Osteoclast Cytosolic Calcium, Regulated by Voltage-gated Calcium Channels and Extracellular Calcium, Controls Podosome Assembly and Bone Resorption

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Abstract. The mechanisms of Ca\(^{2+}\) entry and their effects on cell function were investigated in cultured chicken osteoclasts and putative osteoclasts produced by fusion of mononuclear cell precursors. Voltage-gated Ca\(^{2+}\) channels (VGCC) were detected by the effects of membrane depolarization with K\(^+\), BAY K 8644, and dihydropyridine antagonists. K\(^+\) produced dose-dependent increases of cytosolic calcium ([Ca\(^{2+}\)]\(_i\)) in osteoclasts on glass coverslips. Half-maximal effects were achieved at 70 mM K\(^+\). The effects of K\(^+\) were completely inhibited by dihydropyridine derivative Ca\(^{2+}\) channel blocking agents. BAY K 8644 (5 \times 10^{-6} M), a VGCC agonist, stimulated Ca\(^{2+}\) entry which was inhibited by nicardipine. VGCCs were inactivated by the attachment of osteoclasts to bone, indicating a rapid phenotypic change in Ca\(^{2+}\) entry mechanisms associated with adhesion of osteoclasts to their resorption substrate. Increasing extracellular Ca\(^{2+}\) ([Ca\(^{2+}\)]\(_o\)) induced Ca\(^{2+}\) release from intracellular stores and Ca\(^{2+}\) influx. The Ca\(^{2+}\) release was blocked by dantrolene (10^{-5} M), and the influx by La\(^{3+}\). The effects of [Ca\(^{2+}\)]\(_o\) on [Ca\(^{2+}\)]\(_i\) suggest the presence of a Ca\(^{2+}\) receptor on the osteoclast cell membrane that could be coupled to mechanisms regulating cell function. Expression of the [Ca\(^{2+}\)]\(_o\) effect on [Ca\(^{2+}\)]\(_i\) was similar in the presence or absence of bone matrix substrate. Each of the mechanisms producing increases in [Ca\(^{2+}\)]\(_i\), (membrane depolarization, BAY K 8644, and [Ca\(^{2+}\)]\(_o\)) reduced expression of the osteoclast-specific adhesion structure, the podosome. The decrease in podosome expression was mirrored by a 50% decrease in bone resorptive activity. Thus, stimulated increases of osteoclast [Ca\(^{2+}\)]\(_o\), lead to cytoskeletal changes affecting cell adhesion and decreasing bone resorptive activity.

The cellular basis of bone remodeling is not completely understood. The osteoclast, the multinucleated cell involved in bone resorption, is a complex unit that develops a specialized apparatus for dissolving the bone matrix (King and Holtrop, 1975; Holtrop and King, 1977). Using cell culture systems, several advances have recently been made indicating the molecular events involved in osteoclast bone resorbing activity. For bone resorption to be initiated, the osteoclast polarizes (Baron et al., 1985) and directly attaches to the bone surface by a specialized area termed the clear zone (Holtrop and King, 1977), in which the contact with the substrate is established by specific adhesion structures called podosomes (Marchisio et al., 1984, 1987; Zambonin-Zallone et al., 1988). Morphologically, podosomes appear as short membrane protrusions with a core of microfilaments linked to the plasma membrane by talin and vinculin (Marchisio et al., 1984, 1987). Recent data suggest that podosomes play a pivotal role in substrate recognition by osteoclasts as a specific \(\beta_3\) integrin of the RGD-superfamily of matrix receptors is expressed on their cell membrane surface (Davies et al., 1989; Zambonin-Zallone et al., 1989). Substrate recognition is a necessary early step in the initiation of bone resorption, and it may induce phenotypic differences in cellular responses as the osteoclast changes from a motile cell seeking bone substrate to an actively resorbing cell.

The organization of the podosome-containing clear zone allows tight sealing of the resorbing compartment between the osteoclast plasma membrane and the bone surface. The acidification of this extracellular microenvironment (Baron et al., 1985; Blair et al., 1989) produces hydroxyapatite solubilization. Lysosomal enzymes, secreted into this space by a mannose-6-P receptor driven mechanism (Baron et al., 1988; Blair et al., 1988), and activated by the acid pH, digest the organic components of the bone matrix (Blair et al., 1988). Tight sealing of the compartment is needed to maintain the pH of 5 and the Ca\(^{2+}\) concentrations of up to 40 mM (Silver et al., 1988).
While the mechanisms of osteoclast regulation are incompletely understood, we have recently reported that extracellular protons decrease cytosolic calcium ([Ca\(^{2+}\)]\(_i\)) and intracellular pH (pH\(_i\)) of osteoclasts attached to bone (Teti et al., 1989). Moreover, these changes in intracellular cation concentration directly stimulate podosome formation (Teti et al., 1989) leading to activation of bone resorption (Arnett and Dempster, 1986; Carano et al., 1990). In contrast, ionophore-induced enhancement in [Ca\(^{2+}\)]\(_i\) decreased expression of podosomes (Teti et al., 1989). While these findings are provocative, the mechanisms by which changes in osteoclast [Ca\(^{2+}\)]\(_i\) are mediated physiologically and their relevance to resorptive activity are unknown.

In the studies reported herein, we focused on the mechanisms of [Ca\(^{2+}\)]\(_i\) regulation in osteoclasts and their relevance to the control of podosome organization and bone resorption activity. In our previous study of osteoclasts attached to bone (Teti et al., 1989), we noted that depolarization of the membrane potential by extracellular potassium chloride produced a prompt decrease in [Ca\(^{2+}\)]. However, Rizzoli, Schlegel, and Bonjour (personal communication) have noted that KCl addition to osteoclasts attached to glass resulted in increased [Ca\(^{2+}\)]. These conflicting studies prompted us to (a) identify and characterize voltage-gated calcium channels (VGCCs) in the osteoclast plasma membrane; (b) study modulation of VGCCs during changes in osteoclast activity from an inactive to an active resorbing state; (c) further characterize a mechanism recently reported (Malgaroli et al., 1989) whereby extracellular Ca\(^{2+}\) ([Ca\(^{2+}\)]\(_o\)) elicits changes in [Ca\(^{2+}\)]\(_i\) for its action on cell function and (d) analyze the role of [Ca\(^{2+}\)]\(_i\) regulation in podosome organization and osteoclast bone-resorbing activity.

**Materials and Methods**

**Materials**

The acetylomethyl ester of fura-2 (fura-2 AM) was purchased from Molecular Probes (Eugene, OR). BAY K 8644 and nitrendipine were obtained from Miles Laboratories (West Haven, CT), and diitiazem hydrochloride from Marion Laboratories (Kansas City, MO). Ionomycin was from Calbiochem-Behring Corp. (La Jolla, CA), and all other reagents were of analytical grade from Sigma Chemical Co. (St. Louis, MO), Eurobio (Paris, France), and Carlo Erba (Milan, Italy).

**Osteoclast Preparation**

In our previous report (Teti et al., 1989) adherence of osteoclasts to bone particles was used as a purification technique. The objectives of the studies reported here required cells detached from bone, thereby excluding the use of the bone particle purification technique. Thus, osteoclasts were isolated by a modification of a previously described method (Zambonin-Zallone et al., 1982). Briefly, the medullary bone from femurs and tibias of calcium-deficient laying hens was removed and pressed through a 100-μm nylon sieve. The filtrate was centrifuged for 5 min at 300 g and then suspended for 2 min in a hypotonie solution (0.2% NaCl) to lyse erythrocytes. The osteoclast-rich suspension was centrifuged at 235 g for 20 rain at 4°C on Ficoll-Hypaque in PBS (density 1.077), and the osteoclast-containing pellet was collected. Centrifugation of the cell suspension was repeated to increase osteoclast enrichment. Because isolated osteoclasts did not express podosomes as they attached to the glass coverslips, they were cultured at a density of 30,000 osteoclasts/3.5 cm in Petri dishes containing glass coverslips.

**Activation of VGCCs**

VGCCs were activated in osteoclasts by depolarizing the cells with high K⁺.

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1. **Abbreviation used in this paper**: VGCC, voltage-gated calcium channels.
KRH. Experiments were performed in isotonic conditions by substituting from 6.2 to 100 mM KCl for corresponding amounts of NaCl in the KRH buffer. Activation of VGCCs was also obtained using BAY K 8644, a specific dihydropyridine VGCC agonist. The effects of several VGCC antagonists were evaluated, including diltiazem, verapamil, nicardipine, or nitrendipine (10⁻¹₀⁻¹⁰⁻⁵ M) before depolarization with high K⁺ KRH (100 mM) or addition of BAY K 8644. A complete series of parallel experiments were performed using osteoclast cultures in which devitalized bone particles (38-63-µm-diam) were added 5 h before the experiments were performed.

**Activation of Calcium-operated Regulation of [Ca²⁺].**

Changes in [Ca²⁺] were observed during changes in extracellular calcium concentrations. Osteoclasts, previously incubated in KRH containing 2 mM Ca²⁺, were treated with increasing extracellular calcium concentrations. To block release of calcium from intracellular stores, a series of experiments utilized thapsigargin, a drug pretreated with dantrolene (10⁻³ M) 10 min before CaCl₂ additions. To block Ca²⁺ entry, LaCl₃ and Ca²⁺ channel antagonists were studied for their effects on the changes in [Ca²⁺], stimulated by adjustments in [Ca²⁺]. Parallel experiments in the presence of bone particles were also performed to evaluate the effects of increasing extracellular calcium concentration on [Ca²⁺] during bone resorption.

**Cytoskeletal Studies.**

The effect of membrane depolarization on podosome expression was evaluated in osteoclasts incubated for 90 min in MEM in which 30 or 50 mM NaCl was isotonically substituted with KCl. Control osteoclasts were incubated in regular MEM containing 5.0 mM KCl. The effect of extracellular calcium on podosome expression was evaluated by incubating osteoclasts in nominally calcium-free MEM and adding CaCl₂ from 0 to 4 mM. Incubation times were 90 min unless otherwise indicated.

Microfilaments were detected by decoration of F-actin with rhodamine-conjugated phalloidin (R-PHD). Cells were fixed for 5 min at room temperature with 3% formaldehyde, 2% sucrose in PBS. They were then permeabilized for 3 min at 0°C with 50 mM MgCl₂, 300 mM sucrose, 20 mM Hepes (pH 7.4), 3 mM MgCl₂, 0.5% Triton-X 100, and then they were incubated for 45 min at 37°C with 5 µg/ml R-PHD. Coverslips were then washed, mounted in 10% mowiol, and observed with a Leitz Diavert fluorescence microscope. Due to the presence of a core of microfilaments perpendicularly oriented with respect to the substrate, podosomes were recognized as fluorescent dot-like structures distributed at the level of the ventral surface of the cell.

To quantitate the results, the numbers of osteoclasts presenting podosomes in each treatment expressed as the percent of the total number of osteoclasts present. Data were expressed as mean percentage ± SE. The statistical significance was calculated by the t test. For each treatment, an average of 300 osteoclasts was counted. A decrease in podosome expression did not cause the cells to lift off the coverslip since the osteoclast has other mechanisms of substrate adhesion besides podosome expression (Zambonin-Zallone et al., 1989).

**Bone Resorption.**

The effects of increasing [Ca²⁺], by activation of VGCC or changing [Ca²⁺], on the bone-resorbing activity of osteoclast cultures was determined. For this purpose, 2-d-old osteoclast cultures were incubated for 48 h with [³H]proline prelabeled devitalized rat or chicken bone particles (Blair et al., 1986) at a density of 400 µg of bone/50,000 osteoclasts in 1.5 cm² culture dishes. The cells were cultured in serum-free MEM in the presence of varying calcium concentrations, varying K⁺ concentrations or preincubating the cells for 30 rain with the experimental medium, then adding the bone particles, and (b) preincubating the cells for 24 h with the bone particles, then substituting the control medium with the experimental medium.

Bone resorption was evaluated by measuring the radioactivity present in the medium, which derived from osteoclast-mediated release of tritiated products of bone collagen degradation (Blair et al., 1986). Parallel samples, in absence of cells, were evaluated to measure the nonspecific [³H]release, which was subtracted from the corresponding experimental values. The total radioactivity present in the 400 µg of bone added to the cultures was measured after demineralization and solubilization of the organic matrix, as previously described (Blair et al., 1986), and the micrograms of bone resorbed were calculated. Data were expressed as mean micrograms of bone resorbed ± SE. The statistical significance was evaluated by the t test. Each experiment was performed with at least three different osteoclast preparations in quadruplicate.

**Results.**

**Effect of Membrane Depolarization on Osteoclast [Ca²⁺] .**

Basal [Ca²⁺] of osteoclasts on glass coverslips in KRH was 123 ± 9 (n = 41) (mean ± SE). The response of osteoclasts [Ca²⁺], to 100 mM K⁺ is shown in Fig. 1. The effect of K⁺ on [Ca²⁺], was directionally opposite to the response we previously reported in osteoclasts attached to bone particles (Teti et al., 1989). High K⁺ induced an immediate increase in [Ca²⁺], and a second slower rise to a new steady state of 267 nM within 300 s. High K⁺ increased [Ca²⁺], in a similar manner in 83% of examined cells attached to glass coverslips (n = 18). The other 17% of cells demonstrated a decrease in [Ca²⁺] upon depolarization with K⁺. The increase in [Ca²⁺], from basal to peak levels achieved by various concentrations of K⁺ in high K⁺ KRH was dose-dependent with a half-maximal effect achieved by 66 mM (Fig. 2). When cells were placed in a Ca-free KRH (CaCl₂ omitted from the buffer and 1 mM EGTA added), KCl additions failed to elevate [Ca²⁺], (not shown). This indicated that the increases in [Ca²⁺], stimulated by high K⁺ were due to calcium entry from the extracellular fluid. The effects of high K⁺ were almost completely inhibited by the dihydropyridine, nicardipine (Fig. 1 b).

The Effect of BAY K 8644 on [Ca²⁺].

BAY K 8644 is a dihydropyridine-derivative Ca²⁺ channel agonist that increases opening frequency of dihydropyridine-sensitive Ca²⁺ channels (Duncan and Misler, 1989; Guggino et al., 1989; Meier et al., 1988). After the addition of BAY K 8644 (5 × 10⁻⁴ M) in calcium containing KRH a...
Concentration dependence of the K⁺-induced changes in \([\text{Ca}^{2+}]_i\) of single osteoclasts. The maximal increase in \([\text{Ca}^{2+}]_i\) produced with increasing K⁺ concentrations is plotted against \(K^+\). The number of experiments is indicated in parentheses. Results are the mean ± SE.

The increase in \([\text{Ca}^{2+}]_i\), of 78 ± 8 nM (\(n = 3\)) was observed, reaching plateau levels in 7–8 min (Fig. 3 a). BAY K 8644 (5 × 10⁻⁶ M) had no effect on \([\text{Ca}^{2+}]_i\); BAY K 8644 was completely abolished by nicardipine (10⁻⁶ M) (Fig. 3 b). The effects of BAY K 8644 were slower in onset than high K⁺ KRH probably due to time for incorporation into plasma membranes in our system. The increase in \([\text{Ca}^{2+}]_i\), produced by 5 × 10⁻⁶ M BAY K was similar to that of 70 mM K⁺. These findings suggest that BAY K 8644 stimulated Ca²⁺ influx through dihydropyridine-sensitive voltage-gated Ca²⁺ channels.

**Effects of Ca²⁺ Channel Blocking Agent on the K⁺-induced Increase in \([\text{Ca}^{2+}]_i\)**

The effects of the dihydropyridine Ca²⁺ channel blocker, nicardipine (10⁻⁷ M), on the K⁺-stimulated changes in \([\text{Ca}^{2+}]_i\), are shown in Fig. 1 b. KRH with nicardipine (10⁻⁷ M) was added for 2 min before high K⁺ with nicardipine. K⁺ had no significant effect on \([\text{Ca}^{2+}]_i\) in the presence of nicardipine. The K⁺-induced increase in \([\text{Ca}^{2+}]_i\), was restored after transfer to nicardipine-free KRH and a second addition of K⁺.

The effects of various Ca²⁺ channel blockers on high K⁺ KRH- (100 mM) induced elevations of \([\text{Ca}^{2+}]_i\), were compared, as shown in Fig. 4. Dihydropyridine Ca²⁺ channel blockers (nicardipine, nitrendipine at concentrations of 10⁻⁹–10⁻⁵ M (\(n = 3\) or 4 of each concentration) inhibited the K⁺-induced \([\text{Ca}^{2+}]_i\), increases in a dose dependent manner. The half-maximal inhibition was observed at 5 × 10⁻⁹ M. Verapamil was less potent than dihydropyridines, and diltiazem was less effective than verapamil.

**Effects of Changing Extracellular Calcium on \([\text{Ca}^{2+}]_i\)**

As we have previously reported (Malgaroli et al., 1989), increasing extracellular Ca²⁺ concentrations induced rapid dose-dependent increases in \([\text{Ca}^{2+}]_i\). As shown in Fig. 5, basal \([\text{Ca}^{2+}]_i\), of 108 nM was increased by addition of 2 mM CaCl₂ to KRH containing 2 mM Ca²⁺ (final concentration: 4 mM) induced a biphasic transient involving a rapid increase in \([\text{Ca}^{2+}]_i\), followed by a return towards baseline which was incomplete resulting in a sustained elevation.
Ca\(^{2+}\) to a peak of 194 nM in 80 s, and then decreased to a steady state at 123 nM (Fig. 5). The threshold dose of CaCl\(_2\) needed to increase [Ca\(^{2+}\)], was 0.25 mM. Half-maximal increases in [Ca\(^{2+}\)], 182 ± 16 nM, \(n = 7\), were observed at addition of 4 mM CaCl\(_2\) (final concentration 6 mM), and the increases in [Ca\(^{2+}\)], were maximal with addition of 8 mM CaCl\(_2\). The Ca\(^{2+}\) channel blockers (10\(^{-3}\) M nicardipine, nitrendipine, verapamil, and diltiazem) failed to inhibit the CaCl\(_2\)-induced changes, which, however, were partially blocked by LaCl\(_3\) (10\(^{-4}\)–10\(^{-5}\) M). As shown in Fig. 6 a, LaCl\(_3\) (10\(^{-4}\) M) did not alter basal [Ca\(^{2+}\)], levels, but reduced the CaCl\(_2\)-prompted increase in [Ca\(^{2+}\)], by 43% (40 ± 4% in three similar experiments). The increases in [Ca\(^{2+}\)], stimulated by external Ca\(^{2+}\) were not affected by removing extracellular Na (Fig. 6 b). This and similar experiments also demonstrated the reproducible elevations in [Ca\(^{2+}\)], observed with repeated additions of CaCl\(_2\) after washes. Dantrolene (10\(^{-5}\) M), which inhibits mobilization of Ca\(^{2+}\) from intracellular stores (Kojima et al., 1985; Reid et al., 1987), dampened the CaCl\(_2\) induced rise in [Ca\(^{2+}\)], by 80% (55.4 ± 17% in three experiments) and eliminated the spike phase of the increases stimulated by CaCl\(_2\) (Fig. 6 c). Together, Dantrolene (10\(^{-5}\) M) and LaCl\(_3\) (10\(^{-4}\) M) were sufficient to completely inhibit stimulation of [Ca\(^{2+}\)], by additions of CaCl\(_2\) (Fig. 6 d).

**Effects of K\(^+\) and [Ca\(^{2+}\)], on Osteoclasts Attached to Bone Particles**

Osteoclasts cultured on glass coverslips attached to devitalized bone particles (38–63 μm diameter) as they settled. Basal [Ca\(^{2+}\)], levels in the particle-attached cells were 136 ± 7, \(n = 28\), similar to osteoclasts not exposed to bone. Addition of 2 mM CaCl\(_2\) increased [Ca\(^{2+}\)], by 100 ± 22 nM (mean ± SE), \(n = 7\) (Fig. 7 a). In contrast to the effects of K\(^+\) on osteoclasts not attached to bone, high K\(^+\) KRH prompted a decrease in [Ca\(^{2+}\)], after 5 h of osteoclasts attaching to bone. As shown in Fig. 7 b, [Ca\(^{2+}\)], decreased from 125 to 75 nM in such a representative osteoclast. This 5-h contact with bone reduced the percentage of osteoclasts expressing VGCC from 83% without bone to 10%. Furthermore, osteoclasts attached to bone particles were insensitive to BAY K 8644, and this agent produced no change in [Ca\(^{2+}\)], in these cells. These findings indicate that, with osteoclastic bone attachment, the voltage-gated Ca\(^{2+}\) channel is functionally lost, but the Ca\(^{2+}\)-induced Ca\(^{2+}\) release mechanism was not inactivated. Furthermore, the effect of K\(^+\) to decrease [Ca\(^{2+}\)], in osteoclasts attached to bone appeared to be a stimulation of Ca\(^{2+}\) efflux since inhibition of Ca\(^{2+}\) entry had no significant effect on the decrease stimulated by K\(^+\) (Fig. 7 c).

![Figure 6](image-url)

**Figure 6.** Effects of La\(^{3+}\) and dantrolene on external Ca\(^{2+}\)-elicited increases in [Ca\(^{2+}\)]. a illustrates the effect of CaCl\(_2\) (2 mM) on [Ca\(^{2+}\)]-induced biphasic in a single osteoclast followed (after washings) by treatment with LaCl\(_3\) (10\(^{-4}\) M). La\(^{3+}\) had no effect itself, but reduced the height of the Ca\(^{2+}\) spike after stimulation with CaCl\(_2\). In b, a control experiment is shown to demonstrate that a second addition of 2 mM CaCl\(_2\) after removal of the first addition by washing, produces the same increment in [Ca\(^{2+}\)]. We have previously demonstrated (Teti et al., 1989; Malgaroli et al., 1989) that removal of Na\(^+\) had no effect on osteoclast stimulated [Ca\(^{2+}\)]. c illustrates the effect of dantrolene (10\(^{-5}\) M) on a 4 mM [Ca\(^{2+}\)]-elicited increase in [Ca\(^{2+}\)]. The [Ca\(^{2+}\)] spike was abolished, while the sustained phase still occurred. d illustrates that together, LaCl\(_3\) and dantrolene were sufficient to completely inhibit the effect of CaCl\(_2\) (4 mM).
Figure 7. Effects of increasing extracellular Ca²⁺ and K⁺ on [Ca²⁺]ᵢ of osteoclasts attached to bone particles. (a) Increasing Ca²⁺ of KRH from 2 to 4 mM elicited a transient increase in [Ca²⁺]ᵢ similar to the effect observed in osteoclasts on glass coverslips (Fig. 5). (b) High K⁺ (100 mM) KRH decreased [Ca²⁺]ᵢ. The mean decrease of [Ca²⁺]ᵢ from baseline by high K⁺ (100 mM) KRH was 73 ± 12 nM (n = 9). (c) High K⁺ (100 mM) KRH decreased [Ca²⁺]ᵢ in a LaCl₃-treated cell. The mean decrease of [Ca²⁺]ᵢ of LaCl₃-treated cells was 65 ± 11 nM (n = 5). This was not significantly different from the effect of high K⁺ (100 mM) in cells not treated with LaCl₃.

Cytoskeletal Studies

The distribution of microfilaments in osteoclasts at different times of culture was evaluated by decoration of F-actin with R-PHD and observation by fluorescent microscopy. Podosomes, due to the perpendicular orientation of F-actin-containing microfilaments with respect to the substrate, appear as fluorescent dot-like structures located at the level of the ventral surface of the cell (Fig. 8). In osteoclasts cultured in standard conditions on glass coverslips, podosome number increased with time, and they were spontaneously organized into several concentric rows located at the cell edge, in an area resembling the actin-rich clear zone (Fig. 8). In osteoclasts cultured in high K⁺ conditions, podosome expression decreased by 65%. However, this dose of K⁺ increased [Ca²⁺]ᵢ by only ~25% of maximal. Thus K⁺ may affect podosome expression by mechanisms other than opening VGCC. Further evidence for VGCC-regulated podosome expression came from the fact that as BAY K 8644 increased [Ca²⁺]ᵢ, it inhibited appearance of these attachment structures (Fig. 9 a). Similarly, increasing [Ca²⁺]ᵢ from 0 to 4 mM led to a clear dose-dependent decrease in podosome expression (Figs. 8 c and 10 a). The specificity of the [Ca²⁺]ᵢ effect on osteoclast microfilaments was demonstrated by failure of the cation to impact on fibroblast focal adhesions and stress fibers (Fig. 8, d and e).

Bone Resorption

We examined the effects of depolarization by K⁺ or increases in [Ca²⁺]ᵢ on osteoclastic bone resorption and found that K⁺-KRH (50 mM) elicited a 60% inhibition of H² release from bone particles at 48 h of culture. However, as for podosome expression, this effect may represent actions other than opening VGCC. BAY K 8644 added prior to the addition of the labeled bone particles inhibited bone resorption in a dose-dependent manner (Fig. 9 b). Similarly, increasing extracellular calcium reduced osteoclastic bone resorption. An increase in [Ca²⁺]ᵢ, from 2 to 4 mM reduced resorption by 50% (Fig. 10 b). BAY K 8644 had no effect on bone resorption if the osteoclasts were allowed to adhere to bone particles for 24 h before its addition. On the other hand, increasing [Ca²⁺]ᵢ continued to inhibit resorptive activity of osteoclasts similarly preincubated with bone. Furthermore, the addition of bone particles to osteoclasts in 4 mM [Ca²⁺]ᵢ for 5 h before a return to 2 mM restored resorptive activity that of cells maintained in 2 mM Ca²⁺ for the full 48 h, documenting reversibility of the inhibitory effects of [Ca²⁺]ᵢ.

Discussion

Osteoclasts are cells involved in the manipulation of high calcium concentrations. This is due to their peculiar physiology which produces dissolution of the mineralized bone matrix and the release of calcium ions to the extracellular fluid. Silver et al. (1988) have shown that the calcium concentration achieved in the resorbing compartment during bone mineral dissolution is severalfold higher than in the extracellular fluid. This is possible because of the low pH (5.0) actively created by an outwardly directed H⁺-pump mechanism located on the osteoclast ruffled border membrane (Baron et al., 1985; Blair et al., 1989). The low pH of the resorption space, on one hand, causes hydroxypatite solubilization and, on the other hand, prevents calcium precipitation.

Very little is known of the mechanisms involved in calcium transport and storage by osteoclasts. A Ca²⁺ ATPase has been immunolocalized on the membrane opposite the ruffled border (Akisaka et al., 1988), and we have shown that this transport mechanism is responsible for the decrease in [Ca²⁺]ᵢ, stimulated by metabolic acids (Teti et al., 1989).
Furthermore, we found that a divalent cation-operated mechanism present in both chicken and rat osteoclasts (Malgaroli et al., 1989) stimulates $[\text{Ca}^{2+}]$, transients through both calcium entry and the release of calcium from intracellular stores. In rat osteoclasts, this system is potentiated by treatment with calcitonin, and we hypothesized that it could have an inhibitory role on osteoclast activity. In the present report, we demonstrate that inhibition of $\text{Ca}^{2+}$ entry by $\text{La}^{3+}$, but not dihydropyridine $\text{Ca}^{2+}$ channel antagonists, partially blocked enhancement of $[\text{Ca}^{2+}]$, by increasing $[\text{Ca}^{2+}]$. Importantly, the early spike phase of the change in $[\text{Ca}^{2+}]$, which is derived from intracellular stores, was not affected by $\text{La}^{3+}$ treatment, indicating that the presence of $\text{Ca}^{2+}$ entry blockade, the effect of increasing $[\text{Ca}^{2+}]$, was derived from $\text{Ca}^{2+}$ release. This was also supported by the observation that dantrolene, a more specific blocker of $\text{Ca}^{2+}$ release from intracellular stores than TMB8 previously used (Malgaroli et al., 1989), diminished the response to changes in $[\text{Ca}^{2+}]$, and removed the early spike phase of the transient. The resultant tonic elevation in $[\text{Ca}^{2+}]$, to a higher plateau is consistent with stimulated $\text{Ca}^{2+}$ entry. Altogether, our data indicate that increases in $[\text{Ca}^{2+}]$, stimulate both $\text{Ca}^{2+}$ entry and $\text{Ca}^{2+}$ release. Moreover we have shown that $\text{Cd}^{2+}$ stimulates transient elevations in $[\text{Ca}^{2+}]$, in the absence of extracellular $\text{Ca}^{2+}$ (Malgaroli et al., 1989). Similar to the parathyroid glands, our data indicate that $\text{Ca}^{2+}$ may act through a receptor-operated mechanism stimulating $\text{Ca}^{2+}$ release from intracellular stores (Nemeth et al., 1986).
In this report, we also demonstrate that osteoclasts transiently express VGCC. Depolarization of the membrane potential elevated \([\text{Ca}^{2+}]_o\), in osteoclasts cultured without bone. The addition of bone produced a time-dependent disappearance of VGCC. Specifically, whereas 83% of the bone-free cells studied had increased levels of \([\text{Ca}^{2+}]_o\), after 5 h in the presence of bone, depolarization prompted a decrease in \([\text{Ca}^{2+}]_o\), as previously reported (Teti et al., 1989). The decrease in \([\text{Ca}^{2+}]_o\), is compatible with an increase of \(\text{Ca}^{2+}\) influx produced by depolarization.

The VGCCs of the osteoclast exhibit the functional properties of those described in other cell types. They are more sensitive to dihydropyridine agonists (BAY K 8644) and antagonists (nicardipine and nitrendipine) than to phenylal-chilamine (verapamil) and benzodiazepine (diltiazem) antagonists. These data are consistent with the presence of an L-type VGCC found in the plasma membrane of excitable and nonexcitable cells (Nowycky et al., 1985; Schramm and Towart, 1985; Miller, 1987; Meier et al., 1988).

The next phase of this study involved assessing the effects of increasing \([\text{Ca}^{2+}]_o\), on osteoclast activity. First, we studied the effects of membrane depolarization, BAY K 8644 and increasing external \(\text{Ca}^{2+}\) on podosome expression. We found that each mechanism of increasing \([\text{Ca}^{2+}]_o\), decreased podosome expression. The effect of K+ on podosome expression appeared more effective than other means of increasing \([\text{Ca}^{2+}]_o\). This suggested that K+ additions were affecting osteoclastic functions besides stimulating VGCC. However, BAY K 8644 is a specific VGCC agonist and thus it indicates that VGCC stimulation decreases podosome expression. These results are consistent with the effects of \(\text{Ca}^{2+}\) ionophores on podosome expression previously reported (Teti et

**Figure 9.** Effect of BAY K 8644 on podosome expression and bone resorption. (a) \(5 \times 10^{-6} \text{ M}\) BAY K 8644 decreased podosome expression. (b) Dose-dependent inhibition of bone resorption in osteoclasts treated with increasing dose of BAY K 8644. Cells were preincubated for 30 min with BAY K 8644, then the bone particles were added. Bone resorption was evaluated as described in Materials and Methods. The data are expressed as mean ± SE in quadruplicate.

**Figure 10.** Effects of extracellular \(\text{Ca}^{2+}\) on podosome expression and bone resorption (a) increasing \([\text{Ca}^{2+}]_o\), from nominally absent to 4 mM resulted in dose-dependent inhibition of podosome expression in osteoclasts. 4 mM extracellular \(\text{Ca}^{2+}\) (final concentration) induced 42% inhibition of osteoclast presenting podosomes with respect to the cultures treated with 2 mM \(\text{Ca}^{2+}\). Data are mean ± SE of three experiments performed in triplicate. (b) Dose-dependent inhibition of bone resorption in osteoclasts treated with increasing doses of extracellular calcium. 4 mM extracellular calcium (final concentration) reduced osteoclast resorbing activity by 50% of the value obtained at 2 mM. Data are mean ± SE of at least three experiments performed in triplicate.
activity (Janmey and Matsudaira, 1988; Yin et al., 1988). Gelsolin, after complexing calcium, is capable of fragmenting pre-existing microfilaments and nucleating new ones, thereby contributing to the rearrangement of the microfilament network of the cell (Yin and Stossel, 1979).

Furthermore, gelsolin presents a site for binding membrane phosphatidylinositol 4,5-bisphosphate, which inhibits its activity (Janmey and Matsudaira, 1988; Yin et al., 1988). We have only preliminary information concerning the metabolism of polyphosphoinositides in osteoclasts, suggesting that the PIP2-gelsolin-calcium complex could contribute to their cytoskeletal organization and adhesion properties.

Finally, we studied the effect of VGCC-dependent and [Ca2+]i-elicted [Ca2+] increase on osteoclastic bone resorption. We found a reduction of bone collagen degradation by osteoclasts exposed to BAY K 8644 or increases in [Ca2+]i. These results suggest that increases in [Ca2+]i negatively regulate osteoclast resorptive activity. They also demonstrated a direct correlation between reduced podosome expression and decreased bone resorption.

It therefore appears that [Ca2+]i-stimulated increase in cytosolic calcium may be a mechanism for inhibiting avian osteoclasts, an event reminiscent of the cation’s ability to block parathyroid hormone secretion (Schoback et al., 1983; Nemeth and Scarpa, 1986; Wallfert et al., 1988). Calcitonin synergistically augments [Ca2+]i, enhanced [Ca2+]i, (Margaroli et al., 1989), further indicating that the Ca2+ signal may be a regulated osteoclast function. The inhibition of osteoclast adhesion and bone resorption by [Ca2+]i, through podosome disassembly is a potential feedback mechanism for signaling to the cell that the products of bone resorption have accumulated at the cell–matrix interface. Inhibition of adhesion, leading to leakage of the resorptive microenvironment could lead to release of these products into the extracellular fluid.

The role of the VGCC in bone resorption is more complex at this point than the modulation by [Ca2+]i. The decrease in bone resorptive activity with BAY K 8644 pretreatment can be explained by the inhibition of podosome formation. However, osteoclasts allowed to attach to bone and begin resorption were resistant to BAY K 8644, consistent with the observed disappearance of functional VGCC after addition of bone particles. The possibility exists that, during the cell’s motile phase, VGCC are expressed on the plasma membrane of osteoclasts and promote movement. Activation of these cells by BAY K 8644 would decrease their ability to promote their adhesive capacity, express podosomes, and resorb bone.

Addendum

While this manuscript was in review, Zaidi et al. (1989) reported that extracellular Ca2+ increases [Ca2+]i in neonatal rat long bone osteoclasts and inhibits bone resorption in agreement with the results reported herein and our previous report (Margaroli et al., 1989).

We thank Dr. Harry Blair, for assistance with the osteoclast preparation, and Pat Harris and Betty Yztaina for preparation of the manuscript.