusted with NH$_2$OH.HCl). The resulting NP1-Peg or NP1-MNP-Peg was washed and centrifuged in ethanol three times and sterile water once. Zeta potential was measured using a Zetasizer Nano ZS90 (Malvern Instruments Ltd., Malvern, UK) at a concentration of 1 mg/mL in water. The following results were obtained: NP1 (~3.1 ± 1.6 mV), NP1-MNP (~7.6 ± 3.7 mV), NP1-MNP-Peg (~28.1 ± 1.2 mV), NP1-MNP-Peg (~8.3 ± 1.2 mV), as reported previously.

Cell Culture and Reagents. Murine MC3T3-E1 cells were cultured in α-modified Eagle’s medium (α-MEM; Thermo Scientific), Waltham, MA supplemented with 10% fetal bovine serum (FBS; Atlanta Biologicals, Lawrenceville, GA). All growth media were supplemented with 1% l-glutamine (Invitrogen), and 1% of penicillin/streptomycin (Thermo Scientific). All cell lines were cultured at 37 °C in 5% CO$_2$. Inhibitors were purchased from Sigma (3-Methyladenine (3-MA) and Chloroquine (CQ)) and from Santa Cruz Biotechnologies, Inc. (Santa Cruz, CA), actin, LC3, p62, pERK1/2, ERK1/2, pJNK, pP38, and Rab5, and from Invitrogen (Carlsbad, CA). Control primer sequences were designed using qPrimerDepot software (http://mouseprimerdepot.nci.nih.gov/) with sequences as follows: OSC: F-5'- AACCAGGAAGGGCGAATG-3'; R-5'- AAGCTCAAGGATGCT-3'. p62: F-5'- AGAATTGTTGAGGAGAGTCTG-3'; R-5'- GCTGAGGATCTGGCTA-3'. UbC: F-5'- TACCAGAGAGCTCACCCTGAG-3'; R-5'- CAGCTGATGCTCAGG-3'. Fold change was calculated using the 2$^{-\Delta\Delta Ct}$ method.

Confocal Microscopy. The nanoparticle treated cells were washed with 2.5% glutaraldehyde in 0.1 M cacodylate buffer and followed by 1% osmium tetroxide in the same buffer. After dehydration with ethanol, cells were infiltrated and ultimately embedded in Epon resin. Ultrathin sections were counterstained with 4% uranyl acetate and lead citrate and examined on a Hitachi H-7500 transmission electron microscope.

MC3T3-E1 Differentiation, Mineralization, and Alkaline Phosphatase Assays. Osteoblast differentiation using the murine MC3T3-E1 cell line has been previously described.

Western Blot Analysis. The nanoparticle treated cells were rinsed with PBS and lysed in p300 lysis buffer (250 mM NaCl, 0.1% NP-40, 20 mM sodium phosphate, 30 mM sodium pyrophosphate, 5 mM EDTA, and 10 mM sodium fluoride, adjusted at pH 7.0) supplemented with Halt protease & phosphatase single-use inhibitor cocktail (Thermo Fisher Scientific). Whole cell lysate (10–30 μg) was separated by polyacrylamide gel electrophoresis (10, 12, and 15%) and electrotransferred to PVDF membrane Hybond-P (GE Health Sciences, Piscataway, NJ). After blocking in 1× TBST with 5% nonfat dry milk, blots were incubated with specific primary antibodies overnight at 4 °C and visualized by horseradish peroxidase-conjugated secondary antibody using Pierce ECL Western blotting substrate (Thermo Fisher Scientific). Antibodies were purchased from Cell Signaling (Danvers, MA), LC3, p62, pERK1/2, pJNK1/2, pP38, and Rab5, and from Santa Cruz Biotechnologies, Inc. (Santa Cruz, CA), actin, JNK3, Ubiquitin, Flotillin, Caveolin-1. Western blots were further analyzed using ImageJ software (National Institutes of Health, Bethesda, MD).

RNA Extraction, cDNA Synthesis, and qRT-PCR for Osteoblast Differentiation Genes. RNA was extracted using TRIzol reagent following the manufacturer’s protocol (Invitrogen) and cDNA was synthesized using high capacity cDNA reverse transcription kit (Applied Biosystems, Foster City, CA). qRT-PCR was performed using EvaGreen qPCR master mix (Biotium, Hayward CA) on an Applied Biosystems, Foster City, CA). qRT-PCR was performed using EvaGreen qPCR master mix (Biotium, Hayward CA) on an Applied Biosystems, Foster City, CA). qRT-PCR was performed using EvaGreen qPCR master mix (Biotium, Hayward CA) on an Applied Biosystems, Foster City, CA). qRT-PCR was performed using EvaGreen qPCR master mix (Biotium, Hayward CA) on an Applied Biosystems, Foster City, CA). qRT-PCR was performed using EvaGreen qPCR master mix (Biotium, Hayward CA) on an Applied Biosystems, Foster City, CA). qRT-PCR was performed using EvaGreen qPCR master mix (Biotium, Hayward CA) on an Applied Biosystems, Foster City, CA). qRT-PCR was performed using EvaGreen qPCR master mix (Biotium, Hayward CA) on an Applied Biosystems, Foster City, CA). qRT-PCR was performed using EvaGreen qPCR master mix (Biotium, Hayward CA) on an Applied Biosystems, Foster City, CA).
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