Topical therapy with negative allosteric modulators of the calcium-sensing receptor (calcilytics) for the management of asthma: the beginning of a new era?

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Negative allosteric modulators of the calcium-sensing receptor (calcilytics) delivered topically to the airways have the potential to revolutionise asthma therapy https://bit.ly/3tdSZkC

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Abstract

In this review article we present the evidence to date supporting the role of the calcium-sensing receptor (CaSR) as a key, pluripotential molecular trigger for asthma and speculate on the likely benefits of topical therapy of asthma with negative allosteric modulators of the CaSR: calcilytics.

What is the calcium-sensing receptor and what are calcilytics?

The extracellular calcium-sensing receptor (CaSR) is a G-protein-coupled receptor (GPCR) originally identified as the body's master controller for extracellular, free ionised calcium. It is widely expressed as a regulator of global calcium metabolism, *e.g.* it is responsible for homeostasis of the extracellular [Ca^{2+}] by regulating parathyroid hormone secretion, Ca^{2+} resorption in the renal loop of Henlé, calcitonin release in the thyroid and osteoclast-mediated bone resorption. The CaSR provides the means by which these cell types sense the extracellular [Ca^{2+}] and maintain it within a narrow physiological range [1]. It is now recognised, however, that the CaSR is widely expressed in many other cell types and has functions unrelated to regulation of extracellular Ca^{2+} homeostasis. Other important physiological roles include sensing of dietary nutrients in the gut, glucose-mediated insulin secretion, taste satiety and vascular smooth muscle function [1–3]. In this review we propose a novel, causal role for the CaSR in the pathophysiology of airways smooth muscle (ASM) hyperresponsiveness, airways inflammation and the key mechanism by which this inflammation exacerbates bronchial smooth muscle spasm in human asthma.

The CaSR is expressed in the cell membrane as a constitutive homodimer with large extracellular domains which enclose a ligand-binding cleft (figure 1). In addition to Ca^{2+} it responds to other di-, tri- and polyvalent cations such as Mg^{2+} and Gd^{3+}, and other orthosteric agonists including polyamines and polycationic proteins [2, 3]; as will be explained in the following, this ability to respond to cationic proteins forms a keystone of its potential importance in asthma pathogenesis. The CaSR couples through several different G-protein-mediated signalling pathways, including $G_{q,11}$ (releases Ca^{2+} from intracellular stores; activates protein kinase C), $G_{i/o}$ (inhibits the generation of cAMP) and $G_{12,13}$ (activates Rho kinase

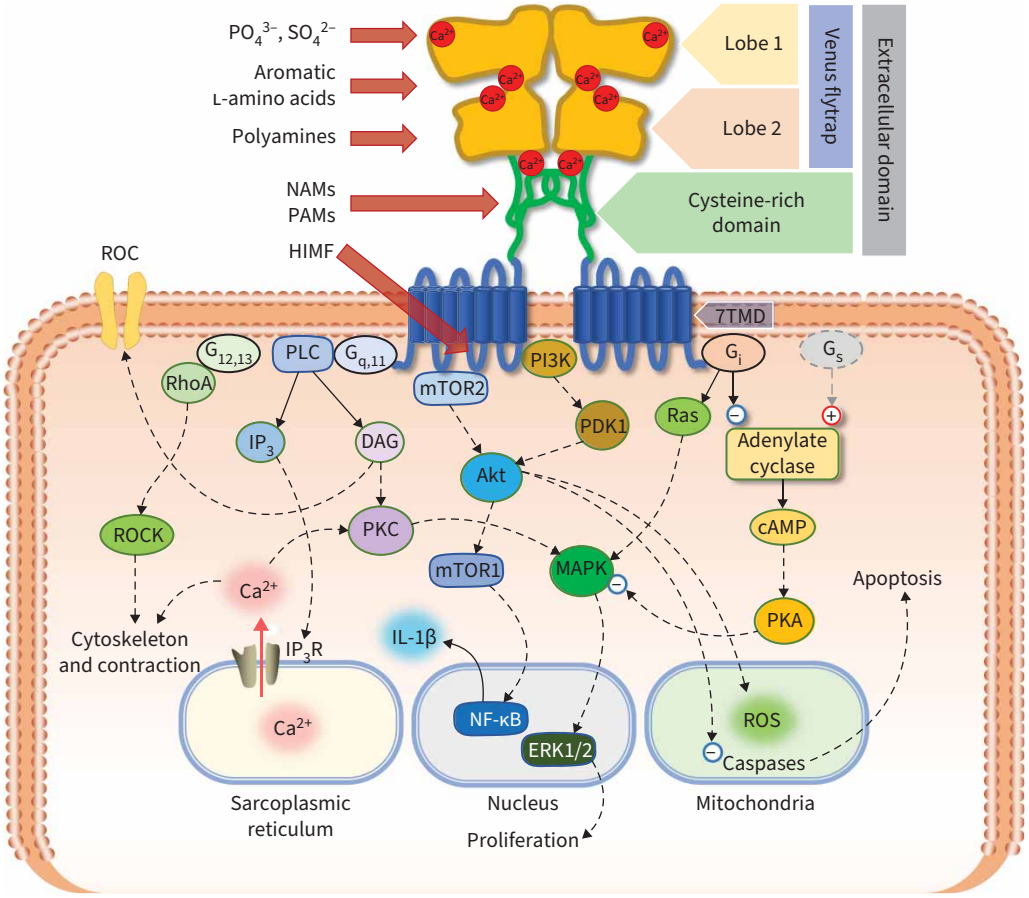

FIGURE 1 Overview of ligand-binding sites and signalling pathways of the calcium-sensing receptor (CaSR). The CaSR functions as a constitutive homodimer comprising 1) a large extracellular domain consisting of a cysteine-rich domain and bi-lobar "Venus flytrap" structure which binds to cations, anions and allosteric modulators (positive and negative allosteric modulators (PAMs and NAMs)), 2) a seven transmembrane domain (7TMD) and 3) an intracellular domain containing a binding site for hypoxia-induced mitogenic factor (HIMF). Ca^{2+}-binding sites are indicated as red circles. The CaSR couples to three heterotrimeric G-proteins: 1) $G_{q,11}$ which activates phospholipase C (PLC) to generate inositol trisphosphate (IP_3) and diacylglycerol (DAG) with subsequent Ca^{2+} release from the sarcoplasmic reticulum, Ca^{2+} entry *via* the receptor operated channel (ROC), and activation of protein kinase C (PKC), and consequently the mitogen-activated protein kinase (MAPK) cascade and extracellular signal-regulated kinase 1 and 2 (ERK1/2); 2) G_i which both inhibits adenylate cyclase, thus supressing protein kinase A (PKA)-mediated inactivation of MAPK, and activates MAPK *via* a $G_{\beta/\gamma}$ and Ras pathway; and 3) $G_{12,13}$ which activates the RhoA/ROCK pathway. The CaSR also signals *via* the phosphoinositide 3-kinase (PI3K) and mTOR (mechanistic target of rapamycin complex) pathways, leading to activation of Akt (protein kinase B) and NF-κB-mediated interleukin (IL)-1β release. Akt also induces reactive oxygen species (ROS) production and suppresses caspase activation in mitochondria.

and other effector kinases). In addition, the CaSR can also signal *via* mitogen-activated protein kinase (MAPK) cascades, including extracellular signal-regulated kinase (ERK), p38 MAPK and c-Jun N-terminal kinase MAPK, and phosphoinositide 3-kinase (PI3K) and mechanistic target of rapamycin (mTOR) pathways [1, 2]. Because of its ability to couple to multiple G-proteins, the CaSR is complex and exhibits "biased agonism", whereby different ligands activate (or inhibit) specific subsets of signalling pathways preferentially [1–3].

The CaSR also binds a range of positive and negative allosteric modulators (PAMs and NAMs). Natural PAMs of the CaSR include aliphatic and aromatic amino acids that enhance the sensitivity of the CaSR to its primary ligand, Ca^{2+} [4]. Synthetic PAMs of the CaSR, also known as calcimimetics, include the clinically available drugs cinacalcet, evocalcet and etelcalcetide. These compounds are currently in general clinical therapeutic use to treat hypercalcaemia arising from hyperparathyroidism of various aetiologies,

including parathyroid carcinoma, hyperparathyroidism secondary to renal failure, familial hypocalciuric hypercalcaemia and primary hyperparathyroidism in neonates or those patients with parathyroid carcinoma who are not suitable for surgical excision. Calcimimetics exhibit ligand-biased signalling, with preferential activation of CaSR-mediated phosphorylation of ERK1/2 over Ca^{2+} mobilisation (reviewed in [5]).

Synthetic NAMs of the CaSR, also known as calcilytics, were first discovered as a result of high-throughput screening of compounds based on an arylalkylamine scaffold (reviewed in [6]) and now include the amino alcohol compounds, such as ronacaleret, JTT-305 (also known as MK-5442), NPSP795, and the quinazolin-2-one derivatives ATF936 and AXT914 [7]. Some of these calcilytics have been evaluated for therapy of osteoporosis but found to be clinically ineffective, likely because they exert opposing effects on key processes such as calcium mobilisation and osteoblast activity (reviewed in [1]). Recently, the calcilytic NPSP795 has been repurposed to treat autosomal dominant hypocalcaemia with hypercalciuria, which is caused by activating mutations in the *CASR* gene [8], while others are under investigation for therapy of other hypocalcaemic disorders, *e.g.* idiopathic hypercalciuria.

What is the clinical evidence that the CaSR is involved in the pathogenesis of ASM hyperresponsiveness in human asthma?

From the account in the previous section it will be self-evident that the function of the CaSR is influenced not only by its binding of Ca^{2+} and other inorganic cations, but also by sensing organic, polycationic species, the local concentrations of which may be greatly increased in the airways as a result of inflammation and environmental exposure. It has long been known from studies on murine surrogates [9] and patients with occupational asthma caused by exposure to aliphatic polyamines [10] that exposure to these compounds increases the risk of manifestation of ASM hyperresponsiveness. Similarly, it is well recognised that elevated airways concentrations of the eosinophilic cationic proteins, while not specific for asthma, correlate with disease severity in the context of asthma [11]. In asthma, polyamines and polycationic protein products of airways inflammatory cells in particular have the potential to bind to and activate the CaSR directly, functioning as orthosteric agonists which markedly heighten the signal output of the CaSR. Thus, it is entirely plausible to assume that overexpression of the CaSR and/or activation of the CaSR by local, environmental stimuli accounts for the phenomenon of ASM hyperresponsiveness which characterises human asthma, and for the regulation of the degree of this hyperresponsiveness by the concentrations of cationic products of local, asthma-relevant inflammatory cells. In this section we present data, from our group and others, in direct support of this hypothesis and discuss in more detail the role of the CaSR in regulating ASM contraction and airways inflammation. We also summarise and discuss the evidence that the concentrations of polyamines and polycationic proteins are elevated in the airways in asthma and, in many previous studies, have been shown to correlate with disease severity.

ASM hyperresponsiveness is responsible for the short-term, spontaneous variability in airways obstruction which causes asthmatic subjects (but not nonasthmatic subjects) to develop sudden wheezing and breathlessness when exposed to a range of specific and nonspecific stimuli such as smoke, cold air, allergens in sensitised subjects, exercise and respiratory tract infections. In a recent key study it was demonstrated that human asthma is accompanied by overexpression of the CaSR on ASM cells compared with nonasthmatic controls, and furthermore that exposure of this receptor to NAMs abrogated asthmatic ASM hyperreactivity to contractile stimuli *ex vivo* and *in vitro* [12]. It was also demonstrated that expression of the CaSR is upregulated on human ASM cells exposed to asthma-associated cytokines: it was hypothesised that this is driven by the STAT (signal transducer and activator of transcription) and κB response elements in the *CASR* gene promoters [13]. Exposure of murine lung slices to the CaSR agonist spermine *ex vivo* potentiated ASM contraction induced by acetylcholine; this effect was abolished in lung slices from animals with selective CaSR ablation in their ASM cells and abrogated by calcilytics in lung slices from wild-type mice but not those with the selective CaSR ablation [12]. Moreover, wild-type mice exhibited airway hyperresponsiveness following exposure to inhaled poly-L-arginine (another CaSR agonist) *in vivo*, an effect which was abolished by inhaled calcilytics [12]. In addition, the calcilytic drug NPS2143 attenuated basal, elevated intracellular $[Ca^{2+}]$ ($[Ca^{2+}]_i$) as well as Ca^{2+} release in response to acetylcholine or histamine in ASM cells from asthmatic patients, but not nonasthmatic controls [12]. This latter observation is particularly notable because it demonstrates that calcilytics, while normalising $[Ca^{2+}]$ in ASM cells from asthmatic patients, do not appear to alter the function of ASM cells in nonasthmatic individuals.

In the same study [12] it was discovered that, in addition to the arginase products spermine, spermidine and putrescine, the CaSR was also activated by products of eosinophils, including eosinophil cationic proteins and major basic protein, providing a clear functional basis for the regulation of asthma severity by the products of these cells.

It is also noteworthy that exposure of fetal lung ASM cells to hyperoxia has been reported to upregulate CaSR expression, inducing hyperresponsiveness to histamine and increased proliferation. Again these effects were attenuated by calcilytics, providing a therapeutic avenue to the management of neonatal airways diseases, including hyperoxia-induced, neonatal asthma [14].

It may also be relevant that a recent bioinformatics study of genetic variants of the CaSR uncovered clinically relevant associations with several diseases unrelated to regulation of circulating Ca^{2+}, including asthma [15]; it remains to be seen if and how these genetic mutations which dysregulate total body calcium homeostasis might also affect polycation sensing of the CaSR in inflamed ASM.

Pathophysiological mechanism of ASM hyperresponsiveness in asthma

There is good evidence that bronchial hyperresponsiveness in asthma is associated with increased ASM contractile function, the mechanisms of which have yet to be fully defined but include alterations to the ASM cell $[Ca^{2+}]_i$ handling and sensitivity, contractile machinery, and cytoskeletal dynamics and structure [16–20]. In this section we briefly outline the mechanisms underlying ASM contraction and relaxation, how they may be altered in asthma, and the potential key role of the CaSR.

Elevation of $[Ca^{2+}]_i$ is central to ASM contraction and activation of other cell types, including epithelial and inflammatory cells. Multiple pathways contribute to $[Ca^{2+}]_i$ homeostasis, including Ca^{2+} release and sequestration by the sarcoplasmic reticulum and mitochondria, and Ca^{2+} flux into and out of the cell [19, 21]. These are activated (or inhibited) by a variety of GPCRs (figure 2) [22]. Most bronchoconstrictors activate

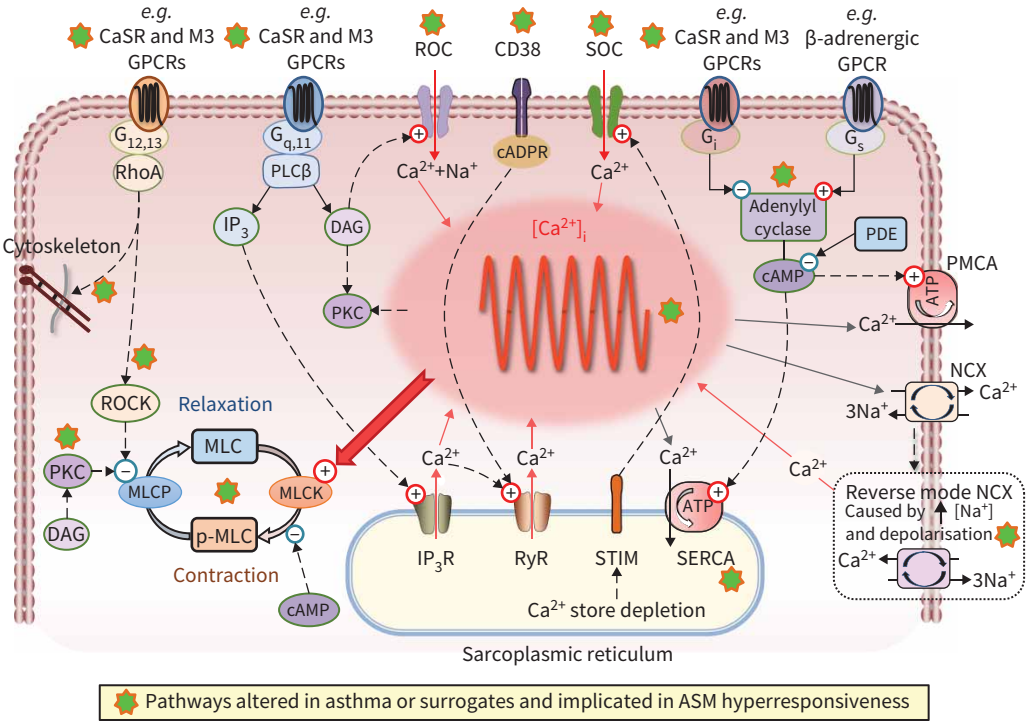

FIGURE 2 Signalling pathways underlying bronchial smooth muscle contraction and hyperresponsiveness. The figure displays key pathways regulating intracellular Ca^{2+} homeostasis and Ca^{2+} sensitivity, and thus contractile function in bronchial smooth muscle cells. Those reported to be altered in tissue from asthmatic subjects or asthma surrogates and implicated in airways smooth muscle (ASM) hyperresponsiveness are indicated. Some intermediate components are omitted for clarity. cADPR: cADP ribose; CD38: cADP ribose hydrolase; CaSR: calcium-sensing receptor; DAG: diacylglycerol; GPCR: G-protein-coupled receptor; IP_3: inositol trisphosphate; IP_3R: inositol trisphosphate receptor; M3/M2: muscarinic receptors; MLC: myosin light chain; MLCK: myosin light chain kinase; MLCP: myosin light chain phosphatase; NCX: Na^+/Ca^{2+} exchanger; p-MLC: phosphorylated myosin light chain; PDE: phosphodiesterase; PKC: protein kinase C; PLCβ: phospholipase Cβ; PMCA: plasma membrane Ca^{2+} ATPase; ROC: receptor operated channel; ROCK: Rho kinase; RyR: ryanodine receptor (Ca^{2+} release channel); SERCA: sarcoendoplasmic reticulum Ca^{2+} ATPase; SOC: store operated channel; STIM: stromal interaction molecule.

GPCR coupled *via* $G_{q,11}$ to phospholipase Cβ, generating inositol trisphosphate (IP_3) and diacylglycerol (DAG). IP_3 elicits Ca^{2+} release from the sarcoplasmic reticulum, whereas DAG activates nonselective (Ca^{2+} and Na^+ permeable) receptor operated channels (ROC), and protein kinase C (PKC). Ca^{2+} released by IP_3 activates adjacent ryanodine receptors (RyRs; Ca^{2+}-induced Ca^{2+} release), amplifying the response [21]. RyRs are also activated by cADP ribose, generated by CD38 [23]. Depletion of sarcoplasmic reticulum Ca^{2+} content activates store operated channels (SOCs) *via* STIM and thus further increases Ca^{2+} entry. Voltage-gated Ca^{2+} channels (L-type) appear to be of limited significance in ASM or indeed the pathogenesis of asthma, which is why calcium channel blockers have proven ineffective for asthma prophylaxis and therapy [24, 25].

Cytosolic Ca^{2+} is sequestered back into the sarcoplasmic reticulum by the sarcoendoplasmic reticulum ATPase (SERCA), and expelled from the cell by a Na^+/Ca^{2+} exchanger (NCX) and plasma membrane Ca^{2+} ATPase [19]. As NCX exchanges three Na^+ for each Ca^{2+} it is membrane potential- and Na^+ gradient-dependent; the resulting depolarisation and local increases in $[Na^+]_i$ following Na^+ entry *via* ROC causes NCX to operate in reverse mode, facilitating Ca^{2+} entry [26].

The ASM cell is highly organised, with cell membrane, peripheral sarcoplasmic reticulum and mitochondria creating signalling micro-domains that allow rapid regulation of the temporal and spatial aspects of changes in $[Ca^{2+}]_i$. This facilitates generation of oscillations in $[Ca^{2+}]_i$ on stimulation by bronchoconstrictors [27, 28], while bronchodilators reduce the Ca^{2+} oscillation frequency [29]. Importantly, the magnitude of ASM shortening correlates with Ca^{2+} oscillation frequency and not amplitude [27]. ASM also exhibits slower oscillations in membrane potential on stimulation, which may switch NCX between forward and reverse modes, producing corresponding $[Ca^{2+}]_i$ oscillations [30]. Many enzymes decode Ca^{2+} oscillation frequency in a wide variety of cell types, and may contribute to both contraction and proliferation of ASM cells [19, 30].

Elevation of ASM $[Ca^{2+}]_i$ leads to Ca^{2+}-calmodulin-mediated activation of myosin light chain kinase (MLCK), phosphorylation of myosin light chain (MLC), and consequently activation of myosin ATPase and cell shortening. Relaxation requires dephosphorylation of MLC by its phosphatase (MLCP), so force generation depends on the balance between MLCK and MLCP activities. MLCP is constitutively active, but can be inhibited by RhoA kinase (ROCK). ROCK is activated by the monomeric G-protein RhoA, which is itself activated by $G_{12,13}$-coupled GPCRs [31]. Inhibition of MLCP means more force is generated for the same elevation of $[Ca^{2+}]_i$ (Ca^{2+} sensitisation); PKC similarly induces Ca^{2+} sensitisation *via* phosphorylation of the MLCP inhibitor CPI-17 [32]. Notably, many bronchoconstrictors act through both $G_{q,11}$- and $G_{12,13}$-coupled pathways. For example, acetylcholine activates M3 muscarinic receptors which couple to both $G_{q,11}$ and $G_{12,13}$, thus stimulating IP_3-induced sarcoplasmic reticulum Ca^{2+} release, and activation of ROC and PKC, simultaneously with RhoA/ROCK-mediated Ca^{2+} sensitisation [33]. Notably, some bronchoconstrictors also activate G_i-coupled GPCR, thus inhibiting adenylyl cyclase (see following paragraph).

β_2-adrenoreceptor agonists and most endogenous bronchodilators (*e.g.* catecholamines, vasoactive intestinal peptide and prostaglandin E_2) elicit relaxation by activating adenylyl cyclase *via* G_s-coupled GPCRs to elevate cAMP; cAMP is degraded by phosphodiesterases (PDEs), so PDE inhibitors (*e.g.* theophylline) also elevate cAMP. Elevation of cAMP supresses multiple bronchoconstrictor pathways, mediated either by protein kinase A (PKA) or Epac (exchange factor directly activated by cAMP); these include Ca^{2+} influx and mobilisation, RhoA activation, and MLC phosphorylation (reviewed in [22, 32]). It also stimulates SERCA, thus reducing $[Ca^{2+}]_i$ [34], slows Ca^{2+} oscillations [29] and enhances degradation of bronchoconstrictor GPCRs [35].

Numerous studies have shown asthma-associated perturbations of the pathways discussed, either using ASM derived from asthmatic subjects or animal surrogates, or treated with asthma-associated mediators; as these have been extensively reviewed [16, 19, 20, 22, 36], discussion here is limited to a few salient points. There is a wide consensus that asthma is associated with ASM hyperresponsiveness, while enhanced $[Ca^{2+}]_i$ mobilisation is well documented, being attributed to increased Ca^{2+} entry and release [28, 37, 38] and reduced activity of SERCA and Ca^{2+} reuptake into the sarcoplasmic reticulum [39, 40]. Similarly, Ca^{2+} sensitisation and RhoA/ROCK have also been strongly implicated in ASM hyperresponsiveness [31, 41–43].

The role of the CaSR in ASM hyperresponsiveness and the potential of calcilytics

Under normal, "healthy" conditions, CaSR expressed on ASM cells would be expected to reside in a continuous state of low-level activation in the presence of normal concentrations of interstitial Ca^{2+}; this is consistent with the finding that calcilytics reduced $[Ca^{2+}]_i$ in acetylcholine-stimulated human ASM cells

from both healthy and asthmatic donors [12]. Asthma is, however, accompanied both by elevated expression of the CaSR in ASM [12] and elevated concentrations in the airways of potent CaSR activators, including eosinophil cationic protein and major basic protein, and cationic polyamines (putrescine, spermidine and spermine). The latter are elevated in asthma owing to both increased arginase activity and reduced polyamine catabolism [12, 44–47], and have been previously associated with the pathophysiology of bronchial hyperresponsiveness [9, 48, 49]. It has also been proposed that inflammation leads to localised elevations of extracellular [Ca^{2+}] which may also increase CaSR activity [50, 51].

The effects of all of these stimuli acting in concert would inevitably result in a leftward shift in the CaSR [Ca^{2+}] response relationship and greatly increased signal output, potentiated by the elevated expression of CaSR [1, 3, 12]. Thus, ASM Ca^{2+} mobilisation and RhoA/ROCK- and PKC-mediated Ca^{2+} sensitivity would be elevated (*via* $G_{q,11}$, $G_{12,13}$, G_i and MAPK cascades), whereas adenylyl cyclase and cAMP generation would be inhibited (*via* G_i). Collectively, this would potentiate ASM contractility and sensitivity to other bronchoconstrictor autacoids that act through these same intracellular signalling pathways (*e.g.* acetylcholine, histamine, neuropeptides, prostaglandins and leukotrienes) (figure 2). These effects would be further amplified by the asthma-associated perturbations in ASM signal transduction pathways discussed in the previous section [16, 19, 20, 22, 36] and sufficient to account for ASM hyperresponsiveness in asthma.

This scenario again underlines the concept that ASM hyperresponsiveness in asthma is highly dependent upon the environment of the ASM (where the ASM cells are immersed in cationic proteins bathing the interstitium) and not entirely an intrinsic, functional abnormality of the ASM itself. This might in turn explain why not all studies performed on human ASM obtained from asthmatic patients and studied *ex vivo* report differences in ASM contractility or Ca^{2+} homeostasis when compared with ASM from healthy donors [16, 17, 52]. When ASM is excised for study *ex vivo*, it is perforce removed from its surrounding inflammatory milieu and exposure to asthma-associated mediators, including polycationic CaSR ligands. It is possible to hypothesise that the continued presence of such stimuli is necessary to effect detectable functional alterations in ASM under some circumstances *ex vivo*. Similar reasoning underlies the suggestion that ASM may be normal in asthma, but its function altered by an abnormal environment (discussed in [16]). It is interesting to speculate that one of the effects of this "abnormal environment" might be to upregulate CaSR expression on ASM, at least in susceptible patients who develop asthma [12]. It is also possible to hypothesise, although this seems less likely, that this phenomenon might also be partly attributable to variation in disease severity and therapy and/or the anatomical source of the ASM, since ASM from the trachea and main bronchi is known to differ functionally from that of the more relevant, intrapulmonary bronchi. In particular, ASM from the latter has been shown to exhibit hyperreactivity in asthma when this was not the case for the larger airways [17, 36].

Taken together, the data presented are consistent with the hypothesis that overexpression and activation of the CaSR by relevant, asthma-associated extracellular ligands in the immediate vicinity of the ASM is a critical driver of ASM hyperresponsiveness in asthma, with the corollary that therapy with calcilytics has the potential to abolish it. This is consistent with the recent observation referred to earlier [12] that inhibition of the CaSR by calcilytics attenuates or ablates bronchial hyperresponsiveness in animal surrogates of asthma.

The potential for calcilytics to inhibit airways inflammation and their effects on ASM hyperresponsiveness in human asthma

In addition to its putative role in engendering ASM hyperresponsiveness in human asthma, signalling mediated through the CaSR is increasingly recognised to have key roles both in immune surveillance and the regulation of ongoing inflammation in the airways and elsewhere [53–55], *e.g. via* activation of the NLRP3 inflammasome [50]. Both of these key immunological functions of the CaSR have recently been implicated in the pathogenesis of other chronic inflammatory diseases such as rheumatoid arthritis (figure 3) [51].

The CaSR is known to be expressed on monocyte/macrophages, neutrophils [56] and T-cells [57], rendering them sensitive to activation by extracellular, locally released, inflammation-associated ligands of the CaSR as well as elevation of local extracellular [Ca^{2+}] which has been shown to activate the NLRP3 inflammasome in macrophages [50] and NF-κB and other downstream signalling pathways in neutrophils and T-cells. In addition, the recent demonstration that eosinophils express the CaSR [12] raises the possibility that release of eosinophil cationic proteins in the course of asthmatic mucosal inflammation may further activate other local eosinophils as well as other cells *via* the CaSR, in addition to prolonging their lifespan by inhibition of apoptosis [47] through an autocrine feedback loop. Finally, it is noteworthy that structural cells of the airways may also contribute to polyamine-driven inflammation in asthma. For

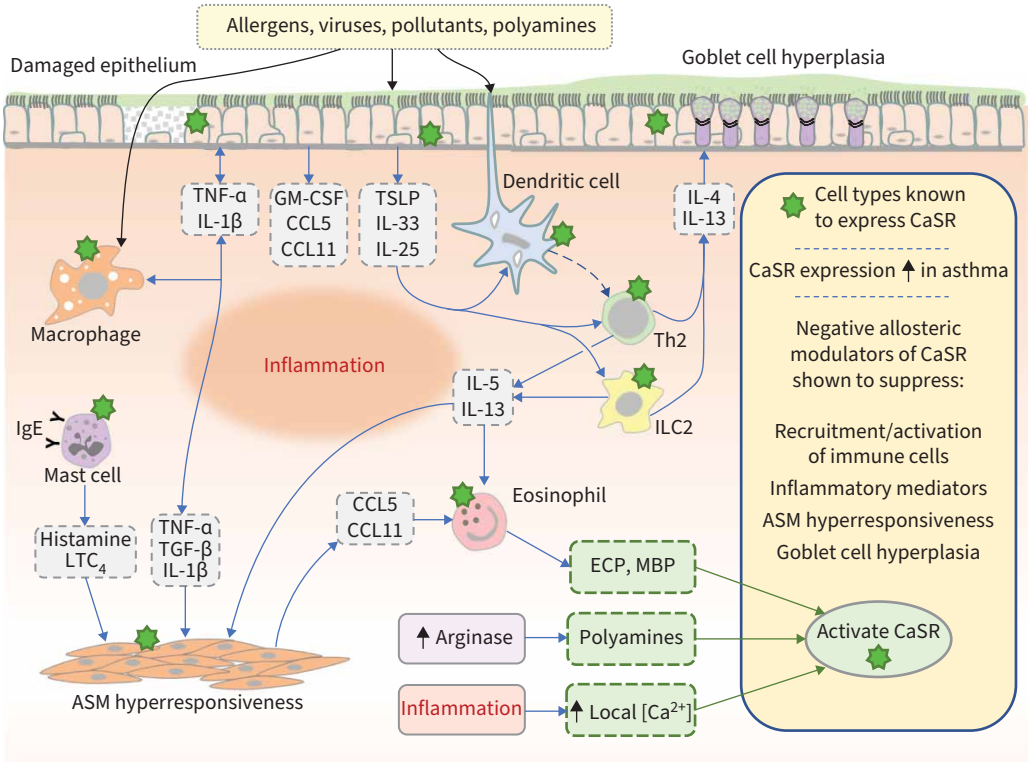

FIGURE 3 Signalling pathways in the asthmatic airway: role of the calcium-sensing receptor (CaSR) and likely actions of its negative allosteric modulators. The figure represents a simplified schematic of key cell types, cytokines, chemokines and growth factors involved in the pathogenesis of asthma. All cell types illustrated have been shown to express CaSR and would thus be affected by modulators of CaSR activity. ASM: airways smooth muscle; CCL5: CC chemokine ligand 5 (RANTES); CCL11: CC chemokine ligand 11 (eotaxin); LTC_4: cysteinyl leukotriene C_4; ECP: eosinophil cationic protein; GM-CSF: granulocyte–macrophage colony-stimulating factor; IL: interleukin; ILC2: type 2 innate lymphoid cell; MBP: major basic protein; TGF: transforming growth factor; Th2: T-helper 2 cell; TNF: tumour necrosis factor; TSLP: thymic stromal lymphopoietin.

example, airways epithelial damage, a pathognomonic feature of asthma, in addition to triggering alarmin release, results in the loss of activity of polyamine catabolic enzymes, resulting in further local injury to the epithelium [45].

These recent experimental findings likely underlie, at least in part, the longer established findings that the expression of CaSR agonists such as polyamines and eosinophil cationic proteins in many previous studies of asthma involving both human subjects and animal surrogates from a multidisciplinary literature correlates positively with airways inflammation and remodelling, as well as disease activity [46–49, 58]. Conversely, in murine asthma surrogates, chronic treatment with calcilytics has been reported to attenuate airways hyperresponsiveness, inflammation and remodelling [12, 59]. Taken together, all of these data suggest that, in addition to abolishing ASM hyperresponsiveness, topical therapy of asthmatic patients with calcilytics has the potential to exert an anti-inflammatory effect. Furthermore, regardless of any possible anti-inflammatory effects, calcilytic therapy would be expected to abolish direct exacerbation of ASM hyperresponsiveness in patients with asthma by stimulation of the overexpressed CaSR byproducts of inflammatory cells such as polyamines and eosinophil-derived proteins.

In closing this section, it is worth noting that other recent studies are consistent with the hypothesis that signalling *via* the CaSR may play a role in other aspects of asthma pathophysiology. For example, signalling *via* the CaSR has also been reported to be responsible for hypoxia-induced proliferation of rat pulmonary artery smooth muscle cells [60], suggesting a role in the pathogenesis of hypoxic pulmonary hypertension and consistent with the hypothesis that it similarly contributes to ASM hypertrophy in asthma. Similarly, a very recent study referred to earlier [14] has presented evidence that signalling *via* the CaSR is responsible for the ASM hyperreactivity observed in some premature infants ventilated with supplemental oxygen.

The potential to deliver established calcilytics topically to the airways of patients with asthma

As mentioned earlier, several small-molecule calcilytics have been developed and assessed for oral therapy of osteoporosis, including the amino alcohols ronacaleret and JTT-305 in phase 2 clinical trials and NPSP795 (a zwitterion amino alcohol) and AXT914 (a quinazolin-2-one) in phase 1 trials. Although, when administered systemically by oral dosing, these drugs were not found to be efficacious for the treatment of post-menopausal osteoporosis, an indication for which they were originally developed [61, 62], they were importantly observed to be safe and tolerable in human subjects (some were observed to cause mild hypercalcaemia in a small fraction of normal human volunteers). A very recent study addressed the likely suitability of these four calcilytics for topical delivery to the airways of human asthmatic patients, potentially using devices similar or identical to existing inhaler devices [63]. This included an assessment of the feasibility of delivering them to the airways in sufficient quantities to abolish bronchial hyperresponsiveness and airways inflammation in a murine surrogate of chronic asthma. All four calcilytics [8, 64–66], when delivered topically, inhibited poly-L-arginine-induced airways hyperresponsiveness in naïve mice and suppressed both airways hyperresponsiveness and inflammation in an asthma surrogate, confirming class specificity. Repeated exposure to inhaled calcilytics did not alter blood pressure, heart rate or serum calcium concentrations, providing considerable precedent for the expectation that topically delivered drugs will not disrupt systemic calcium regulation in human asthmatic patients. Optimal candidates for repurposing for topical therapy of human asthma were identified based on their effects on airways hyperresponsiveness and inflammation, pharmacokinetics/pharmacodynamics, formulation, and micronisation properties. In the study, whereas both inhaled calcilytics and inhaled corticosteroids were observed to reduce airways inflammation, only the former obviated features of airways remodelling such as goblet cell hyperplasia [63].

Outstanding issues

The CaSR is expressed by many structural and inflammatory cells of the lung, from the ASM to the bronchial mucosa. Furthermore, it is capable of being activated by many ligands other than Ca^{2+}, including basic proteins and arginine metabolites at sites of inflammation. It is possible, therefore, that the consequences of CaSR activation or blockade may vary according to the precise situation in the lungs and the nature of the local environment, which may be influenced both by intrinsic inflammation and the effects of external factors such as infectious agents and inhaled environmental pollutants.

As with all drugs, aside from the potential beneficial effects of calcilytics on hyperoxia-induced bronchial hyperresponsiveness in premature neonates referred to earlier [14], the potential for topically delivered calcilytics to exert unwanted effects on lung development or immune surveillance can only be determined by clinical experience. However, the fact that a range of systemically delivered calcilytics has been used successfully in human subjects for many years to manage a range of disorders of calcium metabolism provides considerable reassurance that topically delivered drugs will be both safe and tolerable. Furthermore, as has been emphasised throughout this article, calcilytics are least likely to exert any functional effects in "normal" tissue, where the CaSR is expressed at baseline density and is not in an "inflammatory" environment of orthosteric agonists.

The future positioning of calcilytic therapy for asthma

In summary, the data presented herein suggest that it should be possible to repurpose calcilytics as topical therapy, with a favourable pharmacokinetics/pharmacodynamics, safety and tolerability profile, for human asthma delivered using inhaler devices familiar to patients and that this therapy has the potential to abolish ASM hyperresponsiveness, and thereby wheezing and breathlessness. As long as they are compliant with therapy, patients need not live in fear of sudden wheezing or breathlessness, which is also a likely cause of sudden death from asthma (according to the most recent National Review of Asthma Deaths in the UK [67], at least half of the patients who die from asthma in the UK are deemed to have "mild/moderate" disease and presumably therefore die as a result of bronchospasm possibly exacerbated by mucous plugging). The suitability of topical calcilytic therapy to replace conventional bronchodilator therapy for asthma is further underlined by recent evidence that calcilytics elevate cAMP concentrations in human ASM cells, particularly from asthmatic patients [12], and dilate acetylcholine pre-contracted murine airways [63] or lung slices, an effect at which they demonstrate greater potency than conventional bronchodilators such as salbutamol and formoterol [68]. This is most likely attributable to signalling *via* $G_{i/o}$ and not off-target L-type calcium channel inhibition [63], and provides yet another therapeutic avenue through which calcilytics may relieve bronchospasm. Furthermore, experimental evidence suggests that topical calcilytics can inhibit airways mucosal inflammation in asthmatic patients at least as efficiently as corticosteroids (but with none of their unwanted effects), in addition to suppressing the effects of polyamine and other cationic protein CaSR ligands released from inflammatory and other cells on ASM and other local inflammatory and airways structural cells. Above all, calcilytic therapy has the potential directly to target the receptor triggering a wide

TABLE 1 The scope of calcilytic therapy compared with "conventional" therapy for asthma

	β_2-agonists	Anti-muscarinics	PDE4 inhibitors	Steroids	Biologicals	Calcilytics
Airway hyperresponsiveness						✓
Inflammation			✓	✓	✓	✓
Remodelling/fibrosis						✓
Bronchoconstriction	✓	✓				✓
Restrictions/adverse effects	Black box warning[#]		Diarrhoea, weight loss	Pneumonia, osteoporosis, bone fracture		

PDE4: phosphodiesterase 4. [#]: black box warning refers to the potential danger of treating asthma with long-acting β_2-agonists in the absence of corticosteroids.

range of pathophysiological and pro-inflammatory events in asthma rather than intervening in downstream signalling (table 1).

If these expectations are fulfilled, calcilytic therapy has the potential to completely replace stepwise therapy with inhaled bronchodilators and corticosteroids advocated in current asthma guidelines, enabling administration of the therapy once or twice daily to adults and children in a limited range of devices, thus facilitating compliance, and teaching and valid checking of inhaler technique.

With this background and the recent identification of calcilytics that appear both safe and suitable for topical delivery to the airways in asthma, these data firmly suggest that first-in-human studies will be feasible, desirable and achievable in the short term. In the first instance we propose experiments 1) to address the hypothesis that inhaled calcilytics abolish ASM hyperresponsiveness in mild asthmatic subjects, and 2) to address the hypothesis that they abolish both early- and late-phase bronchoconstriction following allergen bronchial challenge of mild, atopic asthmatic patients prior to studies in wider groups of asthmatic patients. It will be of particular interest, in the longer term, to follow-up clinically the initial indications that, unlike corticosteroids, calcilytics have the capacity to alter the natural history of airways remodelling in asthma and thereby reduce or obviate irreversible airways obstruction.

Previous articles in this series: No. 1: Asher MI, García-Marcos L, Pearce NE, *et al.* Trends in worldwide asthma prevalence. *Eur Respir J* 2020; 56: 2002094. *No. 2*: Hinks TSC, Levine SJ, Brusselle GG. Treatment options in type-2 low asthma. *Eur Respir J* 2021; 57: 2000528. *No. 3*: O'Byrne PM, Reddel HK, Beasley R. The management of mild asthma. *Eur Respir J* 2021; 57: 2003051. *No. 4*: Pijnenburg MW, Frey U, De Jongste JC, *et al.* Childhood asthma: pathogenesis and phenotypes. *Eur Respir J* 2022; 59: 2100731.

Conflict of interest: C.J. Corrigan, J.P.T. Ward and D. Riccardi hold a patent for the development of calcium receptor antagonists for the treatment of inflammatory lung disease (https://patents.google.com/patent/WO2014049351A1/en), and D. Riccardi and P.L. Yarova have a pending Composition of Matter patent currently undergoing filing for development of new chemical entities: "Novel calcilytics for pulmonary disease" (IP from NCE GB1719023.2). These authors and the remaining authors L.J. Janssen, T.H. Lee and S. Ying declare no other conflicts of interest relevant to the content of this manuscript, including grants or contracts from any other entity, royalties or licences, consulting fees, payment or honoraria for lectures, presentations, speakers bureaus, manuscript writing or educational events, payment for expert testimony, support for attending meetings and/or travel, participation on a data safety monitoring board or advisory board, leadership or fiduciary role in other board, society, committee or advocacy group, paid or unpaid, stock or stock options, receipt of equipment, materials, drugs, medical writing, gifts or other services or other financial or nonfinancial interests.

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