

RESEARCH ARTICLE

High-affinity P2Y₂ and low-affinity P2X₇ receptor interaction modulates ATP-mediated calcium signaling in murine osteoblasts

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Data Availability Statement: All relevant data are within the manuscript and its [Supporting Information](#) files. The codes used to generate the computational results are available here: www.medicine.mcgill.ca/physio/khadralab/Codes/code_ploscomp2.html.

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Abstract

The P2 purinergic receptor family implicated in many physiological processes, including neurotransmission, mechanical adaptation and inflammation, consists of ATP-gated non-specific cation channels P2XRs and G-protein coupled receptors P2YRs. Different cells, including bone forming osteoblasts, express multiple P2 receptors; however, how P2X and P2Y receptors interact in generating cellular responses to various doses of [ATP] remains poorly understood. Using primary bone marrow and compact bone derived osteoblasts and BMP2-expressing C2C12 osteoblastic cells, we demonstrated conserved features in the P2-mediated Ca²⁺ responses to ATP, including a transition of Ca²⁺ response signatures from transient at low [ATP] to oscillatory at moderate [ATP], and back to transient at high [ATP], and a non-monotonic changes in the response magnitudes which exhibited two troughs at 10⁻⁴ and 10⁻² M [ATP]. We identified P2Y2 and P2X7 receptors as predominantly contributing to these responses and constructed a mathematical model of P2Y2R-induced inositol trisphosphate (IP₃) mediated Ca²⁺ release coupled to a Markov model of P2X7R dynamics to study this system. Model predictions were validated using parental and CRISPR/Cas9-generated P2Y2 and P2Y7 knockouts in osteoblastic C2C12-BMP cells. Activation of P2Y2 by progressively increasing [ATP] induced a transition from transient to oscillatory to transient Ca²⁺ responses due to the biphasic nature of IP₃R_s and the interaction of SERCA pumps with IP₃R_s. At high [ATP], activation of P2X7R modulated the response magnitudes through an interplay between the biphasic nature of IP₃R_s and the desensitization kinetics of P2X7R_s. Moreover, we found that P2Y2 activity may alter the kinetics of P2X7 towards favouring naïve state activation. Finally, we demonstrated the functional consequences of lacking P2Y2 or P2X7 in osteoblast mechanotransduction. This study thus provides important insights into the biophysical mechanisms underlying ATP-dependent Ca²⁺ response signatures, which are important in mediating bone mechanoadaptation.

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Author summary

ATP-sensitive purinergic receptors comprise a network of cell-surface receptors that activate upon ATP binding, allowing them to transmit information in a tissue- and context-dependent manner. In bone, mechanically stimulated osteoblasts release ATP that stimulates low- and high-affinity P2 receptors in neighboring cellular populations, inducing appropriate physiological responses. P2 receptor signaling is characterized by elevations in intracellular calcium levels. When simultaneously stimulated by their common ligand, ATP, the contribution of each P2 receptor subtype gives rise to a complex calcium response, exhibiting oscillatory characteristics and biphasic dose-dependent behaviours. Here we used experimental and computational modeling approaches to determine the underlying dynamics of ATP-mediated calcium signaling in osteoblasts. The latter was done by developing a mathematical model that was comprised of a subset of low- (P2X₇) and high- (P2Y₂) affinity P2 receptors, reflecting the conserved P2 expression observed across different osteoblast models. We demonstrated that this model recapitulates experimental recordings of ATP-induced calcium signaling in osteoblasts and describes the dynamic interplay between P2Y₂ and P2X₇ receptors in the P2 receptor network.

Introduction

Extracellular ATP has long been implicated in diverse physiological functions [1], including neurotransmission [2], mechanical adaptation [3] and the regulation of inflammation [4]. Extracellular purines signal through 7 ionotropic receptors, i.e., the P2X ligand-gated nonspecific cation channels, and 8 metabotropic receptors, i.e., the P2Y G-protein coupled receptors [5].

ATP is the physiological agonist for all P2X receptors (P2XRs) as well as the P2Y₂ and P2Y₁₁ receptors (P2Y₂R and P2Y₁₁R, respectively) [6]. Together they cover a range of extracellular ATP concentrations ([ATP]) spanning six orders of magnitude (10^{-8} M to 10^{-2} M) [7]. P2XRs are fast acting (~10 ms activation), allowing the permeation of Na⁺, K⁺ and Ca²⁺ through the channel [8] whereas P2YRs activate various types of secondary messengers, and thus act on a slower timescale than P2XRs [9]. Elevations in cytosolic free Ca²⁺ concentration ([Ca²⁺]_i) is one of the hallmarks of ATP-induced signaling in many cell types, including bone-forming osteoblasts [7,10–13]. The mechanism by which P2XRs and P2YRs alter [Ca²⁺]_i differs: P2XR activation increases Ca²⁺ influx across the plasma membrane [14] while P2YR activation enhances Ca²⁺ release from the endoplasmic reticulum (ER) by stimulating the G_q protein signaling pathway, ultimately leading to the production of inositol triphosphate (IP₃) and the activation of IP₃ receptors (IP₃Rs) [15]. The ATP dose dependence of osteoblast responses to [ATP] was shown to be complex and does not have a clear plateau component, an outcome not explainable by the addition of individual receptor responses [7]. While it was proposed that specific interactions between the high-affinity, mid-range and low-affinity P2Rs may explain the [ATP]-dependence, no mechanistic studies at the level of cellular signaling has yet been performed.

Markov models of P2X_{2/4/7}R were previously developed to decipher the kinetics of ATP binding to these receptors and illustrate the interplay between receptor activation, priming, desensitization, internalization and deactivation [16–21]. Mathematical modeling has similarly been used to provide insights into the P2Y receptor signaling, particularly in the regulation of IP₃R-mediated Ca²⁺ release [22,23]. However, how P2X and P2Y receptors interact and what are their respective roles in generating cellular responses to various doses of [ATP] remains poorly understood.

In this study, we combined detailed experimental and computational studies of ATP-induced Ca²⁺ signals in primary mouse osteoblasts and BMP2-transfected C2C12 osteoblastic cells. We demonstrated the specific contributions of P2Y₂ and P2X₇ receptors to global Ca²⁺ responses using CRISPR/Cas9-generated P2Y₂ and P2Y₇ knockouts in osteoblastic C2C12-BMP cell lines, and dissected the mechanisms of P2Y₂ and P2X₇ contributions to generating different patterns of oscillatory and sustained Ca²⁺ signals using mathematical modeling.

Results

ATP-mediated P2R Ca²⁺ responses in murine osteoblasts

ATP-stimulated P2R Ca²⁺ responses were assessed in three independent murine osteoblast models: BMP2-transfected C2C12 osteoblastic cells (C2-OB), bone-marrow-derived osteoblasts (BM-OB), and compact-bone-derived osteoblasts (CB-OB). Osteoblasts were loaded with Ca²⁺-indicator dye Fura2, stimulated with varying doses of ATP, and changes in [Ca²⁺]_i were recorded using live cell fluorescent microscopy (Fig 1). Qualitatively, the recorded Ca²⁺ response time-series signatures demonstrated a general trend of exhibiting transient single-peaked responses at low [ATP], multi-peaked oscillatory responses at mid-range [ATP], and relatively sustained single/multi-peaked response at high [ATP] (Fig 1A). The Ca²⁺ responses at each [ATP] were analysed by quantifying several parameters, including overall response magnitudes and activation times, as well as oscillatory fractions, magnitudes, periods and peaks (see S1 Table for definitions) [13]. Similar to previous study [7], we harmonized dose-response profiles across osteoblast models by first aligning the responses along the dose-axis to match troughs/peaks, followed by rescaling the responses to a [0,1] interval (S1 Fig). Such alignment allowed us to account for (i) inconsistencies in ATP solution preparations between experiments and (ii) varied dose-sensitivities across cell lines. Calcium responses induced by low [ATP] (<10⁻⁷ M) were consistently associated with low response magnitudes and slow activation kinetics (Fig 1A, left two columns), with little to no oscillatory component (Fig 1B). Increasing [ATP] further induced responses with faster activation kinetics and higher magnitudes (Fig 1A, middle two columns). This also coincided with the emergence of high frequency oscillations (~10–20 s periods; Figs 1B and S1B and S1C) which peaked at ~10⁻⁵ M ATP stimulation. Notably, the oscillatory peak did not coincide with the peak magnitude. Instead, as cells were stimulated with higher [ATP], the oscillatory component began to diminish, exhibiting lower frequency oscillations and fewer oscillatory peaks, while response magnitude continued to increase, peaking at ~2×10⁻⁴ M [ATP] (Fig 1A, right two columns, and 1B). For [ATP] >2×10⁻⁴ M, the response magnitude decreased with increasing [ATP] in all osteoblast lines. Thus, in all osteoblast models, the intracellular Ca²⁺ response to ATP shifts with increase in [ATP] from a transient with a single narrow peak, to oscillatory and back to transient with a pronounced wide peak.

P2Y₂ and P2X₇ receptors orchestrate the ATP-mediated Ca²⁺ responses

To examine which P2 receptors contribute to the ATP-induced Ca²⁺ responses, we first examined their expression in osteoblastic cells of different origin. Among the P2Y family, *P2ry2*, *P2ry4*, *P2ry12*, and *P2ry14* transcripts were detected in all osteoblastic cells by RT-qPCR (Fig 2A top). Among the P2X family, *P2rx4* and *P2rx7* transcripts were the most abundantly expressed in all osteoblastic cells (Fig 2A bottom). These expression profiles suggest that P2Y₂, 4, 12, 14 and P2X₄, 7 are the predominant P2 receptor subtypes expressed in osteoblastic cells, among which P2Y₂ and P2X₇ were the most abundant transcripts. To confirm that P2Y₂ and P2X₇ receptors are functional, we stimulated Fura2-loaded C2-OB cells with ATP and receptor-specific agonists: the P2Y₂-agonist UTP and P2X₇-agonist bzATP (Fig 2B). Consistent with previously characterized P2 receptor sensitivities [7], we found that the estimated EC₅₀s

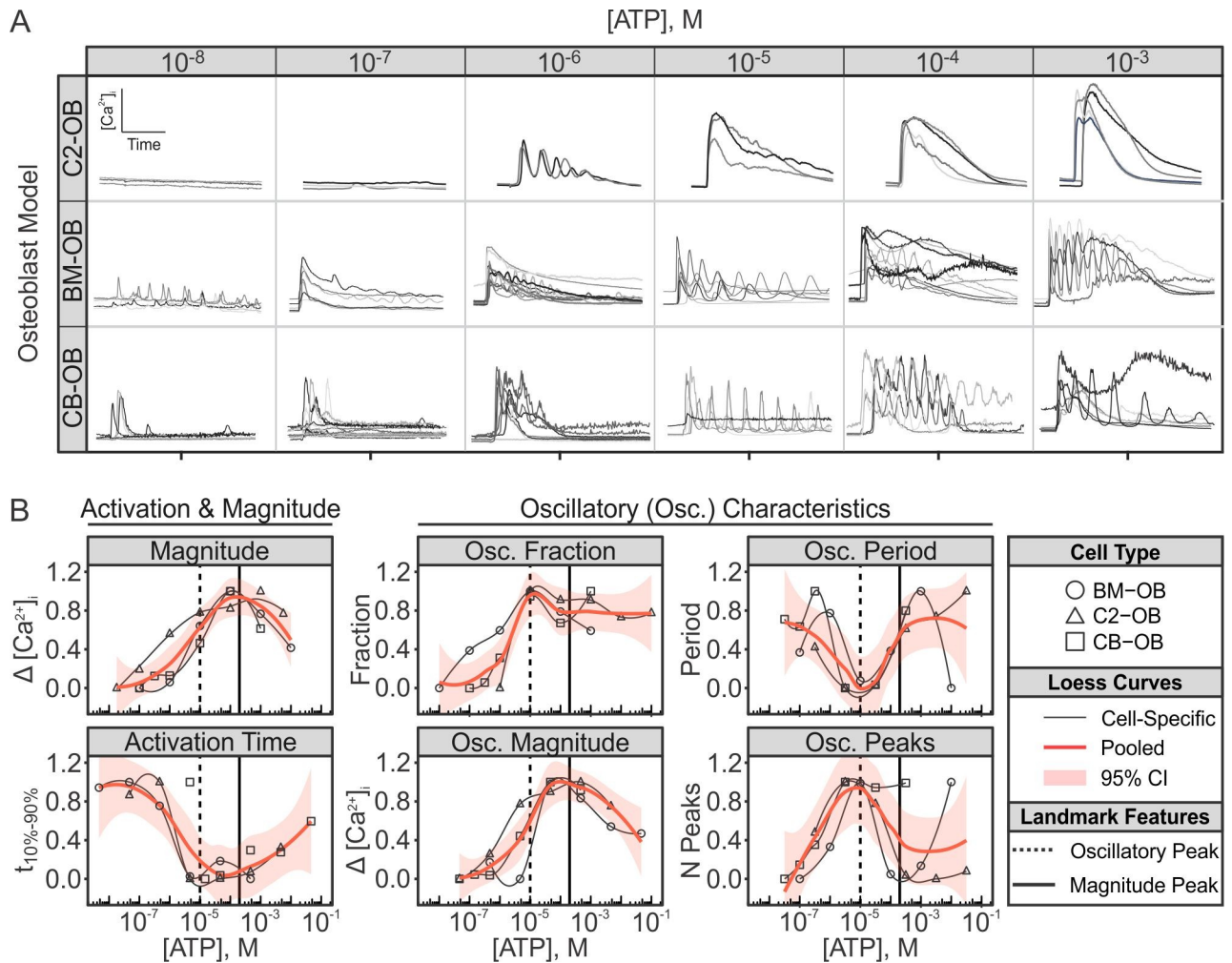


Fig 1. ATP-induced Ca²⁺ response characteristics are conserved across murine osteoblast lines. Fura2-loaded BMP2-transfected C2C12 osteoblastic cells (C2-OB), bone-marrow-derived osteoblasts (BM-OB), or compact-bone-derived osteoblasts (CB-OB) were stimulated with ATP (10⁻⁸ to 10⁻³ M), changes in [Ca²⁺]_i were recorded, and characteristic parameters of individual cell-level Ca²⁺ responses were quantified. (A) Representative ATP-induced Ca²⁺ signature responses for different osteoblastic lines. *Recording duration:* 120 s. (B) Activation time, magnitude and oscillatory characteristics of Ca²⁺ responses in different osteoblastic cells were aligned to obtain consensus on dose-dependency behaviours (see S1 Fig for intermediary alignment steps). Data are response means, normalized to peak dose-response. *Solid curves:* Loess curves fit to normalized response means. *Vertical solid lines:* peak magnitude; *Vertical dashed lines:* peak oscillatory activity; CI: confidence interval, M: molar concentration.

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were 1.0 μM for ATP, 2.8 μM for UTP and 26.4 μM for bzATP in C2-OB cells. Importantly, the oscillatory Ca²⁺ responses evoked by 10⁻⁶ M ATP were recapitulated following stimulation with 10⁻⁶ M UTP, and similarly, the sustained responses evoked by 1 mM ATP were observed following 1 mM bzATP stimulation, suggesting that P2Y₂ and P2X₇ receptors dominate the responses to lower and higher [ATP], respectively (Fig 2C). Using CRISPR-Cas9 double-nickase constructs, we generated clonal C2-OB cells harboring mutations in *P2ry2* (*P2ry2Δ*) or *P2rx7* (*P2rx7Δ*) (Fig 2D) to further investigate the independent contribution of P2Y₂ and P2X₇ to the P2-mediated Ca²⁺ responses (presented in subsequent sections).

A flux-balance-based model of P2Y₂R and P2X₇R driven Ca²⁺ responses

To decipher the underlying biophysical mechanisms governing the ATP-stimulated Ca²⁺ responses in osteoblasts, we developed a mathematical model that integrates P2Y₂R-mediated

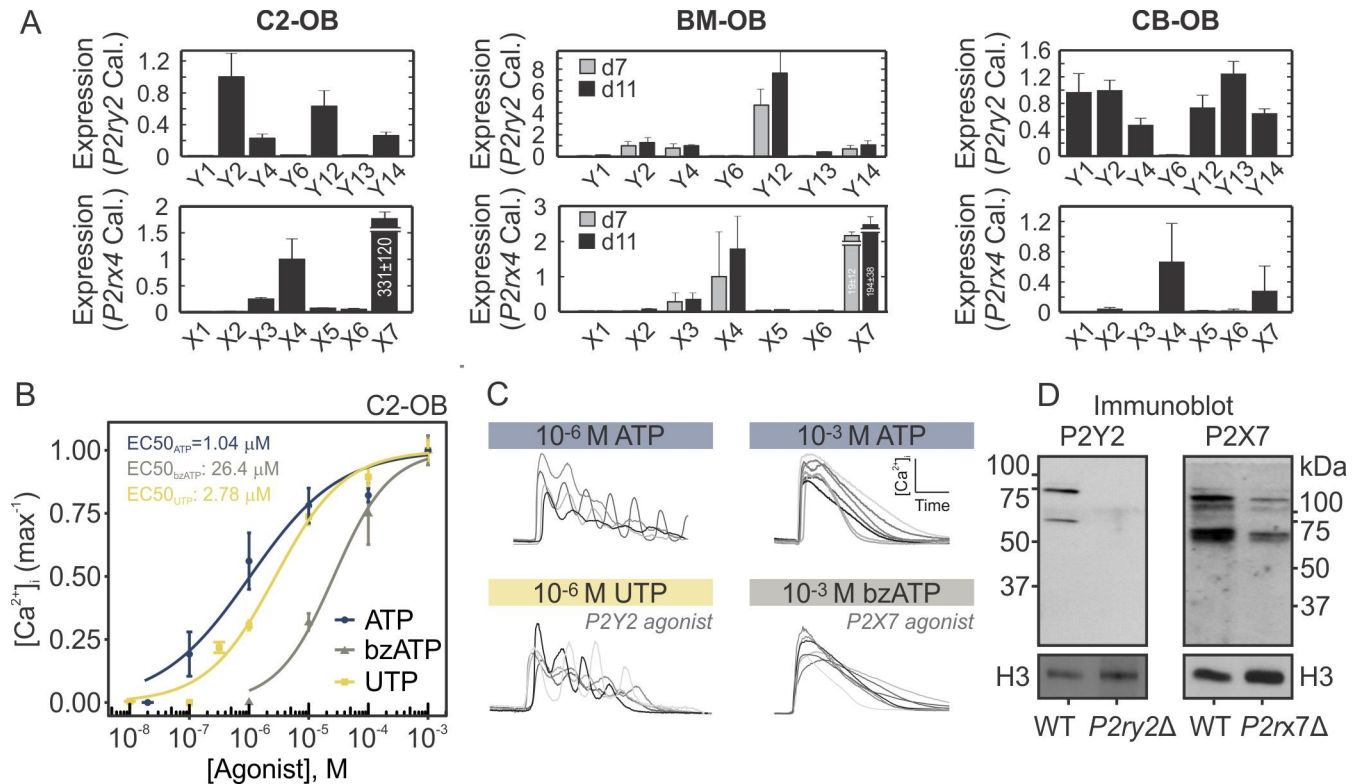


Fig 2. Functional P2Y2 and P2X7 are expressed in osteoblastic cells. (A) P2 expression determined by RT-qPCR in C2-OB, BM-OB, and CB-OB. Relative transcript expression was calculated by $\Delta\Delta$ CT method, and *P2ry2* and *P2rx4* were used as calibrators for P2Y and P2X receptors, respectively. Data are means \pm SEM, n = 3 independent cultures per cell line. (B) Fura2-loaded C2-OB cells were stimulated by ATP, UTP, or BzATP and $[Ca^{2+}]_i$ response magnitudes were measured. Data are normalized means \pm SEM (markers) fitted with hill functions (curves) for their dose-response curves. (C) Representative Ca^{2+} responses observed in C2-OB stimulated by 10⁻⁶ M ATP or UTP, and 10⁻³ M ATP or BzATP. (D) P2Y2 and P2X7 protein expression assessed by immunoblot in WT, *P2ry2* Δ and *P2rx7* Δ C2-OB whole cell lysates. Histone H3 was used as a loading control.

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Ca^{2+} release, as described by the Li-Rinzel model of the IP₃R [24], with a Markov model of P2X7R kinetics adapted from [18] (Fig 3). The cell was divided into two compartments (Fig 3A), the endoplasmic reticulum (ER) and the cytosol, with Ca^{2+} concentrations in each compartment denoted by $[Ca^{2+}]_{ER}$ and $[Ca^{2+}]_i$, respectively. The detailed description of the model is given in *Methods*. Briefly, the model describes (i) Ca^{2+} mobilization across cell membrane, including Ca^{2+} influx through P2X7R receptor channels (J_{P2X7}) and the constant inward leak (J_{INleak}), as well as Ca^{2+} efflux through the plasma-membrane- Ca^{2+} -ATPase (PMCA) pumps (J_{PMCA}); and (ii) Ca^{2+} mobilization across ER membrane, including P2Y2R-mediated Ca^{2+} -induced Ca^{2+} -release (CICR) through IP₃R (J_{IP3R}), Ca^{2+} leak across the ER membrane (J_{ERleak}), and Ca^{2+} uptake through the sarco/endoplasmic Ca^{2+} ATPase (SERCA) pumps (J_{SERCA}). The reduced two-dimensional Li-Rinzel model for IP₃R-mediated CICR was chosen for its simplicity and ability to produce transitions between the desired modes of activity; it follows the Hodgkin-Huxley gating formalism (see *Methods*), with two fast activation variables and one slow inactivation variable that depend on $[IP_3]$ and $[Ca^{2+}]_i$, producing an open probability profile for CICR that is biphasic with respect to $[Ca^{2+}]_i$. Given that P2Ys modulate intracellular Ca^{2+} responses indirectly by stimulating IP₃ production, an equation describing [ATP]-dependent IP₃ production was added to the P2Y2R submodel.

Ca^{2+} flux through P2X7R, J_{P2X7} , on the other hand, was determined by the Ca^{2+} current (I_{P2X7}) through the receptor channels generated by a 12-state Markov P2X7R sub-model

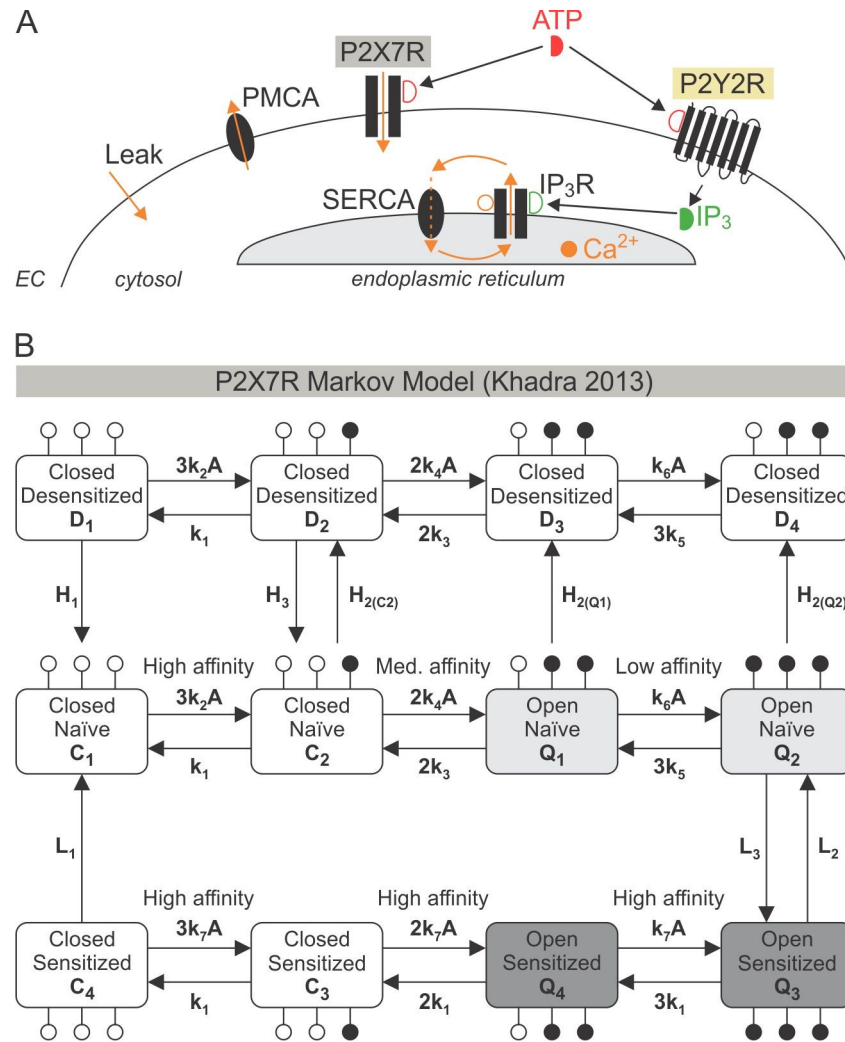


Fig 3. Schematic of the mathematical model describing P2 receptor-mediated Ca²⁺ responses. (A) ATP activates P2X₇ and P2Y₂ receptors on the plasma membrane, stimulating Ca²⁺ entry and IP₃ production, respectively. IP₃ production leads to Ca²⁺ release from the endoplasmic reticulum (ER) through IP₃Rs. Sarco/endoplasmic Ca²⁺ ATPase (SERCA) activity replenishes the ER and allows for Ca²⁺ oscillations when combined with the biphasic response of IP₃Rs to Ca²⁺ due to Ca²⁺-induced Ca²⁺-release (CICR). Ca²⁺ is removed from the cell by plasma membrane Ca²⁺ ATPases (PMCA). A constant inward Ca²⁺ leak ensures positive [Ca²⁺]_i in the absence of ATP. EC: extracellular space. (B) Schematic of the P2X₇R Markov Model. Middle, lower and upper rows: Fraction of P2X₇Rs in naïve, sensitized and desensitized states, respectively. Open and solid circles: Sites unoccupied and occupied by ATP, respectively. Receptors in the closed (C_i) and desensitized (D_i) states have closed channel pores, whereas receptors in the open (Q_i) states, have open channel pores with identical conductance, i = 1–4. Model parameter values are listed in Table 1.

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(Fig 3B) [18]. The P2X₇R submodel assumes that each receptor has three ATP binding sites, two of which must be occupied for the receptor to be open, and that each state represents the fraction of receptors with a given number of occupied ATP-binding sites (Fig 3B, solid circles). The closed, C_i, and desensitized, D_i, states are non-conducting, whereas the open states Q_i (i = 1–4) possess the same conductance g_{X7}. The states were divided into three rows corresponding to desensitized (Fig 3B, top row), naïve (Fig 3B, middle row) and sensitized or primed (Fig 3B, bottom row) states, respectively. The naïve row is comprised of the states C₁, C₂, Q₁, Q₂ that have not been exposed to ATP for a prolonged period of time, whereas the sensitized and desensitized rows are comprised of the states C₃, C₄, Q₃, Q₄ (D₁, D₂, D₃, D₄) that

have been previously exposed to ATP. The forward and backward transitions along each row describe ATP binding and unbinding, respectively, whereas downward and upward transitions between the rows represent receptor sensitization (middle to bottom row), desensitization (middle to top row) or recovery (bottom/top to middle row). The rate of desensitization increases as more ATP molecules bind to P2X₇R and the open probability along the sensitized row is larger than that for the naïve row.

Combining the two submodels together produced the following model:

$$\frac{d[Ca^{2+}]_i}{dt} = f_c(J_{INleak} + J_{P2X7} - J_{PMCA} + J_{IP3R} + J_{ERleak} - J_{SERCA}) \quad (1)$$

$$\frac{d[Ca^{2+}]_{ER}}{dt} = f_{ER}\gamma(J_{SERCA} - J_{IP3R} - J_{ERleak}) \quad (2)$$

$$\frac{d[IP_3]}{dt} = \alpha_{ATP} \frac{[ATP]}{[ATP] + k_{ATP}} - \delta_{ATP}[IP_3] \quad (3)$$

where f_c and f_{ER} represent the fraction of free Ca^{2+} in the cytosol and ER, respectively, as a result of buffering with $0 < f_c < f_{ER} \ll 1$, γ is the ratio between cytosolic and ER volume, α_{ATP} is the maximum rate of IP_3 production by P2Y₂ in response to ATP, k_{ATP} is the half-maximum production of IP_3 through P2Y₂R and δ_{ATP} is the rate of IP_3 degradation.

Using the model parameters provided in [Table 1](#), we simulated Ca^{2+} responses to different [ATP] in three specific cases: (i) in naïve cells expressing both P2Y₂R and P2X₇R using the full model ([Fig 4A](#), blue curves), (ii) in cells that do not express P2Y₂R, using the submodel for P2X₇ component only ([Fig 4A](#), grey curves), and (iii) in cells that do not express P2X₇R using the submodel for P2Y₂ component only ([Fig 4A](#), yellow curves). The simulated Ca^{2+} responses were compared with those obtained experimentally in WT ([Fig 4B](#), blue curves), *P2ry2Δ* ([Fig 4B](#), grey curves) and *P2rx7Δ* ([Fig 4B](#), yellow curves) C2-OB cells. As shown, the responses to low [ATP] were predominantly P2Y₂-mediated, while the response to high [ATP] were jointly mediated by P2Y₂ and P2X₇. Notably, the characteristic two-peaked response to 10^{-3} M observed in experimental recordings ([Figs 1A](#) and [4B](#)) was predicted by the full model ([Fig 4A](#)) of WT cells, but was abolished in *P2ry2Δ* and *P2rx7Δ* recordings and in simulations of P2X₇ and P2Y₂ submodels. These data strongly support the interaction between P2Y₂ and P2X₇ receptors in generating this unique signaling feature.

One interesting aspect of the recordings and simulations displayed in [Fig 4](#) was the observation of oscillatory Ca^{2+} responses at intermediate [ATP], with transient responses at low and high [ATP], indicating that the mathematical model developed in this study recapitulates the characteristic Ca^{2+} signatures observed in C2-OB cells over a physiological range of [ATP].

P2Y₂ drives the transition from transient to oscillatory Ca^{2+} responses

Since the oscillatory component required P2Y₂ activity in both experimental and simulated responses to ATP, we next investigated how the transition between transient and oscillatory responses is achieved by the P2Y₂ receptor. Given that $[IP_3]$ and $[Ca^{2+}]_{ER}$ are slow variables in the model defined by [Eqs \(1\)–\(3\)](#), we set $J_{P2X7R} = 0$ and applied slow-fast analysis on the resulting P2Y₂ receptor model by assuming that these two variables change slowly relative to other “fast” variables in the model. We set the two variables ($[IP_3]$ and $[Ca^{2+}]_{ER}$) as independent adjustable parameters in the P2Y₂ model and investigated how the steady state dynamics of fast variables change when $[IP_3]$ and $[Ca^{2+}]_{ER}$ are altered. The two-parameter bifurcation diagram ([Fig 5](#)) exhibited an oscillatory region in the “parameter” space formed by $[IP_3]$ and

Table 1. Mathematical Model Parameters.

Symbol	Value	Description	Reference
Buffering & Scaling			
f_c	0.01	Cytosolic Ca ²⁺ buffering	[38]
f_{ER}	0.025	ER Ca ²⁺ buffering	[38]
γ	9	cytosol/ ER volume ratio	[39]
Plasma Membrane Fluxes			
J_{INleak}	0.15 μMs^{-1}	Inward leak across plasma membrane	Fitted†
v_{PMCA}	30 μMs^{-1}	Maximum PMCA activation	Fitted†
k_{PMCA}	0.45 μM	PMCA Ca ²⁺ affinity	[32]
ER Fluxes			
v_{SERCA}	22.5 μMs^{-1}	Maximum SERCA activation	Fitted†
k_{SERCA}	0.105 μM	SERCA Ca ²⁺ affinity	[32]
v_{ERleak}	0.03 s ⁻¹	Rate of Ca ²⁺ leak across ER membrane	Fitted†
Li Rinzel IP₃R Models			
d_1	0.13 μM	IP ₃ dissociation constant (Ca ²⁺ unbound from inactivation site)	[24]
d_2	1.049 μM	Ca ²⁺ dissociation constant from the inactivation site (IP ₃ bound)	[24]
d_3	0.9434 μM	IP ₃ dissociation constant (Ca ²⁺ bound to inactivation site)	[24]
d_5	0.08234 μM	Ca ²⁺ dissociation constant from activation site	[24]
a_2	0.2 μMs^{-1}	Ca ²⁺ binding rate to the inactivation site	[24]
v_{IP3R}	15 μMs^{-1}	Maximum flux through IP ₃ Rs	Fitted†
P2X₇R Model			
g_{X7}	2.5x10 ⁻⁸ Ms ⁻¹	P2X ₇ R conductance of both naïve and sensitized open states	Adjusted***
E	0 mV	Reversal potential	[18]
k_1	0.3 s ⁻¹	Transition rates between states (Fig 3B, along the same row)	[18]
k_2	1265 M ⁻¹ s ⁻¹		[18]*
k_3	2.4 s ⁻¹		[18]
k_4	1581 M ⁻¹ s ⁻¹		[18]*
k_5	1.58 s ⁻¹		[18]
k_6	221 M ⁻¹ s ⁻¹		[18]*
k_7	316 M ⁻¹ s ⁻¹		[18]*
L_1	0.0001	Transition rates between naïve (Fig 3B, middle row) and sensitized (Fig 3B, bottom row)	[18]
L_2	0.004		[18]
L_3	0.3		[18]
H_1	0.001	Transition rates between naïve (Fig 3B, middle row) and desensitized (Fig 3B, upper row)	[18]
$H_{2(C2)}$	0.01		[18]
$H_{2(Q1)}$	0.05		Adjusted***
$H_{2(Q2)}$	0.8		Adjusted***
V	-0.06 V	Membrane Potential	[18]
f_{Ca}	0.046	Fraction of P2X ₇ R flux that is Ca ²⁺	[36]
V_{osteo}	6.5 pL	Osteoblast volume	[35,40]
IP₃ Dynamics			
α_{ATP}	0.03 μMs^{-1}	Maximum rate of IP ₃ production driven by ATP	[30,41]**
k_{ATP}	1 μM	Sensitivity of IP ₃ production to [ATP]	Fitted†
δ	0.01 s ⁻¹	Degradation rate of IP ₃	[30,41]**

*Parameter values in [18] were fitted to BzATP. To capture the lower binding affinity of ATP to P2X₇R, these parameter values were rescaled here (by dividing them by the factor 31.625).

**Parameter values from [30] were used as an upper bound for the parameters in this work, based on the significantly slower IP₃ dynamics reported in living cells in [41].

*** As stated in the text, these values were adjusted due to the evidence that P2X₇R do not dilate and that P2X₇R desensitization increases with more ATP binding.

†These parameter values were determined by fitting the model to data of dose-responses of ATP-induced [Ca²⁺]_i elevations shown in Fig 7.

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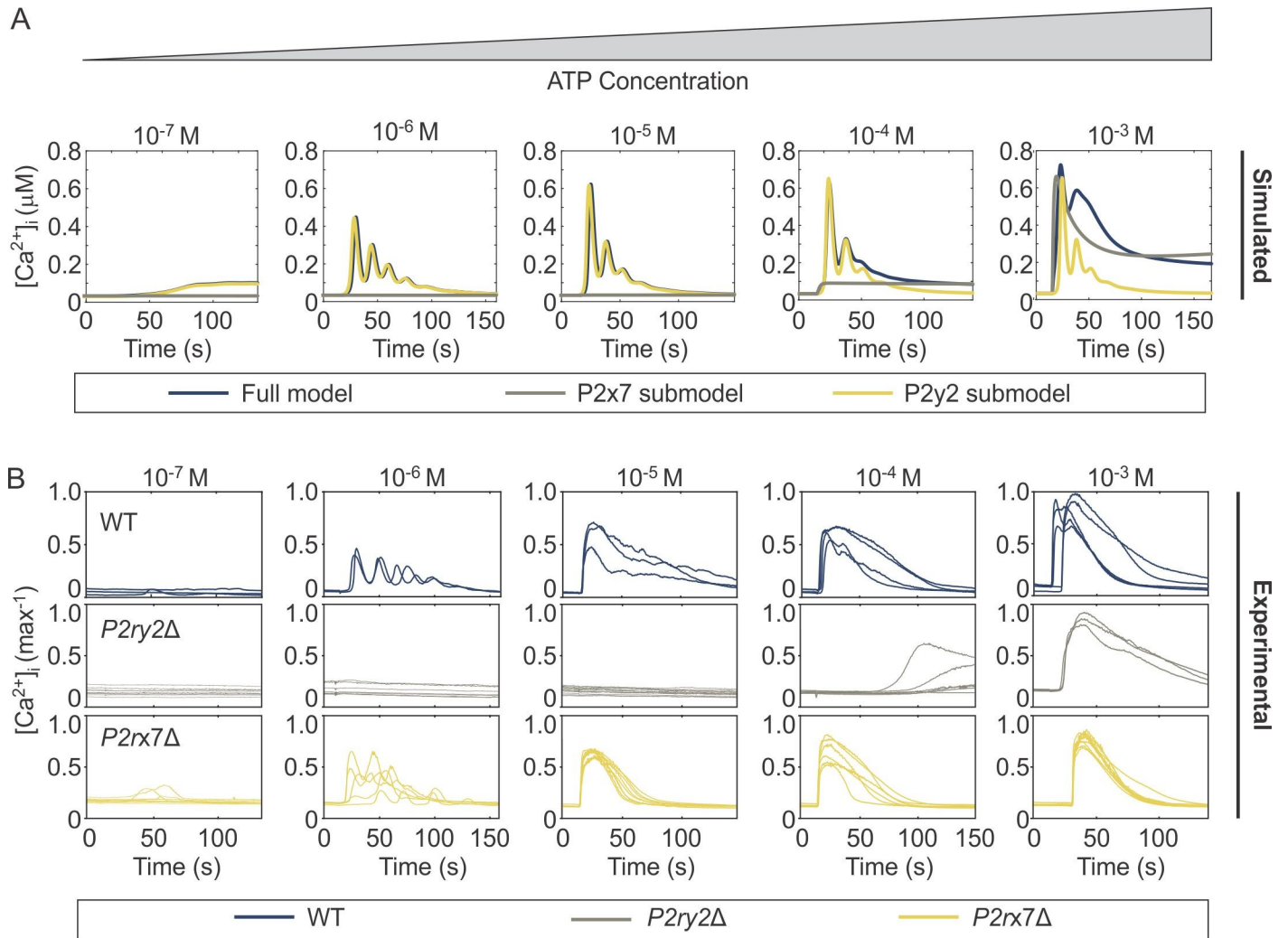


Fig 4. Comparison of simulated and experimental dynamics of ATP-induced [Ca²⁺]_i responses. (A) Time series simulations of [Ca²⁺]_i responses generated by the complete model of P2Y₂ and P2X₇ (full model, blue), P2X₇ submodel (grey) and P2Y₂ submodel (yellow). Parameter values are provided in Table 1. (B) Experimental recordings of [Ca²⁺]_i responses in WT (blue), P2ry2Δ (grey) and P2rx7Δ (yellow) C2-OB cells in response to varying [ATP].

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[Ca²⁺]_{ER} within which [Ca²⁺]_i is periodic (Fig 5, grey region). Outside this region, [Ca²⁺]_i attained steady state values that are [IP₃] and [Ca²⁺]_{ER}-dependent. The boundary of this oscillatory region (generated by two supercritical Hopf bifurcations) defined the threshold for [Ca²⁺]_i to transition between these two main patterns of activity: quiescence and oscillatory. Thus the application of increasing [ATP] in this model would induce an increase in IP₃ (since [IP₃] ∝ [ATP]) and a decrease in [Ca²⁺]_{ER}, generating three possible scenarios for the time courses of [Ca²⁺]_i. When low [ATP] is applied the trajectory stays to the left of the oscillatory region (Fig 5A, red arrow) because the ATP-induced IP₃ increase is low (Fig 5B, red curve) and [Ca²⁺]_{ER} remains high (Fig 5C, red curve), resulting in a low magnitude persistent transient response (Fig 5D, red curve). Intermediate [ATP] results in a hybrid response that becomes periodic when the trajectory crosses the left boundary of the oscillatory regime (Fig 5A, green curve), due to a higher increase in IP₃ and a faster decrease in [Ca²⁺]_{ER} (Fig 5B and 5C, green curves), leading to a response characterized by damped oscillations (Fig 5D, green curve). When high [ATP] is applied, the trajectory crosses the oscillatory region very briefly

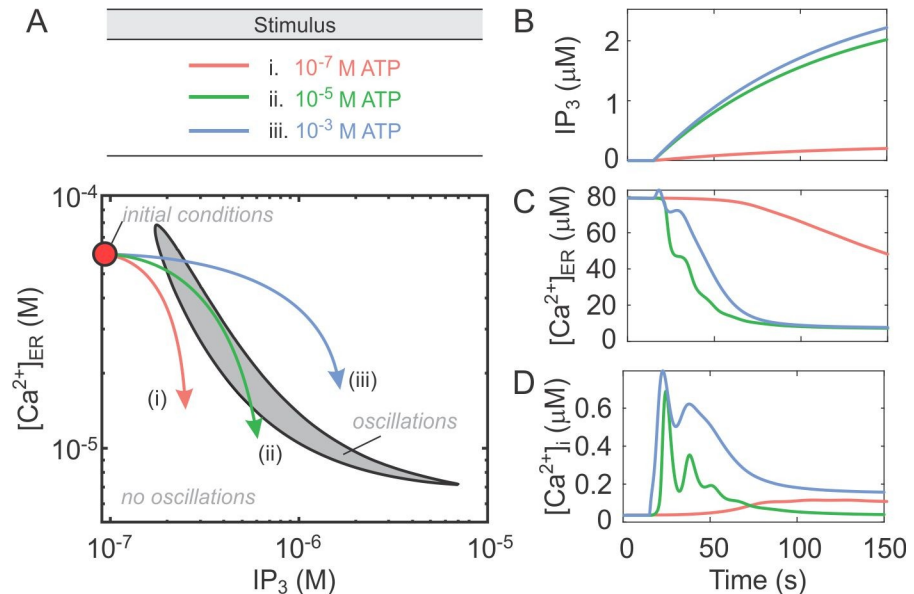


Fig 5. Ca^{2+} oscillatory response dynamics defined by the P2Y₂-induced changes in $[Ca^{2+}]_{ER}$ and $[IP_3]$. The model defined by Eqs (1)–(3), was examined with $J_{P2X7R} = 0$. (A) The slow variables representing $[IP_3]$ and $[Ca^{2+}]_{ER}$ were set to be independent parameters and the continuation method in XPPATU was applied to track two supercritical Hopf bifurcation points that enclose the oscillatory region (grey region). Arrows indicate the three possible scenarios that describe the changes in $[IP_3]$ and $[Ca^{2+}]_{ER}$ during Ca^{2+} responses: 10^{-7} M ATP response trajectory remains outside the oscillatory region (red), 10^{-5} M ATP response trajectory spends an extended period of time inside the oscillatory region (green) and 10^{-3} M ATP response trajectory briefly crosses through the oscillatory region (blue). (B–D) Simulated changes in IP_3 (B), $[Ca^{2+}]_{ER}$ (C) and $[Ca^{2+}]_i$ (D) following the application of 10^{-7} M ATP (red) 10^{-5} M ATP (green) or 10^{-3} M ATP (blue).

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(Fig 5A, blue curve) because even though the ATP-induced IP_3 increase is higher (Fig 5B, blue curve), the $[Ca^{2+}]_{ER}$ does not decrease as fast (Fig 5C, blue curve) due to the biphasic nature of IP_3 R incorporated in the P2Y₂ sub-model and the interaction of SERCA pumps with IP_3 R [24]; this results in a high magnitude semi-persistent response (Fig 5D, blue curve). The aforementioned mechanism suggests that the heterogeneity in Ca^{2+} response profiles at a given [ATP] observed experimentally (Fig 1A) may be due to variations in the initial conditions, such as the expression levels of PMCA/SERCA pumps and IP_3 R, potentially leading to differences in the initial $[IP_3]$ and $[Ca^{2+}]_{ER}$. These simulations demonstrate that the oscillatory response strongly depends on the initial $[IP_3]$ and $[Ca^{2+}]_{ER}$, and that when increasing doses of [ATP] are applied, P2Y₂-mediated changes in $[IP_3]$ and $[Ca^{2+}]_{ER}$ result in different patterns of Ca^{2+} responses.

P2X₇ modulates the magnitude of Ca^{2+} response to ATP

We next investigated the non-monotonic [ATP]-dependent dose-response profile for the magnitude of Ca^{2+} response observed across all osteoblastic lines (Fig 1B). Using the model defined by Eqs (1)–(3), we generated Ca^{2+} responses to [ATP] ranging between 10^{-8} to 10^{-2} M ATP (in 10^{-8} M [ATP] increments), and computed the maximum $[Ca^{2+}]_i$ reached within 120 s (Fig 6A). The full model (Fig 6A, blue curve) recapitulated the experimental magnitude dose-response profile (Fig 6A, blue triangles), including the troughs at moderate (Fig 6A, light grey region) and elevated (Fig 6A, dark grey region) [ATP] within the plateau component of the response. This dose-dependency became monotonic in experimental recordings of Fura2-loaded *P2rx7Δ* C2-OB cells stimulated with ATP (Fig 6A, red circles) and in the model lacking

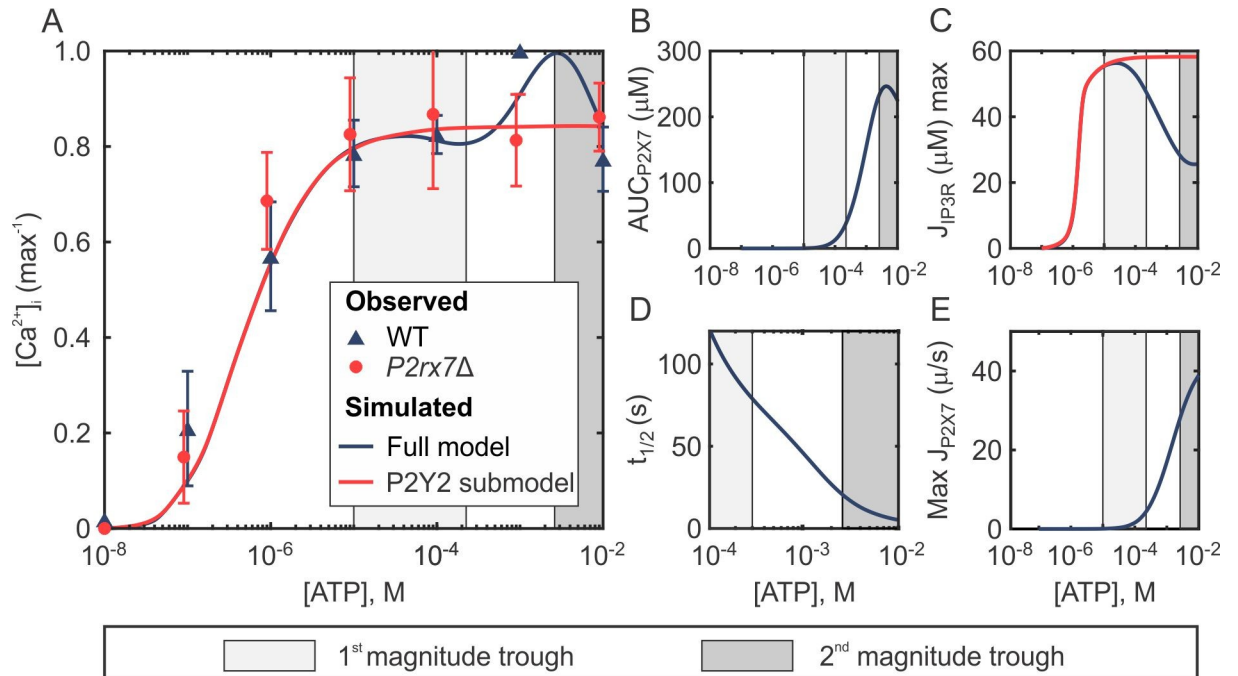


Fig 6. Interaction between P2Y2R and P2X7R underlies the non-monotonic magnitude dose-dependency. (A) The magnitude dose-responses of ATP-induced $[Ca^{2+}]_i$ elevations. Markers indicate experimental means \pm SEM in wild-type (WT; blue) and $P2rx7\Delta$ (red) C2-OB cells. Curves indicate simulated data generated by the full model (blue) and P2Y2 submodel (red). (B) P2X7R-mediated Ca^{2+} entry estimated from simulated area under the P2X7R flux curve (0–10 s). (C) Simulated maximal flux through IP₃Rs in the full model (blue) and P2Y2 only submodel (red). (D) Rate of P2X7R desensitization estimated from simulated time required for P2X7R flux to decay to half of its maximum. (E) Simulated maximum flux through P2X7Rs. Shaded regions in all panels: characteristic first (light grey) and second (dark grey) magnitude troughs observed in WT cells that disappear in $P2rx7\Delta$ cells.

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P2X7Rs (Fig 6A, red curve), strongly implicating P2X7 in this phenomenon. Therefore, we next plotted the total Ca^{2+} flux through P2X7Rs, estimated as the area under the P2X7R flux curve, as well as the maximal Ca^{2+} fluxes through P2X7Rs and IP₃Rs predicted by the model (Fig 6B–6E). When P2X7R-mediated Ca^{2+} entry became evident at 10^{-5} M ATP (Fig 6B, light grey region), the maximum flux through IP₃Rs in the full model (Fig 6C, black curve) dropped below that of the P2X7R-lacking submodel (Fig 6C, red curve) due to the biphasic dependence of IP₃Rs on $[Ca^{2+}]_i$, resulting in the first trough in the dose-response (Fig 6A, light grey region). At high 10^{-2} M [ATP], on the other hand, the time required for the P2X7R flux to decay to half of its maximum ($t_{1/2}$) decreased (Fig 6D). As a result, despite the maximum P2X7R flux continually increasing (Fig 6E), the Ca^{2+} entering through P2X7R began to decrease at elevated [ATP] (Fig 6B, dark grey), resulting in the second trough in the dose-response (Fig 6A, dark grey). Taken together, these simulations indicate that the non-monotonic Ca^{2+} dose-response to ATP is driven by an interplay between the biphasic nature of IP₃Rs and the desensitization kinetics of P2X7Rs.

Contribution of P2Y2 to Ca^{2+} responses at high [ATP]

Next, we examined why the Ca^{2+} response to high [ATP] is dramatically affected in $P2ry2\Delta$ cells (Figs 4B and 7A). We examined the magnitudes of Ca^{2+} responses to 10^{-2} M [ATP] in WT $P2ry2\Delta$ cells, and found that in the absence of P2Y2R, response magnitudes exhibited a distinct bimodal distribution with one cluster of responses similar to those in WT, and another one with much higher response magnitudes (Fig 7B). We hypothesized that the

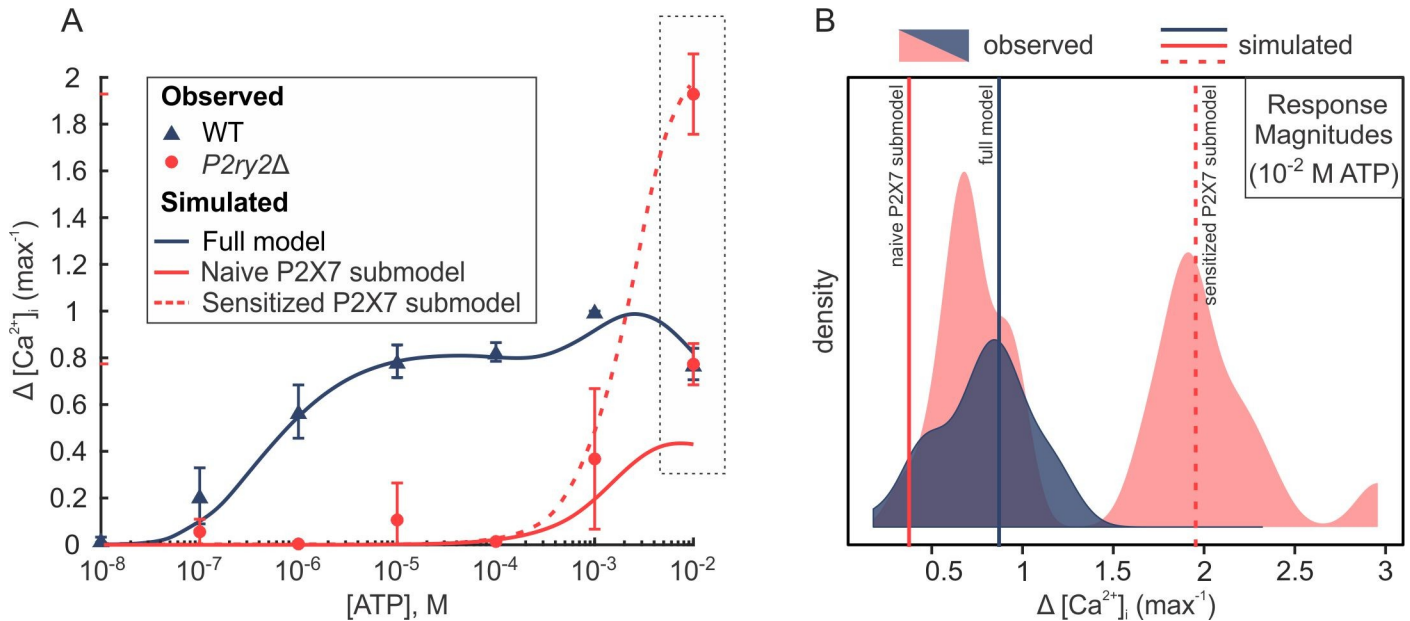


Fig 7. P2Y2 alters P2X7-mediated $[Ca^{2+}]_i$ response to high [ATP]. (A) The magnitude dose-responses of ATP-induced $[Ca^{2+}]_i$ elevations. Markers indicate experimental means \pm SEM in wild-type (WT; blue) and *P2ry2* Δ (red) C2-OB cells. Curves indicate simulated data generated by the full model (blue), a P2X7 submodel initiated from the naïve closed state C_1 (solid red curve), or a P2X7 submodel initiated from the sensitized closed state C_4 (dashed red curve). (B) Density distributions of experimental Ca^{2+} response magnitudes to 10^{-2} M [ATP] in WT cells (blue density; unimodal) and *P2ry2* Δ cells (red density; bimodal). Vertical lines show simulated response magnitudes (10^{-2} M [ATP]) obtained by the full model (solid blue line), naïve P2X7 submodel (solid red line) and sensitized P2X7 submodel (dashed red line).

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bimodality in the P2X7R-mediated responses is due to P2X7Rs being in the naïve or sensitized initial state [20]. To verify this, we used the P2X7 submodel to simulate the Ca^{2+} response in two different scenarios: initiating the P2X7-simulations from the naïve closed state C_1 (i.e., $C_1(0) = 1$, $C_i(0) = 0$, for $i = 2-4$, and $Q_i(0) = D_i(0) = 0$, for $i = 1-4$), or from the sensitized closed state C_4 (i.e., $C_4(0) = 1$, $C_i(0) = 0$, for $i = 1-3$, and $Q_i(0) = D_i(0) = 0$, for $i = 1-4$). These two scenarios reflect the heterogeneity in the distribution of unstimulated P2X7R as being predominantly in the naïve or sensitized states. Plotting the [ATP]-dependent dose-response curve for $[Ca^{2+}]_i$ generated from these time series simulations revealed that P2X7R responses initiated from C_1 produced a dose-response curve that plateaued at a depressed level of $[Ca^{2+}]_i$ ($\sim 40\%$ of max WT response; Fig 7A, solid red curve), close to the mean of the left mode of the distribution (Fig 7B). In contrast, P2X7R responses initiated from C_4 state produced a dose-response curve that plateaued at an elevated $[Ca^{2+}]_i$ ($\sim 200\%$ of max WT response; Fig 7A, dashed red curve), closely matching the mean of the right mode of the distribution (Fig 7B). These data suggest that P2Y2 activation may alter the kinetics of P2X7 towards favouring naïve state activation.

Functional contributions of P2Y2 and P2X7 to mechanotransductive signaling

To investigate the potential functional consequences of the complex interactions between P2Y2 and P2X7, we examined how the absence of each of these receptors affects ATP-mediated mechanotransduction. We have previously shown that mechanical stimulation of a single “primary” osteoblast with a glass micropipette leads to the release of 10^{-5} to 10^{-4} M ATP into the pericellular space, which then diffuses to stimulate neighbouring non-mechanically

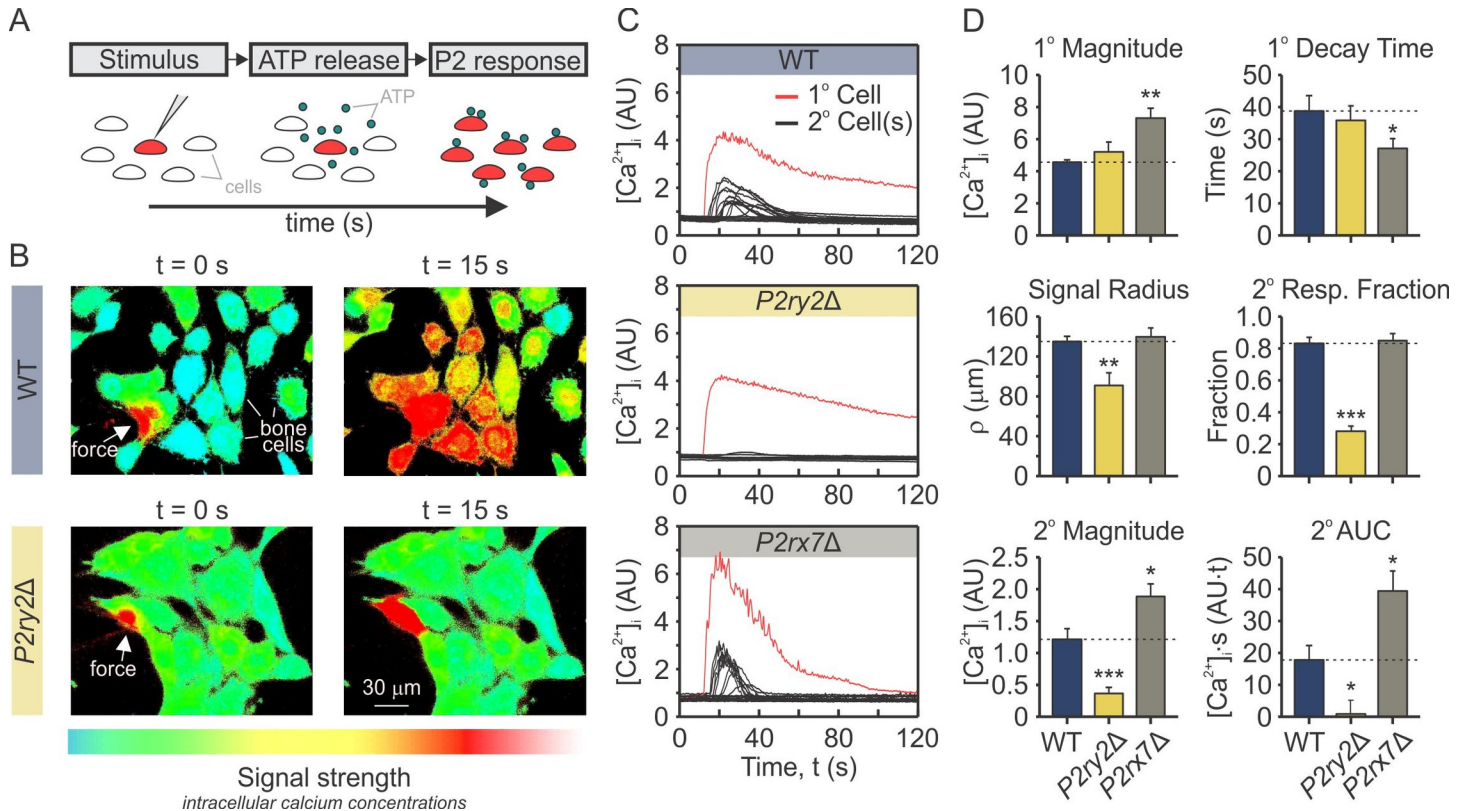


Fig 8. P2Y₂R and P2X₇R contribution to mechanically stimulated signals in bone cells. (A) Fura2-loaded C2-OB cells were plated on a glass-bottom dish and individual cell (*primary*; 1°) was mechanically stimulated with a glass-micropipette inducing ATP release into the extracellular space, which subsequently stimulated P2 responses in neighbouring cells (*secondary*; 2°). (B) Representative images of [Ca²⁺]_i (pseudocolor of 340/380 ratio) in C2-OB parental (*top*) and *P2ry2Δ* (*bottom*) cultures, in which a single cell was mechanically stimulated at t = 0 s (white arrows). The snapshot at 15 s demonstrate secondary responses in neighboring cells. *Red traces*: primary responses; *Black traces*: secondary responses. (C) Time-series recordings in WT (*top panel*), *P2ry2Δ* (*middle panel*), and *P2rx7Δ* (*lower panel*) cells. (D) Quantification of primary and secondary [Ca²⁺]_i response parameters, including signaling radius, fractions of responding cells, response magnitudes and areas under the curves in WT (*blue*), *P2ry2Δ* (*yellow*), and *P2rx7Δ* (*grey*) cells. Data are means ± SEM, **p* < 0.05, ***p* < 0.01 and ****p* < 0.001 indicate comparisons between WT and *P2ry2Δ* or *P2rx7Δ* cells assessed by ANOVA and Bonferroni-corrected t-test. AU: arbitrary units.

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perturbed “secondary” cells [11,12]. Here, we mechanically stimulated a single fura2-loaded osteoblast from parental C2-OB, or clones deficient in P2Y₂, *P2ry2Δ*, or P2X₇, *P2rx7Δ* and recorded [Ca²⁺]_i responses in the primary and secondary cells (Fig 8A). We found that while in *P2rx7Δ* cells the response was qualitatively similar to WT, in *P2ry2Δ* cells secondary responses were abolished (Fig 8B and 8C). Quantitatively, the primary response was unaffected in *P2ry2Δ* cells, but exhibited higher magnitude and faster decay in *P2rx7Δ* cells (Fig 8C and 8D). The suppression of the secondary response in *P2ry2Δ* cells was evident by the reduced signaling radius (*p* = 9 × 10⁻³), fractions of responding cells (*p* = 5 × 10⁻¹¹), response magnitudes (*p* = 2 × 10⁻⁴) and areas under the curves (AUC; *p* = 0.02) (Fig 8B–8D, yellow). In contrast, in *P2rx7Δ* cells, the signaling radius and fraction of responding secondary cells was unaffected; however, the response magnitudes and areas under the curves of secondary cells were significantly higher in *P2rx7Δ* cells compared to parental C2-OB cells (Fig 8C and 8D, grey). These data demonstrate that P2Y₂ receptor is critical for the secondary responses, consistent with its high sensitivity to ATP. In addition, the contribution of P2X₇ to Ca²⁺ responses is evident even though extracellular ATP in these experiments remained below [ATP] required to stimulate P2X₇. Taken together, these data strongly support the importance of an interplay between P2Y₂R and P2X₇R.

Discussion

In this study, we demonstrated that the patterns of P2R-mediated Ca²⁺ responses to ATP are conserved across three independent murine osteoblast models and identified the P2Y₂ and P2X₇ receptors as the dominant P2 receptors contributing to these responses. Based on previous experimental evidence highlighting the role of IP₃ in regulating calcium responses [11], we constructed a flux-balance based mathematical model of Ca²⁺ signals induced by the activation of high affinity P2Y₂R and low affinity P2X₇R. Model predictions were validated by comparing the results of simulations to experimental data of ATP-generated Ca²⁺ signaling in parental and CRISPR/Cas9-generated P2Y₂ and P2Y₇ knockouts in osteoblastic C2C12-BMP cells. We demonstrated that activation of P2Y₂R by progressively increasing [ATP] induces a transition from transient to oscillatory to transient Ca²⁺ responses due to the biphasic nature of IP₃R activation/inactivation kinetics and the interaction of SERCA pumps with IP₃Rs. At high [ATP], activation of P2X₇R was found to modulate the peak response magnitudes through an interplay between the biphasic nature of IP₃Rs and the desensitization kinetics of P2X₇Rs. Moreover, our study suggests that P2Y₂ activity may also alter the kinetics of P2X₇ towards favouring naïve state activation. Finally, we demonstrated that functional consequences of lacking P2Y₂ or P2X₇ are evident beyond the absence of a signal at the expected range of ATP concentrations. Taken together, these findings support a model in which the response to ATP is not a simple superposition of individual P2 receptors, but a complex context-specific functional response build through interactions of multiple P2 receptors.

Our experimental studies focused on characterizing ATP-mediated calcium responses in osteoblasts. In investigating these calcium responses, we chose to stimulate cells with a range of physiologically-relevant ATP concentrations (10 nM to 10 mM), such that 10–100 nM ATP represented small fluxes above baseline extracellular ATP concentrations, 1–100 μM ATP represented concentrations achieved following mechanical stimulation, and 1–10 mM ATP represented intracellular [ATP] that has the capacity to spill into the extracellular space and stimulate P2 receptor signalling following traumatic tissue injury [3,7,11]. We have found that murine osteoblastic cells from different sources exhibit similar patterns in their ATP concentration-dependence of Ca²⁺ responses, including non-trivial features such as the transition of response from transient to oscillatory and back to transient when increasing [ATP], and the presence of two troughs in the plateau phase of the magnitude dose-response curve at high [ATP]. These findings suggest that P2 receptors contributing to these responses are also conserved. P2 receptors are ubiquitously expressed in every mammalian cell, with cell- and tissue-type specific patterns of expression [5]. Consistent with previous reports [25,26], we demonstrated that the pattern of P2 receptors expressed across different murine osteoblast models is consistent at the mRNA level, and identified ATP-sensitive P2X₇ and P2Y₂ receptors as the dominant P2 receptor subtypes in osteoblasts. In keeping with their important roles in bone, *P2rx7*^{-/-} and *P2ry2*^{-/-} mice have been shown to exhibit severe bone phenotypes, with *P2rx7*^{-/-} mice demonstrating significant deficiency in bone mineral density and truncated response to mechano-adaptive loading [27,28], and *P2ry2*^{-/-} mice similarly experiencing osteopenia and altered mechanotransductive responses [29]. In our study, CRISPR-Cas9 double-nickase generated clonal C2-OB cells lacking *P2ry2* or *P2rx7* showed altered responses to sustained ATP stimulation, which translated into significant changes in mechanotransductive [Ca²⁺]_i signaling. Thus, P2Y₂ and P2X₇ receptors play critical roles in mediating the osteoblast response to ATP, particularly in the context of mechanotransductive signaling in bone.

In every osteoblast model, we found that there was a finite range of [ATP] over which oscillatory [Ca²⁺]_i response is prevalent. The oscillatory behaviour was abolished in *P2ry2Δ* cells, but preserved in *P2rx7Δ* cells, strongly implicating P2Y₂ as a mediator of oscillations. Using

the mathematical model of P2Y₂-induced changes in [IP₃] and [Ca²⁺]_{ER} allowed us to examine the mechanism of transition between oscillatory and non-oscillatory (transient) responses. We found that moderate IP₃ production evokes an oscillatory response because of two factors: *i*) CICR by the IP₃Rs that exerts negative feedback on the receptors and inhibits them, and *ii*) the interaction of IP₃Rs with SERCA that pumps Ca²⁺ back into the ER. In contrast, at low [ATP], the Ca²⁺ released by IP₃Rs is insufficient to feedback and inhibit the receptors, whereas at high [ATP], IP₃Rs become constitutively activated, making CICR larger than that in the moderate case but no longer able to inactivate the receptors; this produces, as a result, transient Ca²⁺ responses in both cases. While this model prediction is interesting, its validation is limited by difficulties in experimentally measuring osteoblastic IP₃ dynamics. Specifically, little is known about the basal [IP₃] (assumed to be 0 μM in our model), which plays a significant role in whether solutions will pass through the oscillatory region obtained in the [IP₃] and [Ca²⁺]_{ER} space. Furthermore, the ability of the model to predict some of the experimental response profiles observed at elevated [ATP] is limited by the chosen P2Y₂R-IP₃R sub-model, which is unable to slowly decay after a rapid increase in [Ca²⁺]_i [24]. Given the large heterogeneity of responses at these concentrations, choosing a simplified P2Y₂R-IP₃R sub-model was prioritized over the ability to reproduce some response patterns. In spite of these limitations, experimental and modeling data agree on the critical role of P2Y₂-induced IP₃-mediated Ca²⁺ release from ER in generating oscillatory Ca²⁺ responses to ATP.

Another conserved feature in ATP dose dependence in osteoblasts is the non-monotonic changes in the response magnitude. A similar dose-response curve, with troughs at 10⁻⁴ M and 10⁻² M ATP and a peak at 10⁻³ M ATP was reported in MC3T3-E1 osteoblasts [7]. While we have previously suggested that the decrease in the response magnitude may be mediated by negative effects of one of the receptors that are active at mid-range [ATP] [7], current study demonstrates that similar regulation is achieved through interactions between P2Y₂ and P2X₇. In particular, we have found that these characteristic troughs disappear in *P2rx7Δ* cells. Using the mathematical model, we showed that at 10⁻⁴ M ATP, the additional Ca²⁺ influx through now activated P2X₇ inhibits P2Y₂-induced IP₃R activity due to the biphasic dependence of IP₃Rs on [Ca²⁺]_i. As a result, the peak [Ca²⁺]_i response, which is predominantly mediated by IP₃R activity, decreases, creating the first trough in the dose-response curve at 10⁻⁴ M [ATP]. With further increase in [ATP], the activation of P2X₇Rs, known to monotonically increase with [ATP], starts to outweigh the reduced IP₃R activity, causing the peak [Ca²⁺]_i response to rise, reaching a global maximum around 10⁻³ M ATP. After that, the rate of P2X₇R desensitization (that increases with [ATP]) becomes large enough to impede Ca²⁺ influx through the receptors, resulting in a decrease in the peak [Ca²⁺]_i response (now predominantly mediated by P2X₇Rs) which creates the second trough in the dose-response curve at 10⁻² M ATP. These data demonstrate how activation of low affinity P2X₇ may affect the responses mediated by the high affinity P2Y₂. Our study also suggests the reciprocal effect of P2Y₂ on the function of P2X₇ through facilitating the naïve state activation of P2X₇. Indeed, previous studies have documented such an effect through the allosteric regulation of P2XR (including P2X₇R) by Ca²⁺ [17,19], suggesting that Ca²⁺ release from the ER through the P2Y₂ pathways may underly the altered kinetics of P2X₇. Taken together, our study demonstrates multiple points of interactions between P2Y₂ and P2X₇ receptors, which are not only activated at very different ranges of ATP concentration, but also belong to different classes of receptors.

Finally, our study demonstrates that the absence of either P2Y₂ or P2X₇ has significant implications on ATP-mediated mechanotransduction. We used an experimental setup in which the mechanical stimulation of a single osteoblasts generates a micro-injury in its cell membrane, leading to a release of ATP that signals to neighboring (secondary) cells [11]. First,

we showed that in the absence of P2Y₂, the transmission of ATP signal to neighboring cells is effectively interrupted. These findings are consistent with previous reports that osteoblasts from P2Y₂^{-/-} mice exhibited dramatic reduction in fluid flow-induced Ca²⁺ responses even though the ATP release was similar to WT osteoblasts [29]. Second, we have found that in the absence of P2X₇, both primary and secondary responses are significantly altered. While local ATP concentrations at the site of micro-injury may support the involvement of P2X₇ in generating the Ca²⁺ response of the primary cell [11,12], the observed changes in the secondary responses are surprising, since we have previously shown that the amount of ATP released in these experiments is below the concentrations required for P2X₇ activation [11]. Nevertheless, this observation is consistent with previously suggested alterations in mechanotransductive signaling in P2X₇ deficient mice [27,28]. Thus, our study supports the important role of P2 receptor network in generating a mechanotransductive signal that conveys complex information to neighbouring cells.

In conclusion, this study provided a complex mechanism of interdependency between the action of high affinity G-protein coupled receptor P2Y₂ and a low affinity ligand gated ion channel P2X₇. Using a combination of experimental studies in osteoblastic cells with the full complement of P2 receptors, as well as osteoblasts deficient in P2Y₂ or P2X₇, and mathematical modeling of P2Y₂R-mediated Ca²⁺ release coupled to a Markov model of P2X₇R dynamics, allowed us to explore the intricate details of the subcellular signaling induced by ATP in bone forming osteoblasts. The conclusions drawn demonstrated causative links between the exposure to mechanical force, early ATP-mediated signaling, and mechanoadaptive response of bone tissue.

Materials and methods

Software

Figure preparation: CorelDRAWX8 (Corel); Mathematical Modeling: MATLAB R2018a (MathWorks), XPPAUT 8.0. Statistical Analysis: R version 4.0.0 (R Foundation for Statistical Computing).

Solutions and reagents

Refer to [S1 Text](#) for a complete list of materials used in this study.

Cell culture

The C2C12 cell line (ATCC CRL-1772) stably transfected with BMP-2 (C2-Ob cells) was plated at 10⁴ cells/cm² in DMEM (supplemented with 10% FBS, 1% sodium pyruvate, 1% penicillin streptomycin) and cultured for 2–3 days prior to experiments. Absence of mycoplasma contamination was verified in cryo-preserved stocks of C2-OB cells using PCR-based detection kit.

Generation of P2R knockout cell lines

C2-Ob cells were plated in 6-well plates at 100,000 cell/well density 2 days prior to transfection. On the day of transfection, 7.5 μL lipofectamine was diluted in 125 μL Opti-MEM medium (Solution A) and 5 μg *P2ry2* or *P2rx7* CRISPR/Cas9 plasmid and 10 μL P3000 reagent were diluted in a separate 125 μL aliquot of Opti-MEM (Solution B). Solutions A and B were then pooled in a 1:1 ratio and incubated at room temperature for 15 min. Cell media was aspirated and 250 μL of the pooled DNA-lipid complex solution was added to cells and left to incubate at 37°C for 3 days. 3 days post-transfection, cells were visualized using fluorescent microscope to

verify successful transfection through the presence of GFP-positive cells. Transfected cultures were transferred to fresh DMEM media and treated with 5 μ M puromycin for 7 days to select for puromycin-resistant clones. After selection, cells were transferred into puromycin-free media, allowed 3 days for recovery, and re-plated in 96 well plates at a \sim 1 cell per well density. After 3 weeks of expansion, half of each single-cell colony was re-plated in 96-well plates and the other half was collected for genomic DNA extraction using DNeasy kit. Genomic DNA for each single-cell colony was amplified by touchdown PCR using primer sets designed to flank the genomic region targeted by Cas9 (**S2 Table**), and amplicons were separated on a gel to screen for clones with evident band shifts. Selected clones were subsequently validated by immunoblot analysis, and termed *P2ry2* Δ and *P2rx7* Δ cells, for *P2ry2* and *P2rx7*, respectively.

Quantitative real-time polymerase chain reaction (qRT-PCR)

Total RNA was isolated using RNeasy kit and QIAshredder columns and reverse transcribed using cDNA reverse transcription kit. Real time qPCR was performed using QuantStudio 7 Flex PCR System, with SYBR Green or TaqMan Master Mix. Primer sequences are provided in **S2 Table** and cycling conditions in **S3 Table**.

Intracellular Ca²⁺ recordings and analysis

Cells were plated on glass-bottom 35 mm dishes or 48-well plates (MatTek Corporation), for single-cell mechanical stimulation and agonist application experiments, respectively. Cell were loaded with Fura2-AM for 30 min, acclimatized in physiological solution (PS) for 10 min on the stage of an inverted fluorescence microscope (Nikon T2000), and imaged as described previously [11]. For each recording, all cells within the field-of-view at 40x magnification were imaged (\sim 15–30 cell per imaging experiment). The Ca²⁺ response parameters were analyzed using a previously developed MATLAB algorithm (<https://github.com/NMikolajewicz/Calcium-Signal-Analyzer>) [13]. To assess ATP dose-dependencies, Fura2-loaded C2-Ob or CB-Ob cells were bathed in 270 μ L PS and 30 μ L of UDPG, ATP or ADP solutions at 10 \times final concentration were added (e.g., 30 μ L of 10⁻⁵ M ATP solution was added to cells to achieve 10⁻⁶ M ATP stimulation).

Immunoblotting

Cell lysates were extracted in RIPA lysis buffer and samples were prepared and subject to SDS-PAGE on a 10% (w/v) acrylamide gel as previously described [11]. Blotted nitrocellulose membranes were incubated with primary antibodies overnight (1:1000 dilution, 5% BSA in TBST, 4 $^{\circ}$ C) and secondary antibodies were applied for 1 h (1,1000 dilution, 5% BSA in TBST, rt) prior to visualization with chemiluminescence system.

Mechanical-stimulation

Single osteoblastic cells were stimulated by local membrane indentation with a glass micropipette using a FemtoJet microinjector NI2 (Eppendorf Inc.), as previously described [11].

Statistical analysis

Data are presented as representative images, means \pm standard error (SE) or means \pm 95% confidence intervals (CI), as specified in each figure panel along with sample sizes *N* (number of independent experiments) and *n* (number of technical replicates). Curve fitting and [Ca²⁺]_i transient characterization were performed in R. Statistical significance was assessed by one- or two-way ANOVA (as specified) and post-hoc two-way unpaired Students t-tests were adjusted

using the Bonferroni correction. Significance levels were reported as single symbol (*p<0.05), double symbol (**p<0.01) or triple symbol (**p<0.001).

Mathematical model

The mathematical model consisted mainly of Eqs (1)–(3). The individual terms J_{INleak} , J_{IPR} , J_{ERleak} , J_{PMCA} , J_{SERCA} and J_{P2X7} , listed in Eqs (1) and (2), were the key Ca²⁺ fluxes considered in this model, as described below.

(1) *Plasma Membrane Ca²⁺ Leak (J_{INleak})*. A constant inward leak across cell membrane to ensure that total [Ca²⁺] within the cell remained positive. It was assumed to be constant (see Table 1).

(2) *IP₃R Ca²⁺ Flux (J_{IP3R})*: The Ca²⁺ flux through IP₃Rs, given by

$$J_{IP3R} = v_{IP3R} O_{IP3R} ([Ca^{2+}]_{ER} - [Ca^{2+}]_i), \tag{4}$$

where v_{IP3R} is the maximum rate of Ca²⁺ release by the IP₃R and O_{IP3R} is the IP₃R open probability, defined by

$$O_{IP3R} = m_{\infty}^3 n_{\infty}^3 h^3, \tag{5}$$

which follows a Hodgkin-Huxley gating formalism adopted by De Young and Keizer [30] and later simplified by Li and Rinzel [24]. In this simplification, the activation by IP₃ (defined by m_{∞}) and [Ca²⁺]_i (defined by n_{∞}) through binding to the receptor were assumed to be instantaneous, given by

$$m_{\infty} = \frac{[IP_3]}{[IP_3] + d_1} \text{ and } n_{\infty} = \frac{[Ca^{2+}]_i}{[Ca^{2+}]_i + d_5} \tag{6}$$

whereas the inactivation by [Ca²⁺]_i (defined by the gating variable h), also through binding, was assumed to occur at a much slower time scale governed dynamically by

$$\frac{dh}{dt} = \frac{h_{\infty} - h}{\tau_h}, \tag{7}$$

where

$$\tau_h = \frac{1}{a_2(Q_2 + [Ca^{2+}]_i)}, \quad h_{\infty} = \frac{Q_2}{Q_2 + [Ca^{2+}]_i}, \quad \text{and } Q_2 = d_2 \frac{[IP_3] + d_1}{[IP_3] + d_3}. \tag{8}$$

In the study by De Young and Keizer [30] the values of d_i ($i = 1, 2, 3, 5$) were fit to experimental data [31]. Note that the dependence of activation and inactivation of O_{IP3R} on [Ca²⁺]_i in Eq (5) due to CICR makes the profile of IP₃R open probability biphasic with respect to [Ca²⁺]_i.

(3) *ER Ca²⁺ Leak (J_{ERleak})*. A small leak across the ER membrane [24], given by

$$J_{ERleak} = v_{ERleak} ([Ca^{2+}]_{ER} - [Ca^{2+}]_i), \tag{9}$$

where v_{ERleak} is the maximal rate of Ca²⁺ leak from the ER.

(4) *Ca²⁺ ATPase Activity (J_{PMCA} and J_{SERCA})*. Ca²⁺ removal by PMCA and Ca²⁺ re-uptake into the ER by SERCA described by Hill functions [32,33], given by

$$J_x = v_x \frac{[Ca^{2+}]_i^2}{[Ca^{2+}]_i^2 + k_x^2}, \tag{10}$$

where $x = PMCA, SERCA$, v_x is the maximal pumping rate and k_x is the affinity of the pump to bind to Ca²⁺.

(5) *P2X7R Ca²⁺ Flux (J_{P2X7})*. Ca²⁺ flux through P2X7Rs. A 12-state Markov model [18] was initially used to compute the current, given by

$$I_{P2X7} = g_{X7}(Q_1 + Q_2 + Q_3 + Q_4)(V - E), \quad (11)$$

where g_{X7} is the conductance of the P2X7R open states Q_i , $i = 1-4$ [18]. With emerging evidence suggesting that P2XRs do not dilate [16,34], the maximum conductance of open (Q_1 and Q_2) and sensitized/primed (Q_3 and Q_4) states in this P2X7R sub-model were assumed to be equal. We also assumed that the rate of desensitization increased with ATP binding ($H_2(C2) < H_2(Q1) < H_2(Q2)$) and that the open probability is higher in the desensitized row (i.e., $k_7 > k_j$, $j = 2, 4, 6$). These modifications kept the time series simulations of the P2X7R model generally unchanged. To obtain the overall Ca²⁺ flux through these channels, we then used the formalism from Zeng et al. [35] to convert ionic current to flux, scaled by a fraction that represents the average Ca²⁺ flux [36] relative to that for Na⁺ and K⁺. The latter was necessary as P2X7Rs are non-selective cation channels. Using the above description, the following expression was used to describe this flux

$$J_{P2X7} = -f_{Ca} \frac{I_{P2X7}}{zFV_{osteo}}, \quad (12)$$

where z is the valence of Ca²⁺ ($z = +2$), F is Faraday's constant, V_{osteo} is the volume of the osteoblast in liters and f_{Ca} is the fraction of Ca²⁺ flux through P2X7R.

Slow-fast analysis

“Slow-fast” analysis is a mathematical technique that divides a dynamics model, such as the one described by Eqs (1)–(12), into two subsystems: a fast and slow one, followed by setting the slow variables to be independent parameters. The goal in doing so is to analyze the dynamics of the fast subsystem with respect to those newly defined parameters. This well-known technique that was also applied in [24] allows you to define the distinct regions of behaviour with respect to the slow variables and determine how trajectories of the original model could evolve in time when passing between these regions.

Software and numerical methods

All time-series simulations were performed in MATLAB (Mathworks, Natick, MA). Initially, all simulations were run for a period of 2000 s in the absence of ATP to obtain the resting state of the cell. The basal [IP₃] (the [IP₃] in the absence of extracellular ATP) was assumed to be zero. P2Y₂R and P2X₇R knockout recordings were simulated by setting J_{P2X7} and J_{IP3R} (Eqs (5) and (12)) to zero, respectively. These simulations were then used to compute [ATP]-dependent dose-response curves of [Ca²⁺]_i by evaluating the maximum Ca²⁺ response at each ATP dose in MATLAB. The bifurcation analysis (Fig 5) was performed using XPPAUT (a free-ware available online at <http://www.math.pitt.edu/~bard/xpp/xpp.html>). To facilitate reproduction of results, the codes used to perform simulations of the model can be obtained online [37]. These simulations can be run by solving the function “fullmodel.m” using the ordinary differential equation solver ode15s. Figs 4A, 6 and 7 can be obtained by running the files titled “Fig 4A.m”, “Fig 6.m” and “Fig 7.m”, respectively.

Supporting information

S1 Fig. Aligning and scaling ATP dose-dependence curves. (A-C) Schematic illustrating processing of ATP-dose-dependent response curves (A). ATP dose-dependent responses from

three independent murine cell lines (**A**, *left panel*; **B**) were aligned using a linear transformation to match peaks/troughs (**A**, *middle panel*; **C**) and responses were rescaled to [0,1] interval (**A**, *right panel*; **Fig 1C**). *Curves*: Loess curves; *Markers*: Response means (*circle*: BM-OB; *triangle*: C2-OB; *square*: CB-OB).
(TIF)

S1 Table. Calcium response parameters.

(PDF)

S2 Table. Primer and PAM sequences.

(PDF)

S3 Table. PCR cycling conditions.

(PDF)

S1 Text. Solutions and Reagents.

(PDF)

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