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The resolution of acute inflammation induced by cyclic AMP is dependent on Annexin A1

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Running Title: cAMP induces AnxA1-dependent inflammation resolution

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Abstract

Annexin A1 (AnxA1) is a glucocorticoid-regulated protein known for its anti-inflammatory and proresolving effects. We have previously shown that cAMP enhancing compounds rolipram (ROL - a PDE4 inhibitor) and db-cAMP (cAMP mimic) drive caspase-dependent resolution of neutrophilic inflammation. In this follow up study, we investigated whether AnxA1 could be involved in the proresolving properties of these compounds using a model of LPS-induced inflammation in BALB/c mice. The treatment with ROL or db-cAMP at the peak of inflammation shortened resolution intervals, improved resolution indices and increased AnxA1 expression. In vitro studies showed that ROL and db-cAMP induced AnxA1 expression and phosphorylation and this effect was prevented by PKA inhibitors, suggesting the involvement of PKA on ROL-induced AnxA1 expression. Akin to these in vitro findings, H89 prevented ROL and db-cAMP-induced resolution of inflammation, and it was associated with decreased levels of intact AnxA1. Moreover, two different strategies to block the AnxA1 pathway - by using BOC-1 a nonselective AnxA1 receptor antagonist or by using an anti-AnxA1 neutralizing antiserum - prevented ROL and db-cAMP-induced resolution and neutrophil apoptosis. Likewise, the ability of ROL or db-cAMP to induce neutrophil apoptosis was impaired in AnxA knockout mice. Finally, in vitro settings ROL and db-cAMP overrode the survival-inducing effect of LPS in human neutrophils in an AnxA1dependent manner. Our results show that AnxA1 is at least one of the endogenous determinants mediating the proresolving properties of cAMP elevating agents and cAMP-mimetic drugs.

Annexin A1 (AnxA1, previously known as lipocortin-1) is a 37-kDa member of the
Annexin superfamily which is composed by proteins that bind to cellular membranes in a calcium-dependent manner. Originally described as an endogenous mediator of the anti-inflammatory effects of glucocorticoids, over the past 20 years AnxA1 has been shown to have a broad range of molecular and cellular actions, including modulation of leukocyte migration in acute and chronic inflammation, kinase activities in signal transduction, preservation of tissue maintenance and apoptosis, cell growth and differentiation (1-5). AnxA1 is particularly abundant in cells of the myeloid lineage, including neutrophils, eosinophils, macrophages and mast cells (6). In resting cells, AnxA1 is by and large localized in the cytosol and, upon activation it can be secreted and then resynthesized. Once in the extracellular medium, this protein exerts autocrine, paracrine and juxtacrine effects which are mediated by the FPR2/ALX receptor (7-11).

AnxA1 exerts a variety of anti-inflammatory effects, including inhibition of leukocyte migration, direct inhibition of cytosolic phospholipase A2 (cPLA2), inhibition of COX-2 and iNOS expression and stimulation of IL-10 release (12-18). AnxA1 also possesses genuine proresolving properties by inducing neutrophil apoptosis (10,19,20) and increasing the clearance of apoptotic cells by efferocytosis (10,21-23). Both apoptosis and efferocytosis modulated by AnxA1 are crucial for resolution of inflammation (10,20).

In the context of the discovery of new mechanisms for known drugs, production and action of AnxA1 has been shown to be involved in the proresolution effects of histone deacetylase (HDAC) inhibitors (24), as well as in the anti-inflammatory effects of propofol (25) and cromoglycate-like compounds (6,26). We have previously shown that rolipram (ROL), a selective phosphodiesterase-4 (PDE4) inhibitor that increases intracellular levels of cyclic adenosine monophosphate (cAMP), induces resolution of neutrophil inflammation and it was associated to increased accumulation of AnxA1 in inflammatory cells (20). However, the relevance and mechanisms underlying ROL-induced AnxA1 expression remain unknown.

In addition to the known anti-inflammatory properties of cAMP-elevating agents (27-29), emerging data support a role for cAMP in some steps of the resolution process (30-37). Indeed, cAMP elevation promoted by treatment with ROL or by cAMP mimetic drugs during established eosinophilic or neutrophilic inflammation induced resolution of inflammation via protein kinase A (PKA), the best known cAMP effector (3,32). Of note, modulation of cAMP may account for the proresolving abilities of melanocortins peptides (38) and lysophosphatidylserine (39). In this study, we investigated the ability of ROL and db-cAMP to modulate AnxA1 expression and wondered whether AnxA1 was involved in the proresolving ability of these compounds. Our results demonstrate that AnxA1 is induced by cAMP elevating agents and is indeed involved in the proresolving properties of these compounds, pointing them as potential therapeutic tools to control inflammatory diseases and induce resolution of inflammation.

**Results**

Rolipram and db-cAMP promote resolution of neutrophilic inflammation associated with increased AnxA1 expression. Initially, we evaluated whether ROL (PDE4 inhibitor) and db-cAMP (cAMP mimetic) would improve resolution indices during acute pleurisy. In this self-resolving model of inflammation the intrapleural injection of LPS induces a time-dependent influx of neutrophils into the pleural cavity of mice that is detectable at 2 h and reaches maximal at 8-24 h, decreasing thereafter with resolution occurring after 48hs, as previously reported (20,33,40,41). Therefore, we quantified the resolution interval (Ri) by defining profiles of acute inflammatory parameters (42,43). The treatment of mice with ROL or db-cAMP at the peak of LPS-inflammation significantly reduced the number of PMN recruited to the pleural cavity and shortened Ri in ~ 12 hours (Fig. 1A and 1B).

To investigate the potential relationship between cAMP and AnxA1, we carried out Western blot analysis in whole cell extracts recovered from the pleural cavity of mice treated 4 h after LPS challenge (when inflammatory cell influx was already established). Western blot was performed to quantify the overall AnxA1 content (ie. the sum of intracellularly localized or cell surface-bound). As seen in Fig 1C and 1D, treatment with ROL or db-cAMP decreased neutrophil numbers and increased levels of intact AnxA1 (Fig. 1E and 1F). AnxA1 was constitutively expressed on resident cells from the pleural cavity (PBS-injected). LPS injection
induced AnxA1 cleavage (as detected by presence of the 33 kDa breakdown product) and treatment with ROL or db-cAMP increased levels of intact AnxA1 (37 kDa form) and reduced AnxA1 cleavage in whole inflammatory extracts when compared to LPS.

Dexamethasone, used as an anti-inflammatory control drug, promoted resolution of neutrophilic inflammation and increased AnxA1 expression, as previously shown (20). Interesting, ROL was able to decrease neutrophil numbers and increase intact levels of AnxA1 as early as 1 h after treatment (Supplementary Fig. 1A and 1B).

The N-terminal region of AnxA1 is the major effector portion responsible for the anti-inflammatory action of the protein and its cleavage decreases the resolution-inducing effects of AnxA1 (10,44). Here, we observed that ROL partially decreased LPS-induced AnxA1 cleavage, as evidenced by the lower levels of the 33-kDa fragment when compared to LPS alone (Figure 1E). As AnxA1 can be cleaved by elastase in vivo, we evaluated whether inhibition of elastase activity by ROL could account for the observed effect. We found that ROL decreased LPS-induced elastase activity and expression in whole cell lysates recovered from pleural inflammatory cells (Supplementary Fig. 1C and 1D). The latter results suggest that ROL modulates AnxA1 levels at least by reducing its degradation.

**Regulation of AnxA1 expression and phosphorylation by cAMP in macrophages.** AnxA1 is present in many differentiated cell types (human and murine) but is particularly abundant in neutrophils, eosinophils, macrophages and mast cells (2,6). Protein expression can be modulated through several mechanisms such as the mobilization of intracellular pool of the protein to exportation and secretion, increased phosphorylation (45) or both. To explore the mechanisms underlying the effect of cAMP elevating agents on AnxA1 expression and localization, in vitro experiments using differentiated THP-1 cells, BMDMs and the murine macrophage cell line RAW264.7 were carried out. THP-1 was used in this work to evaluate the expression of AnxA1, since it has been shown to be a suitable cell line to study AnxA1 modulation (45,46). In these experimental settings, Dexamethasone induced dose-dependent induction of AnxA1 expression (data not shown). As shown in the Fig 2, treatment of THP-1 cells with ROL increased AnxA1 levels in a concentration- (Fig 2A) and time- (Fig 2C) dependent fashion. This modulatory property was also observed in BMDM and RAW264.7 cells (Supplementary Fig 2A-C). For more quantitative data, similar experiments were performed to quantify AnxA1 message by qPCR. Significant increases in AnxA1 mRNA were observed in THP-1 cells treated with ROL, with optimal settings at 10 μM and 6 hours incubation (Fig 2B and 2D, respectively). Interesting, ROL also increased the level of phosphorylated AnxA1 in THP-1 cells (Fig 2E) and BMDMs (Supplementary Fig 2A). In line with the ability of ROL to inhibit degradation and increase intracellular levels of cAMP, there was strong phosphorylation of the CRE-binding protein (CREB), which followed the same kinetics of AnxA1 expression (Fig 2A and 2C). In accordance with the requirement of cAMP levels to induce AnxA1 expression, a cell permeable cAMP (db-cAMP) induced AnxA1 accumulation and phosphorylation (Fig 3A and 3B). Densitometry data for both, AnxA1 and P-AnxA1 were represented graphically (Fig 3C). We also measured the intracellular levels of cAMP in THP-1 cells after rolipram treatment (10μM) and we found an increase of 20% over basal levels, which return to the baseline 2h after. As expected for a cell permeable cAMP, db-cAMP greatly increased levels of intracellular cAMP 1h after cell treatment by 150% over basal, decreasing thereafter but still remain high until 2h (85% of increase over basal levels).

Moreover, Forskolin, a direct activator of adenylyl cyclase, was also able to increase AnxA1 levels (Fig 3D). Noteworthy, physiological cAMP-elevating compounds such as PGE2, norepinephrine and adenosine (36,47-51) were able to increase AnxA1 protein levels, as shown in the Supplementary Fig 3A-C. Likewise, monobutyryladenosine cAMP (6MBcAMP), a membrane permeable analog of cAMP that activates protein kinase A and is resistant to degradation by phosphodiesterase, was able to increase AnxA1 accumulation as did db-cAMP (Supplementary Figure 3D). In contrast, a naked cAMP or yet a cell-permeable cGMP analog (8-br-cGMP) did not increase AnxA1 accumulation, as analyzed by Western blot (See Supplementary Figure 3E).

Taken together, the data gathered so far suggested that ROL and other agents which elevate or mimic cAMP are acting in several
ways to regulate the dynamics of AnxA1 accumulation: they increase mRNA expression, protein accumulation and phosphorylation of AnxA1.

**Ropilram and db-cAMP induce PKA-dependent AnxA1 expression.** The promoter region of the AnxA1 gene contains one cAMP-responsive element (CRE) and this is functional since a CRE-binding protein (CREB) is required for either Dexa-induced or cAMP-induced AnxA1 synthesis (8,52). To investigate whether the observed effects of ROL occurred via PKA, the best-known cAMP downstream effector, THP-1 differentiated macrophages were treated with two PKA inhibitors, H89 (nonsel) or cAMPS-Rp (highly selective), 30 min before ROL or db-cAMP treatments. As shown in Supplementary Figure 4A-C, the blockade of PKA with H89 or cAMPS-Rp decreased AnxA1 mRNA and protein levels induced by both ROL and db-cAMP. Of note, the effect of PKA inhibitors on ROL-induced AnxA1 levels was also observed in RAW264.7 murine macrophages (Supplementary Fig 2C).

Since AnxA1 expression was associated to the proresolving role of CAMP (Fig 1) and the expression of AnxA1 in vitro was modulated via PKA (Supplementary Fig 2C and 4), we investigated if such pathway could also be engaged in vivo. In agreement with the in vitro findings, inhibition of PKA by H89 prevented ROL and db-cAMP-induced resolution of neutrophilic inflammation (Fig 4A and 4B) and this effect was associated with reduction of intact AnxA1 and increase of the cleaved form (Fig 4C and 4D).

A nonsel FPR antagonist prevents ropilram and db-cAMP-induced resolution of neutrophilic inflammation. FPR2/ALX, a G protein-coupled member of the formyl peptide receptor (FPR) family, conveys the biological functions of a variety of ligands, including the proresolving mediators AnxA1 and lipoxin A₄ (9). To investigate whether there was involvement of these receptors in our system, we used the non-selective antagonist BOC-1, which blocks also FPR1. Administration of BOC-1, before ROL or db-cAMP injection, prevented resolution of inflammation induced by these cAMP-elevating agents (Fig 5A and 5B) as seen by permanence of neutrophil and decreased apoptosis into the pleural cavity. Apoptosis was evaluated biochemically through Mcl-1 - the most important Bcl-2 family protein that governs neutrophil half-life (53,54) - (Fig 5C and 5D) and AnnexinV staining (Fig 5F) or by morphological criteria (Fig 5E). Mcl-1 is a key anti-apoptotic protein of the Bcl-2 family protein known to be modulated by ROL (33). Of note, treatment of mice with BOC-1 alone had no effect on neutrophil counts (data not show) and apoptosis (Fig 5E and 5F). Prevention of ROL-induced apoptosis by BOC-1 was associated with decreased levels of intact AnxA1 paralleled by increase of the cleaved form in cells from pleural exudates (Fig 5C and 5D).

**Neutralization of endogenous AnxA1 prevents ropilram and db-cAMP-induced resolution of neutrophilic inflammation.** Having established the effect of AnxA1 receptor blockade on ROL and db-cAMP-induced resolution (Fig 5), we evaluated the effects of an anti-AnxA1 neutralizing strategy by using a specific antiserum. The administration of the anti-AnxA1 antiserum prevented ROL-induced resolution (Fig 6A) and apoptosis, as assessed using either morphological criteria (Fig 6B and 6E) or biochemically by Mcl-1 (Fig 6C) and Annexin V staining (Fig 6D). Of note, treatment of mice with a goat nonimmune serum had no effect on the resolution of LPS-induced pleurisy (data not show) reinforcing previous report (20). AnxA1 neutralization was also able to prevent the effect of db-cAMP on neutrophil numbers (Fig 7A) and apoptosis (Fig 7B-E) similarly to the results obtained with ROL.

Furthermore, we carried out experiments using AnxA1 deficient mouse (24) and found results similar to those obtained by inhibition of AnxA1 actions with BOC-1 or AnxA1 neutralization. Indeed, the treatment with ROL or db-cAMP was able to induce neutrophil apoptosis in WT mice, and such an effect was impaired in AnxA KO mice (Fig 8). Therefore, we have shown by pharmacological and genetic strategies the importance of AnxA1 for the proresolving properties of ROL and db-cAMP.

**Ropilram and db-cAMP override the survival-inducing effect of LPS in human neutrophils and such an effect is Anxa1 dependent.** Neutrophil apoptosis is an integral modulatory mechanism that constrains inflammation and contributes to its successful resolution. The fate of neutrophils inside an inflammatory milieu - i.e. whether they undergo apoptosis or remain viable - depends on the
balance of pro-survival stimuli such as LPS, GM-CSF and oxygen availability, as well as the presence of pro-apoptotic stimuli including Fas ligand and TNF (55). Because ROL and db-cAMP induced neutrophil apoptosis in an inflammatory milieu in vivo, we investigated the ability of these cAMP elevating agents to counteract the prosurvival effects of LPS in vitro. As previously showed, LPS decreased the spontaneous apoptosis of cultured human neutrophils (41) and the treatment with ROL and db-cAMP prevented this effect, as evaluated by increased percentage of apoptotic neutrophils when comparing LPS-treated cells with LPS+ROL or LPS+db-cAMP (Fig 9A and 9G). There was no difference among the different doses used (Fig 9B and 9C). Sivelestat, a synthetic protease inhibitor, was used as a positive control for induction of neutrophil apoptosis (Fig 9A), as previously reported (41). In accordance with our in vivo data, the ability of ROL and db-cAMP to decrease the prosurvival effect of LPS was abolished by pretreatment with Anti-AnxA1 serum (Fig 9D and 9E) or by using WRW4, a selective FPR2 antagonist (Fig 9F). Therefore, our data show that cAMP elevating agents can effectively induce or accelerate a pro-apoptotic program in neutrophils leading to resolution of inflammation.

Discussion

Cyclic AMP is a fundamental second-messenger-molecule produced after adenylate cyclase activation in response to several stimuli, endowed with fundamental modulatory activities in cells involved in the inflammatory process, a property exerted primarily through PKA activity. Intracellular levels of cAMP result from a balance of modulatory pathways that involve elevation through agonist ligands (such as PGE2, adenosine and β-adrenergic drugs) and degradation by phosphodiesterases (PDEs) (27,28,56). There are different families of PDEs with various roles in different cells or tissues. The PDE4 isoenzyme family plays a particularly important role in the immune system and is the predominant PDE in inflammatory cells including mast cells, eosinophils, neutrophils, T cells and macrophages (56). Our group has previously shown that ROL and cAMP mimetics induce resolution of an established neutrophilic or eosinophilic inflammation (32,33) by inducing caspase-dependent apoptosis of polymorphonuclear cells.

In this follow up study, we reveal an important role for AnxA1 in the proresolving properties of ROL and db-cAMP, the cyclic AMP mimic of choice. This conclusion is substantiated by the following major findings: (i) ROL and db-cAMP promoted resolution in a model of acute inflammation in mice challenged with LPS, and this process was associated with increased levels of intact AnxA1; (ii) ROL induced AnxA1 expression and phosphorylation in macrophages, an effect associated to CREB phosphorylation. Dibutyril-cAMP, forskolin and physiological cAMP-elevating agents increased AnxA1 expression; (iii) The increase of AnxA1 induced by ROL was PKA-dependent in human (THP-1) and murine (RAW) macrophages; (iv) The effect of ROL and db-cAMP in vivo was via PKA as shown by using PKA inhibitors. The latter drugs not only prevented cAMP-induced resolution, but also prevented the increase in intact AnxA1 levels; (v) Two different pharmacological strategies were employed to inhibit the AnxA1 pathway, FPR antagonism and neutralizing AnxA1 antiserum: in both cases there was marked reduction of the resolution properties displayed by cAMP elevating agents. Importantly, in AnxA1 deficient mice, ROL or db-cAMP treatment could not induce neutrophil apoptosis. (vi) ROL and db-cAMP induced AnxA1-dependent apoptosis of human neutrophil in presence of prosurvival stimuli LPS. Therefore, our results show that the effects of ROL and db-cAMP on resolution of inflammation are at least in part due to modulation of AnxA1 expression, stabilization and mobilization to cell surface. These data identify AnxA1 as a proreresolving molecule involved in pro-resolving actions of cAMP (Fig 10).

In addition to the role of AnxA1 in mediating anti-inflammatory properties of endogenous cortisol, AnxA1 is also an important mediator of anti-inflammatory and proresolving properties of pharmacological doses of glucocorticoids (20,57). During the initial steps of acute inflammation, AnxA1 limits the recruitment of leukocytes and the production of pro-inflammatory mediators (2). During the resolution phase, AnxA1 acts by promoting the apoptosis of neutrophils (10,20) and increasing their efferocytosis by macrophages (10,21). Recent studies indicate that modulation of AnxA1 disposition, levels and indeed
externalization in specific cell targets may represent a common mechanism evoked by anti-inflammatory agents, such as LXA₄ (58) and oestrogens (59). Interestingly, in this study we have found that physiological cAMP-elevating compounds such as adenosine increase AnxA1 protein levels. However, remain to be investigated whether AnxA1 account for the proresolving abilities of adenosine and which receptor is engaged to elicit this effect. Another group of drugs, HDAC inhibitors, endowed with multiple properties like the PDE4 inhibitor used here, also modulate AnxA1 expression and localization. Indeed, administration of HDAC inhibitors such as valproic acid and sodium butyrate at the peak of zymosan-induced peritonitis accelerated resolution in wild type mice, but much more modestly in AnxA1 null mice. These effects were consequence of the capacity of HDAC inhibitors to elevate AnxA1 levels, which then modulated leukocyte apoptosis and efferocytosis (24). During the resolving phase of LPS-inflammation, high levels of AnxA1 have been found in macrophages with resolutive phenotypes (40).

Phosphorylation and release of AnxA1 are central to the mechanism of action of the antiallergic cromoglicate-like drugs on mast cells and are essential for the inhibition of the release of histamine and PGD₂. The latter effects were abolished in the presence of neutralising anti-AnxA1 monoclonal antibody (6). In our studies, we demonstrated that ROL and db-cAMP promoted resolution of neutrophilic inflammation associated to high levels of intact AnxA1 and decreased levels of the cleaved form. Furthermore, ROL induced AnxA1 mRNA expression, accumulation and phosphorylation in macrophage lineages. More importantly, the blockage of the endogenous AnxA1 prevented the proresolving effects of these cAMP elevating agents and ROL and db-cAMP prevented the prosurvival effect of LPS on human neutrophils. cAMP regulates apoptosis in several cell types, inhibiting or stimulating the process depending on the cell type and stage of differentiation (60). There are some in vitro studies using neutrophils that have shown that PDE4 inhibition or an increase of cAMP levels by other cAMP-increasing agents delay neutrophil apoptosis (61-64). In contrast with these in vitro studies, our group demonstrated that in vivo administration of ROL was clearly associated with resolution of neutrophilic inflammation by inducing caspase-3-dependent apoptosis (33). It is important to point out that our experimental settings were designed to investigate if these drugs could interfere with neutrophil accumulation (apoptosis+ efferocytosis/clearance) and not infiltration (migration), since we treated mice 4 h after LPS challenge, when inflammatory cell influx was already established. Indeed, we have previously shown that the neutrophil-active chemokines, such as CXCL1 and CXCL2 peak early in this model of inflammation (1-2h) and their levels are similar to basal at 4h after LPS injection (33). Also, injection of reparixin (an allosteric inhibitor of CXCR2) 4h-after LPS challenge failed to affect the accumulation of neutrophils, while in the same experiment, post-treatment with rolipram greatly decreased neutrophil accumulation in the cavity. Therefore, the effects of ROL and db-cAMP in our experimental settings are not in the migration process of the cells into the pleural cavity, since the cAMP elevating agents were given after the stimulus and after the peak of neutrophil-active chemokine production in the cavity (33).

Here, we went further and clearly showed that cAMP-elevating agents were able to induce AnxA1-dependent resolution of inflammation and increased neutrophil apoptosis associated with loss of Mcl-1. Importantly, the blockage of AnxA1 pathway prevented Mcl-1 loss and it was associated to neutrophil survival. The apoptotic effect of ROL and db-cAMP was also observed in cultured human neutrophils exposed to the prosurvival stimuli of LPS. The apparent contradictory actions of cAMP on isolated neutrophils of the previous studies (61-64) with our study can be explained because ROL and db-cAMP induce apoptosis in the presence of an inflammatory milieu, when these drugs were able to counteract the prosurvival stimuli such as LPS. These data presented here cluster with those generated with HDAC inhibitors and cromoglicate-like drugs to suggest that induction of AnxA1 may account for the anti-inflammatory and resolving mechanisms of a few known drugs. We propose that AnxA1 represents a central check-point mechanism regulating leukocyte survival and reactivity during on-going inflammatory reactions.

After cell activation, AnxA1 is internalized on the cell surface, the N-terminal region is exposed and interacts with its receptor named FPR2/ALX. Once in the extracellular
medium, AnxA1 can be cleaved at the N-terminal region by proteases including NE and PR3, generating the 33-kDa isoform of poorly known properties. Intact AnxA1 (37 kDa) is the biological active form of the protein (13,44,65). Here, we showed that compounds which we have previously show to increase resolution of neutrophilic inflammation (33), are able to increase the levels of intact AnxA1 and prevent partially its degradation. A recent work of our group (66) showed that ROL could increase intact AnxA1 and prevent AnxA1 cleavage associated to ameliorated of inflammation of pneumococcal pneumonia. Interestingly, such an effect was more efficient when ROL was combined with the antibiotic ceftriaxone. Therefore, the effect of ROL on the cleaved levels of AnxA1 may be, at least in part, due to the decreased elastase activity and expression, and associated with decreased neutrophils number since elastase is an important protease present in neutrophils. In the inflammatory context, the decreased elastase levels may be important to resolution occurs. During the resolving phase of LPS-induced inflammation, in which was associated with decreased elastase expression and activity there were more intact AnxA1. Conversely, during the productive phase of inflammation there were high elastase expression/activity and higher proportion of AnxA1 cleavage. Indeed, inhibition of elastase by using synthetic (Sivelestat) or natural inhibitors (elafin or secretory leukocyte protease inhibitor - SLPI) was able to promote resolution of inflammation by protection of endogenous intact levels of AnxA1 and resulting neutrophil apoptosis (13,41,65). Furthermore, cleavage-resistant (CR) AnxA1 exhibited greater anti-inflammatory effect when compared with the parent protein in different animal models of inflammation (13,41,65).

The regulation of cAMP levels is a key feature to regulate a large number of events in the body (67). As a ubiquitous second messenger, cAMP regulates several processes in many cell types including cells from the immune system (30-32,34,35). Elevated cAMP levels were reported at the resolution point in a model of resolving peritonitis, and this was important to clear PMNs and regulate monocyte-derived macrophage functions (31). Sokolowska and colleagues (36) demonstrated that prostaglandin E2, a potent lipid mediator involved in maintaining homeostasis, inhibits NLRP3 inflammasome activation through EPE4 receptor and an increase in intracellular cAMP in human macrophages. In teleost fish, prostaglandin E2 promoted M2 polarization macrophages via a cAMP/CREB signaling pathway (37). Bystrom and colleagues (30) examined whether macrophage phenotype was dictated by cAMP and whether this phenotype could be altered by changing intracellular levels of this potent intracellular second messenger. In M1 macrophages, TNFα production was attenuated by db-cAMP, whereas IL-10 production was increased, suggesting a reversion toward the anti-inflammatory or resolutive phenotype. Noteworthy, cAMP may function as an intermediate of the effects of other pro-resolving molecules, such as melanocortins peptides (38), lysophosphatidylserine (39) and resolving D1 (RvD1) (68,69). Recently it was reported the effect of cAMP on neutrophil extracellular trap (NET). Shishikura and colleagues have described the inhibitory action of PGE2 on PMA-induced NET formation in vitro through EP2 and EP4 Gαs-coupled receptors. Also, incubation with db-cAMP or inhibitors of PDE, also suppressed NET formation (70). Here, we described one more immunomodulatory function for cAMP, induction of AnxA1-dependent resolution of inflammation.

The biology of cAMP is mediated by downstream effector molecules and the most important one is protein kinase A (PKA): cAMP binds directly to PKA provoking a functional rearrangement with enzymatic activity. PKA was shown to mediate, for example, the inhibition on macrophage inflammatory mediator generation induced by cAMP (71), and according to (32), the inhibition of PKA by H89 was able to limit the cAMP-mediated neutrophilic resolution. EPAC is another protein that, together with PKA, is the major binding partner of cAMP (72). In our model we investigated whether inhibition of PKA with H89 could inhibit the resolution induced by ROL and db-cAMP. In agreement with these previous studies, H89 reverted resolution induced by both ROL and db-cAMP in vivo and these events were followed by a decrease in the levels of intact AnxA1. Moreover, our in vitro experiments confirmed the non-redundant function of PKA since pre-treatment with H89 or a more selective cAMP-Rp thethylammonium, reduced cellular levels of AnxA1 below those measured in RAW264.7 or THP-1 cells treated with ROL alone. When this antagonist is used, the levels of AnxA1 are lower, what proves once again the importance of
cAMP to the action of ROL in this system. Altogether, these experiments led us to conclude that PKA is the major effector for cAMP in the processes evoked by ROL.

Obviously, by interfering with cAMP levels we may alter cGMP levels (because some PDEs hydrolyse both cAMP and cGMP, so PDEs that metabolize cGMP may be altered by intracellular cAMP levels) (73,74). In this sense, it will be import in the future to study the cross talk between cAMP and cGMP.

In conclusion, our study showed that cAMP elevating agents increase levels of AnxA1 and this is functionally involved in the pro-resolving abilities of cAMP. These results reinforce the hypothesis that AnxA1 acts at multiple regulatory levels to promote resolution of inflammation and may be a common mechanism that account for the pro-resolving actions of pro-resolving molecules. cAMP elevating drugs may represent a useful therapeutic strategy not only to block inflammatory processes (during onset of inflammation) but also, and equally important, to actively induce the mechanisms underlying the resolution of inflammation.

Experimental procedures

Animals. Male BALB/c mice (8-10 weeks) obtained from the Bioscience Unit of Instituto de Ciências Biológicas (Brazil) were housed under standard conditions of optimum light, temperature and humidity (12:12 h light–dark cycle, 22 ± 1°C, 50–60%) with food and water provided ad libitum. Annexin A1 knockout (BALB/c background) mice were generated as previously described (57) and bred at the Universidade Federal de Minas Gerais. All described procedures had prior approval from the Animal Ethics Committee of Universidade Federal de Minas Gerais (CEUA/UFMG, protocol number 15/2011).

Drugs, reagents and antibodies. Dibutyryl cAMP (db-cAMP), 6MB-cAMP, cAMP, Forskolin, Dexamethasone, Adenosine, (-)-norepinephrine, sodium butyrate, cGMP, Anti-β-actin (#A5316) and LPS (from Escherichia coli serotype 0:111:B4) were from Sigma Aldrich (St. Louis, MO, USA). 8-Br-cGMP was from Calbiochem (EMD chemicals, San Diego, CA). Rolipram was purchased from Enzo Life Science (NY, USA). H89 dihydrochloride and cAMPS-Rp trethylammonium salt were from Tocris (Ellisville, MO, USA). Prostaglandin E2 (PGE2) was from Cayman Chemical (Michigan, USA). Anti-AnxA1 antiserum was a king gift from Dr. Steve Poole (Biotherapeutics Group, National Institute for Biological Standards and Control, UK). Anti-AnxA1 (Sc-11387), anti-elastase (Sc-9521) or secondary anti-mouse (Sc-2005) peroxidase-conjugate antibody were purchased from Santa Cruz Biotechnology (Santa Cruz, CA, USA). Anti P-CREB (#9191) and secondary anti-rabbit peroxidase-conjugate antibody (#7074) were from Cell Signaling Technology (Danvers, MA, USA). We also used Anti-AnxA1 (#713400) from Invitrogen (Carlsbad, CA, USA). BOC-1 (N-t-Boc-Met-Leu-Phe) was from MP Biomedicals (California, USA). Polyclonal anti-Ser27,AnxA1 antibody was generated as previously described (75).

LPS-induced pleurisy model and treatment with drugs. Mice received an intrapleural (i.pl.) injection of LPS (250 ng/cavity) or phosphate-buffered saline (PBS) as previously described (20,33). Four hours later, mice were treated with rolipram (6 mg/kg, i.p.), Dexe (2 mg/kg, i.p.) or with db-cAMP (4 mg/kg, i.pl.). These doses and route of administration were validated in our previous studies (20,32). AnxA1-knockout mice were also treated with these drug doses. To prevent the action of AnxA1, mice were treated with BOC-1, a nonselective AnxA1 receptor antagonist (5 mg/kg, i.p.) 30 min before the drugs or with anti-AnxA1 antiserum (0.1 mL hyperimmune serum diluted in 100 µL PBS/mice, i.p.) given 1 h before the challenge with LPS and again 1 h before ROL. In other cases, the PKA inhibitor H89 (4 mg/kg, i.pl.) was used. Compounds were diluted in DMSO or ethanol and further in PBS. db-cAMP was only diluted in PBS. Control mice received the respective vehicle only. Mice were euthanized by inhalation of CO2. Cells in the pleural cavity were harvested by washing the cavity with 2 mL of PBS and total cell counts performed in a modified Neubauer chamber using Turk’s stain. Differential cell counts were performed on cytocentrifuge preparations (Shandon Cytospin III) and the slides were stained with May-Grünwald-Giemsas using standard morphological criteria to identify cell types (20,33,57). Results are presented as the number of cells per cavity.
Calculation of resolution indices. We quantified the resolution indices as previously described (42,43). Murine pleural exudates were collected at 8, 24, 36 and 48 time points after LPS challenge. The number of PMN and mononuclear cells was determined by total and differential leukocyte counting. The resolution of acute inflammation was defined in quantitative terms by the following resolution indices: 1) magnitude ($\psi_{\text{max}}$ and $T_{\text{max}}$), $\psi_{\text{max}}$ (the maximal PMN numbers in the exudates), $T_{\text{max}}$ (time point when PMN numbers reach maximum); 2) duration ($T_{50}$), $T_{50}$ (time point when PMN numbers reduce to 50% of maximum) and 3) resolution interval $R_i$ (the time period when 50% PMNs are lost from the pleural cavity, i.e., $T_{50}$-$T_{\text{max}}$).

Cell culture and in vitro assays. The human promonocytoid cell line THP-1 and murine macrophages RAW264.7 were obtained from the American Type Culture Collection (ATCC, Rockville, MD, USA). THP-1 cells were cultured in RPMI 1640 medium (Cultilab, São Paulo, Brazil) supplemented with 8% heat-inactivated fetal bovine serum (FBS) and antibiotics (Cultilab, São Paulo, Brazil) and RAW264.7 cells were cultured in DMEM (Cultilab, São Paulo, Brazil) in the same conditions. Cell cultures were maintained at 37°C and 5% CO$_2$, and cell viability was determined using a trypan blue dye-exclusion assay. THP-1 cells were differentiated using 4a-phorbol 12-myristate 13-acetate (PMA - 20 ng/mL, Sigma Aldrich, St. Louis, MO, USA) and deprived with FBS 1% for 24 h; subsequently cells were treated with drugs at different time intervals and concentrations as indicated in the specific figures. Dexamethasone (Dexa) was used as a positive control for AnxA1 induction.

cAMP measurements. cAMP levels in cellular extracts were measure using the cAMP Direct Immunoassay Kit, as described by the manufacturer (Cat#ab65355 Abcam, Cambridge, UK). Briefly, THP-1 cells were lysed completely with 0,1M HCl, following by centrifuging 10.000 RPM for 10 min. The supernatant was collected as the testing sample. To be ready for quantification, cAMP standards and samples were neutralized and acetylated using the neutralizing buffer and acetylating reagent supplied in the Kit, respectively. During the quantification, standard cAMP and testing samples were added to the Protein G coated 96-well plate. After blended with anti-cAMP antibody, the suspension was incubated for 1 h at room temperature with gentle agitation and for another hour with the adding of cAMP-HRP. Then the plate was washed for five times, following by incubation with HRP developer for 1 h. The reaction was stopped by 1M HCl and the absorbance was detected by a microtiter plate reader (Spectra Max 190, Molecular Devices) at 450 nm. The molar concentration of cAMP in cells was determined from standard curves generated using standard preparation. The cAMP levels were expressed by percentage above the control untreated cells.

Bone-marrow derived macrophages (BMDMs). Bone marrow cell suspensions were isolated by flushing femurs and tibias of 8-10 week BALB/c mice with complete DMEM (+10% FCS, + 1% Pen/Strep) and 20% L929 cell-conditioned medium (LCCM) as a source of macrophage colony-stimulating factor (M-CSF) (76). Aggregates were dislodged by gentle pipetting, and debris was removed by passaging the suspension through a cell strainer (BD Biosciences). Cells were seeded on 6-well plates and incubated at 37°C in a 5% CO$_2$ atmosphere. Five days after seeding, another 2 ml of DMEM containing 10% FBS and 20% LCCM was added. On the seventh day, cells were completely differentiated into macrophages. Cells were seeded on 24-well plates (5 x 10$^5$ cells/well) and later were pre incubated with rolipram (10 µM) for one hour and further stimulated with LPS (100 ng/mL) for 24 hours.

In vitro assay to evaluate neutrophil apoptosis. Neutrophils were isolated from human peripheral blood from healthy donors (Ethics Committee of the Universidade Federal de Minas Gerais, Brazil - Institutional Review Board Project number 0319.0.203.000-11) by using histopaque gradient (Histopaque 1119 and 1077 - from Sigma Chemicals, St. Louis, MO, USA) as described previously (41,77). Neutrophils (1 x 10$^6$ cells/well) were resuspended in RPMI 1640 medium, seeded in 96-well culture plates (BD Biosciences) and incubated at 37°C in a 5% CO$_2$ atmosphere. Cell viability was determined using a trypan blue dye-exclusion assay and the purity of
preparations was 95%. To evaluate the effect of ROL or db-cAMP on LPS-induced prosurvival/delayed apoptosis of neutrophils, isolated neutrophils were cultured in the presence of LPS (500 ng/mL) and 1 h after were treated with the drugs for further 5 h as indicated in the figures. In some experiments, neutrophils were pre-treated with an anti-AnxA1 antiserum (αAnxA1 - 100 μg/mL) or a selective antagonist of FPR2, WRW4 - 10 μM (number 344220; Calbiochem, San Diego, CA, USA) before addition of LPS. Sivelestat - 100 μg/mL (number S7198; Sigma-Aldrich, St. Louis, MO, USA) was used as a positive control for neutrophil apoptosis (41). Apoptosis was evaluated morphologically (as described above) and the experiments were performed in biological quadruplicates.

Assessment of leukocyte apoptosis. Apoptosis was assessed as previously reported (20,33). Briefly, cells (5 x 10⁶) collected after LPS challenge or from in vitro experiments were cyto-centrifuged, fixed and stained with May-Grünwald-Giems and counted using oil immersion microscopy (x100 objective) to determine the proportion of cells with distinctive apoptotic morphology (cells with chromatin condensation, nuclear fragmentation and formation of apoptotic bodies out or inside macrophages). At least 500 cells were counted per slide and results are expressed as the mean ± SEM of percentage of cells with apoptotic morphology. Assessment of neutrophil apoptosis (Ly6G⁺/F4/80⁻/AnxV⁺/7AAD⁻) was also performed by flow cytometry using FITC-labeled annexin V and 7- aminoactinomycin D (BD Biosciences, San Jose, CA, USA) as previously reported (40,41). Antibodies used were F4/80 (PEcy7; eBioscience, San Diego, CA, USA) and Ly6G (V450; BD Bioscience, San Jose, CA, USA). Stained cells were acquired in BD FACSCanto II cell analyzer (BD Biosciences) and analyzed using FlowJo software (Tree Star, Ashland, OR).

Western blot analysis. Inflammatory cells harvested from the pleural cavity, THP-1, RAW264.7 or BMDMs were washed with PBS and whole cell extracts were prepared as described (32,78,79). The protein content of the lysate was determined by Bradford assay reagent (Bio-Rad, Hercules, CA, USA). Extracts (20 μg) were separated by electrophoresis on 10% SDS-PAGE and electrotransferred to nitrocellulose membranes, as described (78). Membranes were blocked overnight at 4°C with PBS containing 5% (w/v) nonfat dry milk and 0.1% Tween-20, washed three times with PBS containing 0.1% Tween-20 and then incubated with anti-AnxA1 (Santa Cruz, 1:1000 or Invitrogen, 1:3000), polyclonal anti-Ser²³-AnxA1 (1:1000), anti-P- CREB (1:1000), anti-Mcl-1 (1:1000), anti- elastase (1:1000) and anti-β-actin (1:5000) antibodies in PBS containing 5% (w/v) BSA and 0.1% Tween-20. After washing, membranes were incubated with appropriated horseradish peroxidase-conjugated secondary antibody (1:3000). Immunoreactive bands were visualized by using an ECL detection system, as described by the manufacturer (GE Healthcare, Piscataway, NJ). The values of AnxA1 or P-AnxA1 were quantified by using a densitometric analysis software (ImageJ, Image Processing and Analysis in Java; NIH, Bethesda, MD). Changes in protein levels were estimated by the control (untreated cells) and the results were expressed as fold increase of the arbitrary units of AnxA1 or P-AnxA1 normalized to the values of β-actin in the same sample.

RNA extraction and quantitative RT-PCR. Total RNA was extracted using the RNeasy Mini Kit (Qiagen, Crawley, UK) according to the manufacturer’s instructions. cDNA was synthesized from 1 μg of RNA with SuperScript III Reverse Transcriptase (Invitrogen, Carlsbad, CA, USA), following the manufacturer’s recommended protocol. Synthesized cDNA was added to the relevant forward and reverse primer together with Power SYBR Green PCR Master Mix (Applied Biosystems, Warrington, UK). Real-time PCR was performed in duplicate, with 1 μL cDNA at a concentration of 100 ng, 0.5 mM primers and Power SYBR Green PCR Master Mix (Applied Biosystems, Warrington, U.K.) using StepOne (Applied Biosystems, Foster City, CA, USA). The data were analyzed using StepOne Detection System software with a cycle threshold (Ct) in the linear range of amplification and then processed by the 2⁻⁵ΔΔCt method. Reactions were run in duplicates. Primers (IDT) used were as follows: human AnxA1 (5'-ATCAGCGGTAGCCGCCCTATC-3' / 5'-TTCAATCCAGGGGCTTTCTGTG-3') and human Gapdh (5'- AGAAGACTGTGATGCCTGC-3' / 5'- TGACCTTGCCACAGCCTT-3'). A dissociation step was always included to confirm
the absence of unspecific products. Samples of all groups were run on one plate with two technical replicates. Gapdh was used as an endogenous control to normalize the variability in expression levels and results were expressed as fold increase.

Elastase activity assay. The elastase activity was measured in cell extracts prepared in the absence of proteases inhibitors by using an in-house procedure that relies on the use of MeO-Suc-AA-Pro-Val-pNA (M4765-Sigma Aldrich, St. Louis, MO, USA) as substrate. Cells obtained from pleural cavity of mice were lysed on appropriated buffer (200 mM NaCl, 20 mM Tris-HCl, 1% Triton X-100, pH 8.0). The lysate was centrifuged at 12,000 rpm in a microcentrifuge for 15 minutes at 4º C and supernatant (30 µL) was added to 20 µL of TBS (Tris-HCl, pH 8.0) and 50 µL of the substrate (1 mM) in a 96-well microplate. Following incubation for 2 h at 37º C, the absorbance of samples was analyzed in a spectrophotometer (Spectra Max 190, Molecular Devices) at 405 nm. A standard curve was performed with p-nitroanilide in accordance to the procedures supplied by the manufacturer (BioVision Inc., California, USA). The results are presented as elastase activity absorbance.

Statistical analysis. All results are presented as the mean ± SEM. Data were analyzed by One-way ANOVA, and differences between groups were assessed using the Student-Newman-Keuls post-test. A P value < 0.05 was considered significant. Calculations were performed using the Prism 5.0 software for Windows (GraphPad software, San Diego, CA).

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Conflicts of Interest

The authors declare that they have no conflicts of interest with the contents of this article.

Author Contributions

LPS and MMT designed research, analyzed data and wrote the paper. KML and JPV performed the main experiments, analyzed data and helped to write the paper. RGA, BRCC, AAFC, KML, MAS and IG performed in vitro experiments. KML, TRC and FMS carried out PCR analyses. GLNL and LPT performed some in vivo experiments. VP provided expertise. ES provided the P-AnxA1 antibody and contributed to manuscript revision. MP provided guidance on experimental design and contributed to manuscript writing. All authors approved the final version of the manuscript.

References


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**Footnotes**

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2. KML and JPV are equally contributed authors.

3. The Abbreviations used are: AnxA1, annexin A1; αAnxA1, anti-AnxA1 antiserum; BOC-1, N-t-Boc-Met-Leu-Phe; cAMP, cyclic adenosine monophosphate, CRE, cAMP-responsive element; CREB, cAMP-responsive element binding protein; db-cAMP, dibutyryl cyclic AMP; Dexta, dexamethasone; DMSO, dimethyl sulfoxide; FPR2/ALX, formyl peptide receptor 2/ lipoxin A4 receptor; GC, glucocorticoid; i.pl., intrapleural; i.p., intraperitoneal; PKA, protein kinase A; PMA, 4α-phorbol 12-myristate 13-acetate; ROL, rolipram; WRW4, Trp-Arg-Trp-Trp-NH2.
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Figure legends

Figure 1. Effect of the treatment with rolipram and db-cAMP on resolution of acute inflammation. Evaluation of resolution indices: mice were injected with LPS (250 ng/cavity, i.pl.) or PBS and 8 h later received an injection of ROL (6 mg/kg, i.p.) or db-cAMP (4 mg/kg, i.pl.). Pleural wash were performed at various time points after LPS injection and neutrophils were count from cytopsin preparations (A) to calculate resolution indices (B). In C-F, mice were injected with LPS (250 ng/cavity, i.pl.) or PBS and 4 h later received an injection of ROL or db-cAMP at the same dose of A, or Dexa (2 mg/kg, i.p.) as a control. The cells from pleural cavity were harvested and processed for neutrophils count (C, D) and western blot analysis (E, F) for detection of AnxA1 4 h later drug treatment, i.e., 8 h later LPS-challenge. Two different exposures time of the cleaved band of AnxA1 immunoblot are presented. Results are expressed as number of neutrophils/cavity and are shown as the mean ± SEM of at least five mice in each group. ***P < 0.001 when compared with PBS-injected mice; **P < 0.01 and ***P < 0.001 when compared with LPS-challenged mice. For loading control, membranes were reprobed with anti-β-actin. Blots are representative of three independent experiments using pooled cells from at least five animals in each experiment.

Figure 2. Effect of rolipram on AnxA1 mRNA expression, protein levels and phosphorylation in THP-1 differentiated macrophages. Cells were differentiatied using PMA (20 ng/mL) and serum deprived for 24 h. Later, the cells were untreated or treated with ROL at increasing concentrations for 6 h (A, B, E), or different time intervals (C, D, E) as indicated in the Figure. Whole cell extracts were obtained and subjected to Western blot analysis (A, C, E) to assess for AnxA1, Ser27-phospho-AnxA1, and Phospho-CREB levels (as a marker of PKA activation) or for quantitative RT-PCR (B, D). For loading control, membranes were reprobed with anti-β-actin. Blots are representative of three independent experiments. qRT-PCR data were performed in biological triplicates performed with two technical replicates. The results are presented as fold increase of mRNA expression relative to the amount present in control samples. Data are mean ± SEM. **P < 0.01 and ***P < 0.001, when compared to untreated cells; ###P < 0.001 when compared to ROL treatment at 10 μM or 6 h.

Figure 3. Effect of db-cAMP and Forskolin on AnxA1 expression and phosphorylation in THP-1 differentiated macrophages. Cells were differentiated using PMA (20 ng/mL) and serum deprived for 24 h. After starvation, the cells were untreated or treated with db-cAMP (A, B) or Forskolin (D) at different concentrations (6 h) and times as indicated in the Figures. Total cell extracts were obtained and subjected to Western blot analysis to assess for AnxA1 (A, B, D) or Ser27-phospho-AnxA1 (A). Densitometry data are presented graphically in the panel C. For loading control, membranes were reprobed with anti-β-actin. Blots are representative of three independent experiments. Data are mean ± SEM. *P < 0.05, **P < 0.01 and ***P < 0.001, when compared to untreated cells.

Figure 4. Ropilram and db-cAMP resolve neutrophilic inflammation in a PKA-dependent manner. Mice were injected with LPS (250 ng/cavity, i.pl.) or PBS and 4 h later received an injection of ROL (6 mg/kg, i.p.) or db-cAMP (4 mg/kg, i.pl.). Two groups of mice were pre-treated 30 min with H89 (4 mg/kg, i.p.) before the drugs. The cells from pleural cavity were harvested and processed to neutrophils count (A, B) and western blot (C, D) for detection of AnxA1 4 h after drug treatment, i.e., 8 h after LPS challenge. Two different exposures time of the cleaved band of AnxA1 immunoblot are presented. Results are expressed as the number of neutrophils/cavity and are shown as the mean ± SEM of at least five mice in each group. ***P < 0.001 when compared to PBS-injected mice; *P < 0.05 and **P < 0.01 when compared to LPS-challenged mice. Comparison between the groups H89 and H89+drugs are highlighted in the graphics. For loading control, membranes were reprobed with anti-β-actin. Blots are representative of three independent experiments in pools of cells from at least five animals in each experiment.

Figure 5. Effect of treatment with BOC-1, a FPR/ALX antagonist, on ROL and db-cAMP-induced resolution of acute inflammation. Mice were injected with LPS (250 ng/cavity, i.pl.) or PBS and 4 h later received an injection of ROL (6 mg/kg, i.p.) or db-cAMP (4 mg/kg, i.pl.). An injection of BOC-1 (5 mg/kg, i.p.) was given 30 min before the drugs. The cells from pleural cavity
were harvested and processed to neutrophils count (A, B) and western blot analysis (C, D) for detection of AnxA1 and McI-1. 4 h later drug treatment, i.e., 8 h later LPS challenge. Two different exposures time of the cleaved band of AnxA1 immunoblot are presented. Number of apoptotic neutrophils was determined morphologically (E) and by flow cytometry of Annexin V+ neutrophils (F) 24 h after LPS injection. Results are expressed as the number of neutrophils/cavity (A, B), percentage of neutrophils with apoptotic morphology (E) and number of apoptotic neutrophils (Ly6G+/F4/80+/AnxAV+/7AAD-) (F), and are shown as the mean ± SEM of at least five mice in each group. *P < 0.05 or ***P < 0.001 when compared with PBS-injected mice; **P < 0.01 or ###P < 0.001, when compared with LPS-challenged mice. Comparison between the groups BOC and BOC+drugs are highlighted in the graphics. For loading control, membranes were reprobed with anti-β-actin. Blots are representative of three independent experiments using pooled cells from at least five animals in each experiment.

Figure 6. Effect of treatment with anti-AnxA1 antiserum on ROL-induced resolution of acute inflammation. Mice were injected with LPS (250 ng/cavity, i.pl.) or PBS and 4 h later received an injection of ROL (6 mg/kg, i.p.). Injections of anti-AnxA1 antiserum (αAnxA1, 200 µL, i.p.) was given 1 h before the challenge with LPS and again 1 h before ROL. Numbers of neutrophils (A), cells with distinctive apoptotic morphology (B), and western blot for McI-1 (C) were evaluated 4 h later drug treatment, i.e., 8 h later LPS challenge. The number of Annexin V+ neutrophils (D) was evaluated by flow cytometry 24 h after LPS injection. Representative figures of nonapoptotic (asterisk) and apoptotic (arrows) and apoptotic cells inside macrophages (arrowheads) are shown in (E) - Original magnifications ×20. Results are expressed as the number of neutrophils/cavity (A), percentage of neutrophils with apoptotic morphology (C) and apoptotic neutrophils (Ly6G+/F4/80+/AnxAV+/7AAD- (D) and are shown as the mean ± SEM of at least five mice in each group. *P < 0.05 or ***P < 0.001 when compared with PBS-injected mice; ###P < 0.001 when compared to LPS-challenged mice. Comparison between the groups ROL and ROL+αAnxA1 are highlighted in the graphics. For loading control, membranes were reprobed with anti-β-actin. Blots are representative of three independent experiments using pooled cells from at least five animals in each experiment.

Figure 7. Effect of treatment with anti-AnxA1 antiserum on db-cAMP-induced resolution of acute inflammation. Mice were injected with LPS (250 ng/cavity, i.pl.) or PBS and 4 h later received an injection of db-cAMP (6 mg/kg, i.p.). Injections of anti-AnxA1 antiserum (αAnxA1, 200 µL, i.p.) was given 1 h before the challenge with LPS and again 1 h before db-cAMP. Numbers of neutrophils (A) and cells with distinctive apoptotic morphology (B) were evaluated 4 h later drug treatment, i.e., 8 h later LPS challenge. Representative figures of nonapoptotic (asterisk) and apoptotic (arrows) and apoptotic cells inside macrophages (arrowheads) are showed in (C) - Original magnifications ×20. The number of Annexin V+ neutrophils (D) with representative dot plots (E) was evaluated by flow cytometry 24 h after LPS injection. Results are expressed as the number of neutrophils/cavity (A), percentage of neutrophils with apoptotic morphology (B) and apoptotic neutrophils (Ly6G+/F4/80+/AnxAV+/7AAD- (D) and are shown as the mean ± SEM of at least five mice in each group. *P < 0.05, **P < 0.01 or ***P < 0.001, when compared with PBS-injected mice; #P < 0.05 when compared to LPS-challenged mice. Comparison between the groups db-cAMP and db-cAMP+αAnxA1 are highlighted in the graphics.

Figure 8. Effect of treatment with rolipram and db-cAMP on neutrophil apoptosis on wild-type and AnxA1-knockout mice. WT or AnxA-KO mice were injected with LPS (250 ng/cavity, i.pl.) and 4 h later received an injection of ROL (6 mg/kg, i.p.) or db-cAMP (4 mg/kg, i.pl.). The cells from pleural cavity were harvested and numbers of cells with distinctive apoptotic morphology were evaluated 4 h later drug treatment, i.e., 8 h later LPS challenge. Results are expressed as percentage of neutrophils with apoptotic morphology and are shown as the mean ± SEM of at least five mice in each group. *P < 0.05 or ###P < 0.01 when compared to LPS-challenged mice.

Figure 9. Effect of treatment with rolipram and db-cAMP on human neutrophil apoptosis. Neutrophils isolated from human peripheral blood (1 x 10⁶ cell per well) were cultured with LPS (500 ng/ml) for 1 h, and after with ROL (100 µM), db-cAMP (100 µM) (A, D-F) or different
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concentrations (B, C). The cells were also pre-treated with anti-AnxA1 antiserum (100 μg/mL) or WRW4 (10 μM), a specific FPR2/ALXR antagonist 1 hour before LPS (D, E, F). Sivelestat (100 μg/mL) was used as a positive control for neutrophil apoptosis (A). Neutrophils were processed for cytospin preparations for apoptosis count. Representative figures of nonapoptotic (asterisk) and apoptotic (arrows) neutrophils are show. Original magnifications ×100. **P < 0.01 or ***P <0.001 when compared LPS treated group with untreated (UT) neutrophils. *P < 0.05, **P < 0.01 and ***P < 0.001 when compared LPS treated group with drugs-treated neutrophils. The experiments were performed in biological quadruplicates.

Figure 10. Proposed mechanism by which rolipram and db-cAMP modulate AnxA1 and resolution of acute inflammation. The generation of cAMP is initiated when an extracellular first messenger binds to G protein coupled receptor (GPCR) at the plasma membrane, which is coupled to a stimulatory G protein α subunit (Gαs). The free Gαs subunit activates the enzyme adenylyl cyclase (AC) to convert ATP into cAMP. Forskolin directly activates adenylyl cyclase. Phosphodiesterases (PDEs), which degrade cAMP to 5'-AMP, are another regulator of intracellular cAMP levels. PDE inhibitors such as rolipram prevent cAMP degradation, resulting in accumulation of intracellular cAMP. Cyclic AMP can then to bind and to activate the protein kinase A (PKA), in which in turn phosphorylates CREB. P-CREB binds to the cAMP-response element (CRE) on the promoter region of AnxA1 gene and promotes transactivation. Dibutylryl cAMP (db-cAMP) is a cell-permeable cAMP analog that activates PKA. H89 and cAMPS-Rp are PKA inhibitors. Both rolipram and db-cAMP induce AnxA1 expression and its phosphorylation. Phosphorylated AnxA accumulates on the cell membrane and is externalized. Once in the extracellular medium, this protein exerts autocrine, paracrine and justacrine effects, which are mediated by the FPR2/ALXR. The peptide BOC-1 is a nonselective AnxA1 receptor antagonist. Our results shown that AnxA1 is at least one of the endogenous determinants mediating the proresolving properties of rolipram and db-cAMP.
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**Figure 1**

A. Time course of neutrophil infiltration into the pleural cavity upon LPS challenge and treatment with Rolipram or db-cAMP.

<table>
<thead>
<tr>
<th>Time after LPS (h)</th>
<th>LPS challenge</th>
<th>Injection of drugs</th>
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</tr>
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B. Summary of peak activity, time to peak, and half-maximal activity for different treatments.

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<td>20h</td>
<td>12h</td>
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C. Bar graph comparing neutrophil infiltration in PBS and Rolipram treatments.

D. Bar graph comparing neutrophil infiltration in PBS, db-cAMP, and DEXA treatments.

E. Western blot analysis of AnxA1 and β-actin expression in LPS and Rolipram treatments.

F. Western blot analysis of AnxA1 and β-actin expression in LPS and db-cAMP treatments.
**Figure 2**

A) Rolipram

B) Bar graph showing AnxA1 mRNA fold increase over Gapdh with Rolipram treatment.

C) Rolipram 10µM

D) Bar graph showing AnxA1 mRNA fold increase over Gapdh with Rolipram treatment.

E) Rolipram and Rolipram 10µM treatments.
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**Figure 3**

**A**

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<td>1000</td>
<td>µM</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>UT</td>
<td>100</td>
<td>1000</td>
<td>µM</td>
</tr>
</tbody>
</table>

**B**

<table>
<thead>
<tr>
<th>db-cAMP 100µM</th>
<th>kDa</th>
<th>UT</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>24 (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>37</td>
<td>UT</td>
<td>100</td>
<td>4</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>UT</td>
<td>100</td>
<td>4</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>P-AnxA1Ser27</td>
<td>42</td>
<td>UT</td>
<td>100</td>
<td>4</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>β-actin</td>
<td>42</td>
<td>UT</td>
<td>100</td>
<td>4</td>
<td>6</td>
<td>24</td>
</tr>
</tbody>
</table>

**C**

AnxA1/β-actin (Fold increase)

<table>
<thead>
<tr>
<th>db-cAMP</th>
<th>UT</th>
<th>10</th>
<th>100</th>
<th>1000 µM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
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**D**

Forskolin

<table>
<thead>
<tr>
<th>Rol 10</th>
<th>kDa</th>
<th>UT</th>
<th>10</th>
<th>50</th>
<th>100 µM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>37</td>
<td>UT</td>
<td>10</td>
<td>50</td>
<td>100 µM</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>UT</td>
<td>10</td>
<td>50</td>
<td>100 µM</td>
</tr>
<tr>
<td>AnxA1</td>
<td>K</td>
<td>UT</td>
<td>10</td>
<td>50</td>
<td>100 µM</td>
</tr>
<tr>
<td>β-actin</td>
<td>K</td>
<td>UT</td>
<td>10</td>
<td>50</td>
<td>100 µM</td>
</tr>
</tbody>
</table>
**Figure 4**

CAMP induces AnxA1-dependent inflammation resolution

![Diagram showing experimental setup](http://www.jbc.org/)

**A**

![Graph showing number of neutrophils](http://www.jbc.org/)

**B**

![Graph showing number of neutrophils](http://www.jbc.org/)

**C**

![Western blot analysis](http://www.jbc.org/)

**D**

![Western blot analysis](http://www.jbc.org/)
**Figure 5**

**A**

![Graph of number of neutrophils x 10^5/cavity](image)

LPS challenge

- PBS
- BOC-1

LPS 8h 250ng/cavity

- Rollipram
- db-cAMP

**B**

![Graph of number of neutrophils x 10^5/cavity](image)

Pleural wash:
- cell count
- western blot
- flow cytometry

- PBS-
- BOC-1

LPS 8h 250ng/cavity

- db-cAMP

**C**

![Western blot images of AnxA1 and Mcl-1](image)

- LPS
- Rollipram
- PBS
- BOC-1

kDa

- 37
- 33
- 33
- 37
- 42

AnxA1 (intact)
AnxA1 (cleaved)
Mcl-1
β-actin

**D**

![Western blot images of AnxA1 and Mcl-1](image)

- LPS
- db-cAMP
- PBS
- BOC-1

kDa

- 37
- 33
- 37
- 42

AnxA1 (intact)
AnxA1 (cleaved)
Mcl-1
β-actin

**E**

![Graph of % of Neutrophils with apoptotic morphology](image)

- PBS
- BOC-1
- BOC-1
- BOC-1

LPS 24h (250ng/cavity)

- Rollipram
- db-cAMP

**F**

![Graph of Number of apoptotic neutrophils (Ly6G+ F4/80- AnnexinV + 7AAD-) x 10^4/cavity](image)

- PBS
- BOC-1
- BOC-1
- BOC-1

LPS 24h (250ng/cavity)

- Rollipram
- db-cAMP

P values indicated.
**Figure 6**

**A**

Graph showing the number of neutrophils $\times 10^5$/cavity.

**B**

Bar graph showing the percentage of neutrophils with apoptotic morphology.

**C**

Western blot analysis of Mcl-1 and $\beta$-actin.

**D**

Bar graph showing the number of apoptotic neutrophils ($\text{Ly6G}^+\text{F4/80}^-\text{AnnexinV}^+\text{7AAD}^-$)/cavity.

**E**

Images showing pleural wash: cell count, western blot, and flow cytometry.
**Figure 7**

- **A**
  - Number of neutrophils per cavity
  - Graphs showing effects of LPS and db-cAMP on neutrophil counts.

- **B**
  - Percentage of neutrophils with apoptotic morphology.
  - Graphs illustrating changes with LPS and db-cAMP.

- **C**
  - Microscopy images comparing PBS, LPS, db-cAMP, and AnxA1.

- **D**
  - Number of apoptotic neutrophils (Ly6G+F4/80−AnnexinV+7AAD−) per cavity.

- **E**
  - Flow cytometry plots showing apoptotic neutrophil counts with different treatments.

*Overall, the figure demonstrates how cAMP induces AnxA1-dependent inflammation resolution.*
**Figure 8**

- LPS challenge
- Injection of drugs
- Pleural wash:
  - Cell count
  - Western blot

![Bar chart showing the percentage of neutrophils with apoptotic morphology over time after LPS challenge with and without AnxA WT and AnxA1 KO conditions](chart.png)

- **0h**: Baseline
- **4h**: LPS challenge
- **8h**: Injection of drugs

**Y-axis**: % of Neutrophils with apoptotic morphology

**X-axis**: LPS 250ng/cavity

- **-**
- **ROL**
- **db-cAMP**

**AnxA WT**

**AnxA1 KO**

Key:
- **#**
- **##**

Cell count and western blot data are also shown.
cAMP induces AnxA1-dependent inflammation resolution

Figure 9

A

% of Neutrophils with apoptotic morphology

UT - ROL db-
cAMP
LPS 6h 500 ng/mL

B

% of Neutrophils with apoptotic morphology

UT - 10 30 100 (µM)
LPS 6h 500 ng/mL

C

% of Neutrophils with apoptotic morphology

UT - 10 100 1000 (µM)
db-cAMP
LPS 6h 500 ng/mL

D

% of Neutrophils with apoptotic morphology

UT - αAnxA1 or WRW4
LPS 6h 500 ng/mL

E

% of Neutrophils with apoptotic morphology

UT - 10 µM
LPS 6h 500 ng/mL

F

% of Neutrophils with apoptotic morphology

UT - 10 µM
LPS 6h 500 ng/mL

G

UT
LPS

LPS + ROL
LPS + db-cAMP
cAMP induces AnxA1-dependent inflammation resolution

**Figure 10**

[Diagram showing the interaction between cAMP and AnxA1, involving GPCR, AC, ATP, cAMP, PDE4, Rolipram, PKA, H89, db-cAMP, P, CRE, CREB, AnxA1, Phospho-AnxA1, AnxA1 (mRNA; protein levels), Resolution of inflammation, and FPR2/ALXR.]
The resolution of acute Inflammation induced by cyclic AMP is dependent on annexin A1


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