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## How to detect eosinophil ETosis (EETosis) and extracellular traps

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### Abstract

Eosinophils are short-lived and comprise only a small population of circulating leukocytes; however, they play surprisingly multifunctional roles in homeostasis and various diseases including allergy and infection. Recent research has shed light on active cytolytic eosinophil cell death that releases eosinophil extracellular traps (EETs) and total cellular contents, namely eosinophil extracellular trap cell death (EETosis). The pathological contribution of EETosis was made more cogent by recent findings that a classical pathological finding of eosinophilic inflammation, that of Charcot-Leyden crystals, is closely associated with EETosis. Currently no gold standard methods to identify EETosis exist, but “an active eosinophil lysis that releases cell-free granules and net-like chromatin structure” appears to be a common feature of EETosis. In this review, we describe several approaches that visualize EETs/EETosis in clinical samples and *in vitro* studies using isolated human eosinophils. EETs/EETosis can be observed using simple chemical or fluorescence staining, immunostaining, and electron microscopy, although it is noteworthy that visualization of EETs is greatly changed by sample preparation including the extracellular space of EETotic cells and shear flow. Considering the multiple aspects of biological significance, further study into EETs/EETosis is warranted to give a detailed understanding of the roles played in homeostasis and disease pathogenesis.

### Keywords

Charcot-leyden crystal; EETosis; EETs; Eosinophil; NETs

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.alit.2020.10.002>.

## Introduction

The life of a multicellular organism is made up of a series of individual cellular lives. Eosinophils are short-lived and comprise only a small part of the body; however, they are surprisingly multifunctional leukocytes that are involved in homeostasis and various diseases including allergy and infection.<sup>1</sup> Because bone marrow-derived eosinophils are terminally differentiated, their contributions to individual biological reactions largely depend on production, longevity, accumulation, and activation status (Fig. 1). The expression of various receptors on the eosinophil surface allows these cells to sense and rapidly respond to the microenvironment. Another aspect that makes eosinophils special is their secretory function, by which they release their intracellular contents. Acidic eosin-stained granules (approximately 200/cell) contain four main granule proteins, major basic protein (MBP), eosinophil peroxidase, eosinophil cationic protein, and eosinophil-derived neurotoxin, which exhibit various activities, including cytotoxic activity and activation of inflammatory cells.<sup>2</sup> Eosinophils are also capable of releasing various bioactive substances, including cytokines, growth factors, and lipid mediators that determine the role of eosinophils.

It has been considered that the prolonged survival of eosinophils may contribute to the exacerbation of allergic inflammation. Indeed, eosinophilopoietic cytokines such as GM-CSF and IL-5 markedly prolong the viability of isolated blood eosinophils *in vitro*. Conversely, cytolysis of eosinophils that generate extracellular free granules has been observed in inflamed tissues for more than 100 years.<sup>3</sup> This paradoxical phenomenon of *in vitro* and *in vivo* observations can be explained by active non-apoptotic cell death. Recent research has shed light on active cytolytic eosinophil cell death that releases eosinophil extracellular traps (EETs) and total cellular contents, namely eosinophil extracellular trap cell death (EETosis).<sup>4</sup>

To date, the presence of EETosis has been reported in allergic bronchopulmonary aspergillosis (ABPA),<sup>5–7</sup> eosinophilic chronic rhinosinusitis (chronic rhinosinusitis with nasal polyps),<sup>8–10</sup> eosinophilic otitis media,<sup>9,11,12</sup> sialodochitis fibrinosa,<sup>13</sup> hypereosinophilic syndrome,<sup>4,14</sup> chronic obstructive pulmonary diseases,<sup>15</sup> and eosinophilic granulomatosis with polyangitis (EGPA) (Fukuchi and Kamide *et al.* manuscript in submission). The pathological contribution of EETosis was made more cogent by recent findings that a classical pathological finding of eosinophilic inflammation, Charcot-Leyden crystal (CLC) formation, is closely associated with EETosis.<sup>8,16,17</sup> In this review, we describe how to visualize EETosis and EETs in experimental studies using isolated human eosinophils and biopsy tissue samples.

## Characteristics of EETosis

In 2004, the release of DNA fibers upon cell activation was first reported in neutrophils and termed neutrophil extracellular traps (NETs).<sup>18</sup> In addition to pathogen trapping, NETs contribute to the elimination of pathogens by cytotoxic histones and granular proteins in a phagocytosis-independent manner. Later, the same group proposed a novel programmed neutrophil cell death (i.e. NETosis) that releases NETs.<sup>19</sup> The rapid (0.5–3 h) cell disintegration was quite different from known cell deaths including apoptosis and

necrosis, and was dependent on extracellular serum concentrations. The progression of this response involves a NADPH oxidase-dependent mechanism of ROS production. NETosis does not cause DNA fragmentation as in apoptosis, but instead releases NETs following disruption of the plasma membrane and nuclear envelope. Similar DNA-based fibers and cell death have been reported in other inflammatory cells, and are sometimes collectively termed extracellular traps (ETs) and ETosis.<sup>20,21</sup> Cytolytic ETosis is considered to be an innate immune function as the first line of defense against nonphagocytosable organisms. Some bacterial nucleases are thought to have acquired resistance to ETs by their hosts. Loss of regulation of ETosis has been shown to lead to various pathological conditions.

Based on similar characteristics in terms of ET release and ROS-mediated cytolysis, EETosis has been established<sup>4,22</sup> (Fig. 2A). Despite similar NADPH-oxidase dependent processes, morphological changes in the nucleus and plasma/nuclear membrane rupture, neutrophils and eosinophils have differences in the structures of granules and ETs. When neutrophils undergo NETosis, the granules disintegrate intracellularly and thus granule proteins adhere to the NETs. Conversely, in eosinophils, most of the granules are intact during the process of EETosis, resulting in the generation of free extracellular granules and granule protein-free EETs (Fig. 2B, C).<sup>4,23</sup> Both NETs and EETs retain histones (i.e. chromatin structure), although EETs are thicker in diameter than NETs because of less extensive protease modification of chromatin<sup>9</sup>. During the process of EETosis, extracellular vesicles (EVs) are produced from plasma membrane protrusions.<sup>4,8</sup> Recently, the presence of similar EVs shedding from the plasma membrane has been recognized in NETosis.<sup>24</sup>

Several studies have reported ET formation from immune cells,<sup>19,25</sup> although there are discussions surrounding the definition of ETosis, NETosis or EETosis.<sup>26</sup> Unlike cytolytic release of net-like chromatin structures, several groups have reported ET production from live cell nuclei. Mitochondria-derived ETs from living cells were also reported,<sup>27,28</sup> although questions have been raised as to whether large amounts of ETs can be formed from the small amount of mitochondrial DNA present in cells.<sup>29–32</sup> Our nearly 10 years of research experience has consistently indicated that NETs/EETs are nuclear-derived chromatin fibers accompanied by cell death. Regarding eosinophils, different terms including primary lysis, cytolysis, and lytic degranulation have been used for cell death releasing free granules.<sup>33–35</sup> Although currently no gold standard methods to identify EETosis exist, “an active eosinophil lysis that releases cell-free granules and net-like chromatin structure” appears to be a common and critical feature of EETosis that expands the eosinophil function even beyond their life span.<sup>4,9,22</sup>

### ***In vitro* EETosis inducers**

Various microorganisms, pathogen-associated molecular patterns, damage-associated molecular patterns and chemical substances are known to induce NETosis *in vitro*<sup>32</sup>; however known inducers of EETosis are limited. Because eosinophils isolated from IL-5 transgenic mice showed much lower capacities to undergo EETosis (Ueki *et al.* unpublished data), we have studied human eosinophils isolated from peripheral blood. Selected references that demonstrated stimuli-induced human eosinophil cell death are summarized in Table 1. Early studies have shown the occurrence of cytolysis by stimulation

with calcium ionophore (A23187) and IgG/IgA coated beads,<sup>36,37</sup> and these stimuli have also been revealed as typical inducers of EETosis.<sup>4</sup> In response to phorbol myristate acetate (PMA) and A23187, eosinophils undergo typical EETosis within 30–180 min, indicating the importance of protein kinase C activation and increased intracellular calcium concentration. Immobilized IgG,<sup>4,8</sup> sputum-derived IgG autoantibodies,<sup>30,38</sup> anti-neutrophil cytoplasmic antibody,<sup>39</sup> and immobilized IgA<sup>4</sup> mediate EETosis, likely through FcR cross-linking. Eosinophil “pro-survival factors” IL-5 and GM-CSF paradoxically induce EETosis when co-stimulated with platelet activating factor.<sup>4,8</sup>

Stimuli-induced intracellular calcium concentrations and production of ROS are often necessary to promote ETosis. NADPH oxidase inhibitors such as diphenyleneiodonium chloride inhibit ETosis, as can ROS consuming catalase in culture medium.<sup>4,19</sup> Similarly, presence of red blood cells, serum, or albumin can inhibit EETosis, likely through their capacity to scavenge ROS.<sup>4</sup> However, diverse stimuli utilize different signaling pathways for ETosis.<sup>40</sup> *Aspergillus fumigatus* induces EETosis through a CD11b-dependent, but NADPH-independent mechanism.<sup>5</sup> A recent study indicated that lysophosphatidylserine induces ROS-independent, but peptidylarginine deiminase 4 (PAD4)-dependent EETosis.<sup>41</sup>

As described above, cell culture conditions, especially serum or albumin concentration, could affect the ETosis process, and so must be taken into account when studying ETosis.<sup>42</sup> Fetal calf serum (FCS) used in cell culture (5–10%) may affect the observation of ETs, because FCS (and albumin) induce dissociation of aggregated EETs<sup>9</sup> and FCS contains a heat-stable nuclease capable of dissolving ETs.<sup>43</sup> It should be noted that loss of DNase activity can lead to autoimmune diseases and thrombosis.<sup>44,45</sup> These findings may indicate multiple protective mechanisms to prevent excessive cell death in the blood and limit circulating immunogenic intracellular contents.<sup>4,46</sup> For *in vitro* study of EETosis or NETosis induction, we often use a HEPES-buffered RPMI 1640 medium containing low concentrations (0.1%–0.3%) of bovine serum albumin.

Several studies have demonstrated nonapoptotic eosinophil death. Co-stimulation of immobilized intravenous immunoglobulin with inactivated complement 3b was reported to induce eosinophil cytolysis (necroptosis) and release of “DNA clouds”.<sup>47,48</sup> Eosinophil cell death can be induced by stimulation with immobilized plasma proteins,<sup>23</sup> glass adhesion and coagulation,<sup>49</sup> or exposure to *Staphylococcus aureus* supernatant.<sup>50</sup> In the presence of IL-5, crosslinking of the eosinophil surface receptor, Siglec-8, induces ROS-dependent cell death, which is distinct from EETosis.<sup>51</sup> In a study using a mouse model, it was shown that necrotic liver cells induce eosinophils to undergo caspase-1-mediated pyroptosis.<sup>52</sup>

## Detecting net-like DNA

To induce EETosis *in vitro*, an adhesion process is required to induce EETosis, therefore flow cytometry is not the best option for the study of this event. Adherent cells in clear-bottomed culture plates or chamber slides may be observed using microscopy. Simple bright field imaging or time-lapse live cell study using differential interference contrast or phase contrast microscopy can be used to assess the morphological changes during EETosis, such as loss of nuclear lobulation and membrane disintegration.<sup>4</sup> Chemical stains, such

as Diff-quick and May-Giemsa stains, clearly visualize intact eosinophilic granules and released basophilic nuclear contents (Fig. 2B). Apoptotic cells can be differentiated by typical morphologies of nuclear and cytoplasmic condensation, whereas EETotic cells show disintegration of the cell membrane and release of free granules.<sup>2</sup>

With the sticky and spreadable nature of EETs, they are usually observed as aggregated net-like structures. *In vitro* cell death can be easily observed by cell-impermeable DNA dyes such as SYTOX staining. SYTOX stains the membrane-compromised nucleus of dead cells but not live cells, thus the fluorescence intensity allows the quantification of cell death in plate-based experiments.<sup>4</sup> DNA dyes are commonly used for detection of filamentous EETs, although it is difficult to distinguish EETosis from apoptosis or necrosis in static culture conditions using DNA staining (Fig. 3A). To visualize EETs, we utilize a simple experiment using shear stress.<sup>9,53,54</sup> After induction of EETosis in the SYTOX-containing culture medium using a clear-bottomed 96 well culture plate, the plate was shaken on a plate shaker (relatively hard, at 1000 rpm with sealing). This experimentally mimics the shear stress that EETotic cells might be subjected to *in vivo* (for instance, during coughing and breathing in the airway lumen). This shaking experiment enables the visualization of EETs as aggregated large EETs using an inverted fluorescence microscope (Fig. 3B). The aggregated EETs can be observed without fluorescence dye, using bright field image (Supplementary Materials, Supplementary Video 1). Apoptotic and necrotic eosinophils can be distinguished by the absence of EET formation.

Supplementary video related to this article can be found at <https://doi.org/10.1016/j.alit.2020.10.002>.

One of the most important features of EETs, the trapping capacity, can be studied using bacteria-sized microbeads. Our simple assay allows visualization and quantification of EET trapping *in vitro*.<sup>9</sup> After EETosis induction, fluorescent microbeads are added to the culture medium followed by plate shaking. Because of the hydrophobic interaction between beads and EETs, EETs preferentially bind to the hydrophobic beads to form large aggregates (Fig. 3C). Unbound free beads in the medium can be semi-quantified using fluorescence intensity on a microplate reader. The ultrastructure of EETs can be observed using scanning electron microscopy (SEM).<sup>9</sup> SEM offers detailed 3D structures of *in vitro* EETs, indicating that approximately 30 nm chromatin threads intertwine to form large EET aggregates. With their “sticky” nature, EETs can entrap hydrophobic beads (Fig. 3E), microorganisms (Fig. 3D), and cell debris including free granules<sup>9</sup> (Fig. 2C). These experiments indicate that EETs provide large adhesive surfaces to disturb pathogen dissemination by entangling the pathogen and eosinophil-derived toxic proteins. *In vivo*, aggregated EETs in eosinophilic exudate such as eosinophilic mucin from patients with eosinophilic chronic rhinosinusitis is often observed as clusters of eosinophils in hematoxylin and eosin (H&E) staining. Confocal microscopy of DNA staining and Z-stack reconstruction may help to assess the entire 3D structure of EETs (Fig. 4).

## Detecting histone-bearing chromatin threads

Histones bind nuclear DNA and form nucleosomes, which are the smallest constituent units of chromatin fibers. Histones are a major component of ETs and extracellular histones are known to have pleiotropic effects on the microenvironment including bacterial killing and sterile inflammation.<sup>55</sup> Because histones are not present in mitochondria, it is possible to distinguish between mitochondria-derived EETs and nuclear-derived EETs from EETotic eosinophils. When fixed, non-permeabilized intact eosinophils are immunostained using an anti-histone antibody and fluorescence DNA dye; the antibody does not penetrate the preserved plasma membrane and nuclear envelope (Fig. 5A). Once the plasma and nuclear membrane are compromised, the antibody reaches the histones to stain the lytic cells and EETs (Fig. 5B). In our experience, EETs are always brightly stained with histone antibodies, likely because of conserved chromatin structures.<sup>4,5,9,11</sup> Unlike EETosis cells in static conditions (Fig. 2A), several washing steps in the immunostaining procedure induce spreading and aggregation of EETs (Fig. 5B). However, it should be noted that EETs can be mistaken as being released from intact cells because of adherence to neighboring cells, as shown in Figure 5B (arrows).

Extracellular histone staining is also useful in clinical samples. Smear specimens of exudative secretion might be good examples because net-like EETs are easily obtained in smear samples compared with sections. An example of histone staining of a bronchial secretion smear obtained from a patient with ABPA is shown in Figure 5C. Thick smear samples may be visualized in a 3D reconstructed Z-stack confocal image (Fig. 5D).<sup>6,11</sup> EETs in tissue could be observed by microscopy, although the limited extracellular space (in solid tissue, for instance) makes it difficult to study their detailed structure.<sup>22,56</sup> In fluid form (e.g., culture medium, bloodstream, exudate, and secretion), net-like EETs are relatively easy to observe.<sup>13,22,57,58</sup>

Activation of PAD4, a histone citrullinating enzyme, is thought to promote relaxing of the chromatin structure.<sup>59,60</sup> Neutrophils from PAD4-knockout mice cannot form NETs after stimulation with chemokines or bacteria.<sup>61</sup> However, there are several conflicting studies of human NETosis indicating that histone citrullination is stimuli dependent and not essential for NETs formation.<sup>40</sup> In human eosinophils, our study revealed that histone citrullination was also observed during apoptosis, although EETosis was dependent on PAD4 activation and net-like citrullinated histone H3 was specific for EETosis (Fukuchi and Kamide *et al.* manuscript in submission). Histone hyper-citrullination was not observed in isolated fresh eosinophils or following brief stimulation with PMA that can induce EETosis (Fig. 6A). Conversely, chromatin from EETotic cells were immunoreactive against anti-citrullinated histone H3 antibody (Fig. 6B). To detect EETosis in clinical samples, we utilized immunostaining for citrullinated histone H3 in combination with H&E staining. As shown in Figure 6C, D, lytic eosinophils (or free granules) with chromatolytic nuclei in H&E staining and citrullinated histone H3-positive net-like DNA in immunostaining can be observed in identical fields of the same sample.<sup>5</sup> Eosinophils with intact nuclei are not stained for citrullinated histone H3.



## Detection of cytolytic degranulation

The term “cytolytic degranulation” has been used for the rupture of eosinophils resulting in release of intact extracellular granules assessed by conventional chemical staining or electron microscopy. Transmission electron microscopy (TEM) of human blood eosinophils indicates nuclear heterochromatin and granules with an electron-dense crystalline core and electron-lucent matrix (Fig. 7A). The ultrastructure of exocytosis and piecemeal degranulation show emptying of granule contents or lucent areas within their granule core in intact eosinophils.<sup>62</sup> Conversely, EETosis is characterized by round nuclei with chromatolysis or dissolution of the nuclear and plasma membranes, together with EETs and cell-free intact granules (Fig. 7B).<sup>62,63</sup> TEM also allows direct assessment of identification of cytolytic eosinophils from clinical samples<sup>4,8,10</sup> (Fig. 7C). The disadvantages of electron microscopy might include the cost, small field, and ultrathin section of the samples, in addition to a complex procedure of specimen preparation and observation.

CLCs are slender bipyramidal hexagonal crystals found in eosinophilic diseases.<sup>16</sup> Galectin-10, a constituent protein of CLCs, is thought to comprise 10% of the non-granule fraction.<sup>64</sup> By proteomic analysis of peripheral eosinophils, galectin-10 was shown to be the fifth most common protein among the constituent proteins.<sup>65</sup> A recent study revealed a close relationship between EETosis and the formation of CLCs. Galectin-10 was distributed in the peripheral cytoplasm of eosinophils, but during the process of ETosis, galectin-10 becomes redistributed homogeneously in the cytoplasm and CLCs are occasionally formed in the cytoplasm.<sup>10</sup> These dynamic changes proceed in a short period of time, within 30–60 min. Subsequently, intracellular CLCs, granules, and EETs are released extracellularly by membrane disintegration. Extracellular crystallization of galectin-10 is assumed to occur if eosinophil density and cytolysis are high enough to increase the local concentration of free galectin-10.<sup>8</sup> Under TEM of tissue samples from eosinophilic diseases, CLCs are usually found as electron dense crystals in close proximity to free granules<sup>8,17</sup> (Fig. 7D).

Double immunostaining for eosinophil granule protein MBP and galectin-10 offers a difference between cytolytic and intact eosinophils. MBP is present in the core of specific granules and is the eighth most common eosinophil constituent protein according to a proteomics study.<sup>65</sup> Peripheral blood eosinophils immunostained for galectin-10 and MBP indicates cytoplasmic galectin-10 and granular MBP (Fig. 8A). Conversely, because of free intact granules and loss of cytoplasmic galectin-10, EETotic cells were positive for MBP, but not for galectin-10 (Fig. 8B). Occasionally, galectin-10-stained CLCs can be observed associated with EETotic cells (Fig. 8B, arrows). Even after the originating cells are lysed, galectin-10 was enriched in EVs produced from the plasma membrane protrusion of EETotic cells.<sup>8</sup>

Immunostaining of tissues from eosinophilic diseases also showed cytoplasmic galectin-10 staining in intact eosinophils but loss of galectin-10 in lytic cells (Fig. 8C). Released extracellular free galectin-10 diffuses in the tissue, whereas CLCs (Fig. 8D, arrows), released EVs, free granules, and MBP become deposited in the extracellular space.<sup>8</sup> EVs from ETosis might remain in the tissue likely because of loss of find-me signal on

their surface.<sup>4,8</sup> As shown in Fig. 8B and D, EETs are not co-localized with MBP and galectin-10.

## Conclusions

For decades, eosinophil cell death has been observed in inflamed tissue, although it has erroneously been neglected in many cases. Recent studies indicate that the activation of eosinophils releases intracellular contents not only by means of secretion, but also by the radical means of EETosis. Aggregated EETs,<sup>7,9</sup> crystallization of galectin-10 (CLCs),<sup>66</sup> and eosinophil granule protein<sup>67</sup> have been shown to increase airway mucus viscosities. The impact of EETosis on the microenvironment is not largely understood.

To date, several eosinophilic disorders have been shown to be associated with EETosis. From our experience, EETosis is not a disease-specific phenomenon, therefore its extent and tissue specificity appear to be important for disease progression. The presence of CLCs is associated with disease severity in patients with eosinophilic chronic rhinosinusitis<sup>8,66</sup> and free granules in sputum could be a useful marker of activity in asthma.<sup>68–70</sup> Clinically available markers to monitor EETosis might be of benefit for indication of eosinophil-targeting therapeutic modality including anti-IL-5 treatment and also provide a detailed understanding of disease pathogenesis.

In addition to apoptosis and EETosis, necrosis, pyroptosis, necroptosis, or other types of eosinophil fate might differentially contribute to homeostasis and disease. Future studies might provide a more comprehensive classification of cell death. However, we believe that the newly recognized “active eosinophil lysis that releases cell-free granules and net-like chromatin structure” should be properly studied from the multiple aspects of its biological significance.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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## Conflict of interest

MF received grant support from GlaxoSmithKline (GSK); SU received honoraria for lectures from AstraZeneca (AZ), GSK and grant support from AZ, Novartis, and Maruho. The rest of the authors have no conflict of interest.

## Abbreviations:

**EETosis** eosinophil extracellular trap cell death



<b>ETs</b>	extracellular traps
<b>NETs</b>	neutrophil ETs
<b>EETs</b>	eosinophil ETs
<b>PMA</b>	phorbol 12-myristate 13-acetate
<b>CLCs</b>	Charcot Leyden crystals
<b>CitH3</b>	citrullinated histone H3
<b>MBP</b>	major basic protein
<b>PAD4</b>	peptidylarginine deiminase 4
<b>ROS</b>	reactive oxygen species
<b>EM</b>	electron microscopy
<b>TEM</b>	transmission electron microscopy
<b>SEM</b>	scanning electron microscopy
<b>FEGs</b>	free eosinophil granules

## References

1. Weller PF, Spencer LA. Functions of tissue-resident eosinophils. *Nat Rev Immunol* 2017;17:746–60. [PubMed: 28891557]
2. Nagase H, Ueki S, Fujieda S. The roles of IL-5 and anti-IL-5 treatment in eosinophilic diseases: asthma, eosinophilic granulomatosis with polyangiitis, and eosinophilic chronic rhinosinusitis. *Allergol Int* 2020;69:178–86. [PubMed: 32139163]
3. Persson CG, Erjefalt JS. Eosinophil lysis and free granules: an in vivo paradigm for cell activation and drug development. *Trends Pharmacol Sci* 1997;18: 117–23. [PubMed: 9149540]
4. Ueki S, Melo RC, Ghiran I, Spencer LA, Dvorak AM, Weller PF. Eosinophil extracellular DNA trap cell death mediates lytic release of free secretion-competent eosinophil granules in humans. *Blood* 2013;121:2074–83. [PubMed: 23303825]
5. Muniz VS, Silva JC, Braga YAV, Melo RCN, Ueki S, Takeda M, et al. Eosinophils release extracellular DNA traps in response to *Aspergillus fumigatus*. *J Allergy Clin Immunol* 2018;141:571–85. e7. [PubMed: 28943470]
6. Omokawa A, Ueki S, Kikuchi Y, Takeda M, Asano K, Sato K, et al. Mucus plugging in allergic bronchopulmonary aspergillosis: implication of the eosinophil DNA traps. *Allergol Int* 2018;67:280–2. [PubMed: 28886913]
7. Ueki S, Hebisawa A, Kitani M, Asano K, Neves JS. Allergic bronchopulmonary aspergillosis—a luminal hypereosinophilic disease with extracellular trap cell death. *Front Immunol* 2018;9:2346. [PubMed: 30364279]
8. Ueki S, Tokunaga T, Melo RCN, Saito H, Honda K, Fukuchi M, et al. Charcot-Leyden crystal formation is closely associated with eosinophil extracellular trap cell death. *Blood* 2018;132:2183–7. [PubMed: 30154112]
9. Ueki S, Konno Y, Takeda M, Moritoki Y, Hirokawa M, Matsuwaki Y, et al. Eosinophil extracellular trap cell death-derived DNA traps: their presence in secretions and functional attributes. *J Allergy Clin Immunol* 2016;137:258–67. [PubMed: 26070883]

10. Melo RCN, Wang H, Silva TP, Imoto Y, Fujieda S, Fukuchi M, et al. Galectin-10, the protein that forms Charcot-Leyden crystals, is not stored in granules but resides in the peripheral cytoplasm of human eosinophils. *J Leukoc Biol* 2020;108:139–49. [PubMed: 32108369]
11. Ohta N, Ueki S, Konno Y, Hirokawa M, Kubota T, Tomioka-Matsutani S, et al. ETosis-derived DNA trap production in middle ear effusion is a common feature of eosinophilic otitis media. *Allergol Int* 2018;67:414–6. [PubMed: 29242145]
12. Ueki S, Ohta N, Takeda M, Konno Y, Hirokawa M. Eosinophilic otitis media: the aftermath of eosinophil extracellular trap cell death. *Curr Allergy Asthma Rep* 2017;17:33. [PubMed: 28455742]
13. Kawamura Y, Ikeda R, Hori T, Sasaki T, Miyabe Y, Fukuchi M, et al. Sialodochitis fibrinosa: salivary duct obstruction by eosinophil extracellular traps? *Oral Dis* 2020;26:1459–63. [PubMed: 32436360]
14. Takeda M, Ueki S, Yamamoto Y, Nara M, Fukuchi M, Nakayama K, et al. Hypereosinophilic syndrome with abundant Charcot-Leyden crystals in spleen and lymph nodes. *Asia Pac Allergy* 2020;10:e24. [PubMed: 32789109]
15. Uribe Echevarria L, Leimgruber C, Garcia Gonzalez J, Nevado A, Alvarez R, Garcia LN, et al. Evidence of eosinophil extracellular trap cell death in COPD: does it represent the trigger that switches on the disease? *Int J Chron Obstruct Pulmon Dis* 2017;12:885–96. [PubMed: 28352169]
16. Ueki S, Miyabe Y, Yamamoto Y, Fukuchi M, Hirokawa M, Spencer LA, et al. Charcot-Leyden crystals in eosinophilic inflammation: active cytolysis leads to crystal formation. *Curr Allergy Asthma Rep* 2019;19:35. [PubMed: 31203469]
17. Hamada S, Ueki S, Miyabe Y, Tsukino M, Hirai T. Focal eosinophilic myositis with Charcot-Leyden crystal formation. *Allergol Int* 2020;69:633–5. [PubMed: 32273188]
18. Brinkmann V, Reichard U, Goosmann C, Fauler B, Uhlemann Y, Weiss DS, et al. Neutrophil extracellular traps kill bacteria. *Science* 2004;303:1532–5. [PubMed: 15001782]
19. Fuchs TA, Abed U, Goosmann C, Hurwitz R, Schulze I, Wahn V, et al. Novel cell death program leads to neutrophil extracellular traps. *J Cell Biol* 2007;176: 231–41.
20. Wartha F, Henriques-Normark B. ETosis: a novel cell death pathway. *Sci Signal* 2008;1:pe25.
21. Guimaraes-Costa AB, Nascimento MT, Wardini AB, Pinto-da-Silva LH, Saraiva EM. ETosis: a microbicidal mechanism beyond cell death. *J Parasitol Res* 2012;2012:929743. [PubMed: 22536481]
22. Ueki S, Tokunaga T, Fujieda S, Honda K, Hirokawa M, Spencer LA, et al. Eosinophil ETosis and DNA traps: a new look at eosinophilic inflammation. *Curr Allergy Asthma Rep* 2016;16:54. [PubMed: 27393701]
23. Neves JS, Perez SA, Spencer LA, Melo RC, Reynolds L, Ghiran I, et al. Eosinophil granules function extracellularly as receptor-mediated secretory organelles. *Proc Natl Acad Sci U S A* 2008;105:18478–83. [PubMed: 19017810]
24. Thiam HR, Wong SL, Qiu R, Kittisopikul M, Vahabikashi A, Goldman AE, et al. NETosis proceeds by cytoskeleton and endomembrane disassembly and PAD4-mediated chromatin decondensation and nuclear envelope rupture. *Proc Natl Acad Sci U S A* 2020;117:7326–37. [PubMed: 32170015]
25. von Köckritz-Blickwede M, Goldmann O, Thulin P, Heinemann K, Norrby-Teglund A, Rohde M, et al. Phagocytosis-independent antimicrobial activity of mast cells by means of extracellular trap formation. *Blood* 2008;111:3070–80. [PubMed: 18182576]
26. Boeltz S, Amini P, Anders HJ, Andrade F, Bilyy R, Chatfield S, et al. To NET or not to NET: current opinions and state of the science regarding the formation of neutrophil extracellular traps. *Cell Death Differ* 2019;26:395–408. [PubMed: 30622307]
27. Yousefi S, Stojkov D, Germic N, Simon D, Wang X, Benarafa C, et al. Untangling “NETosis” from NETs. *Eur J Immunol* 2019;49:221–7. [PubMed: 30629284]
28. Yousefi S, Gold JA, Andina N, Lee JJ, Kelly AM, Kozłowski E, et al. Catapult-like release of mitochondrial DNA by eosinophils contributes to antibacterial defense. *Nat Med* 2008;14:949–53. [PubMed: 18690244]

29. Remijsen Q, Kuijpers TW, Wirawan E, Lippens S, Vandenabeele P, Vanden Berghe T. Dying for a cause: NETosis, mechanisms behind an antimicrobial cell death modality. *Cel Death Differ* 2011;18:581–8.
30. Mukherjee M, Lacy P, Ueki S. Eosinophil extracellular traps and inflammatory pathologies-untangling the Web! *Front Immunol* 2018;9:2763. [PubMed: 30534130]
31. Persson C, Ueki S. Lytic eosinophils produce extracellular DNA traps as well as free eosinophil granules. *J Allergy Clin Immunol* 2018;141:1164.
32. Brinkmann V. Neutrophil extracellular traps in the second decade. *J Innate Immun* 2018;10:414–21. [PubMed: 29909412]
33. Cheng JF, Ott NL, Peterson EA, George TJ, Hukee MJ, Gleich GJ, et al. Dermal eosinophils in atopic dermatitis undergo cytolytic degeneration. *J Allergy Clin Immunol* 1997;99:683–92. [PubMed: 9155836]
34. Esnault S, Leet JP, Johansson MW, Barretto KT, Fichtinger PS, Fogerty FJ, et al. Eosinophil cytolysis on Immunoglobulin G is associated with microtubule formation and suppression of rho-associated protein kinase signalling. *Clin Exp Allergy* 2020;50:198–212. [PubMed: 31750580]
35. Persson C Role of primary necrosis/lysis of submucosal eosinophils in obese individuals with asthma. *Am J Respir Crit Care Med* 2013;188:1468.
36. Fukuda T, Ackerman SJ, Reed CE, Peters MS, Dunnette SL, Gleich GJ. Calcium ionophore A23187 calcium-dependent cytolytic degranulation in human eosinophils. *J Immunol* 1985;135:1349–56. [PubMed: 3925008]
37. Weiler CR, Kita H, Hukee M, Gleich GJ. Eosinophil viability during immunoglobulin-induced degranulation. *J Leukoc Biol* 1996;60:493–501. [PubMed: 8864134]
38. Mukherjee M, Bulir DC, Radford K, Kjarsgaard M, Huang CM, Jacobsen EA, et al. Sputum autoantibodies in patients with severe eosinophilic asthma. *J Allergy Clin Immunol* 2018;141:1269–79. [PubMed: 28751233]
39. Mukherjee M, Thomas SR, Radford K, Dvorkin-Gheva A, Davydchenko S, Kjarsgaard M, et al. Sputum antineutrophil cytoplasmic antibodies in serum antineutrophil cytoplasmic antibody-negative eosinophilic granulomatosis with polyangiitis. *Am J Respir Crit Care Med* 2019;199:158–70. [PubMed: 30179583]
40. Kenny EF, Herzig A, Krüger R, Muth A, Mondal S, Thompson PR, et al. Diverse stimuli engage different neutrophil extracellular trap pathways. *Elife* 2017;6:e24437. [PubMed: 28574339]
41. Kim HJ, Sim MS, Lee DH, Kim C, Choi Y, Park HS, et al. Lysophosphatidylserine induces eosinophil extracellular trap formation and degranulation: implications in severe asthma. *Allergy* 2020. 10.1111/all.14450.
42. Neubert E, Senger-Sander SN, Manzke VS, Busse J, Polo E, Scheidmann SEF, et al. Serum and serum albumin inhibit in vitro formation of neutrophil extracellular traps (NETs). *Front Immunol* 2019;10:12. [PubMed: 30733715]
43. von Köckritz-Blickwede M, Chow OA, Nizet V. Fetal calf serum contains heat-stable nucleases that degrade neutrophil extracellular traps. *Blood* 2009;114: 5245–6. [PubMed: 20007813]
44. Keyel PA. DNases in health and disease. *Dev Biol* 2017;429:1–11. [PubMed: 28666955]
45. Jiménez-Alcázar M, Rangaswamy C, Panda R, Bitterling J, Simsek YJ, Long AT, et al. Host DNases prevent vascular occlusion by neutrophil extracellular traps. *Science* 2017;358:1202–6. [PubMed: 29191910]
46. Malm-Erjefält M, Greiff L, Ankerst J, Andersson M, Wallengren J, Cardell LO, et al. Circulating eosinophils in asthma, allergic rhinitis, and atopic dermatitis lack morphological signs of degranulation. *Clin Exp Allergy* 2005;35:1334–40. [PubMed: 16238793]
47. Radonjic-Hoesli S, Wang X, de Graauw E, Stoeckle C, Styp-Rekowska B, Hlushchuk R, et al. Adhesion-induced eosinophil cytolysis requires the receptor-interacting protein kinase 3 (RIPK3)-mixed lineage kinase-like (MLKL) signaling pathway, which is counterregulated by autophagy. *J Allergy Clin Immunol* 2017;140:1632–42. [PubMed: 28412393]
48. Yousefi S, Simon HU. NETosis - does it really represent nature's "Suicide Bomber"? *Front Immunol* 2016;7:328. [PubMed: 27617015]

49. Muniz-Junqueira MI, Barbosa-Marques SM, Junqueira LF Jr. Morphological changes in eosinophils are reliable markers of the severity of an acute asthma exacerbation in children. *Allergy* 2013;68:911–20. [PubMed: 23745834]
50. Prince LR, Graham KJ, Connolly J, Anwar S, Ridley R, Sabroe I, et al. Staphylococcus aureus induces eosinophil cell death mediated by  $\alpha$ -hemolysin. *PLoS One* 2012;7:e31506. [PubMed: 22355374]
51. Kano G, Almanan M, Bochner BS, Zimmermann N. Mechanism of Siglec-8-mediated cell death in IL-5-activated eosinophils: role for reactive oxygen species-enhanced MEK/ERK activation. *J Allergy Clin Immunol* 2013;132:437–45. [PubMed: 23684072]
52. Palacios-Macapagal D, Connor J, Mustelin T, Ramalingam TR, Wynn TA, Davidson TS. Cutting edge: eosinophils undergo caspase-1-mediated pyroptosis in response to necrotic liver cells. *J Immunol* 2017;199:847–53. [PubMed: 28652398]
53. Yamauchi Y, Ueki S, Konno Y, Ito W, Takeda M, Nakamura Y, et al. The effect of hepatocyte growth factor on secretory functions in human eosinophils. *Cytokine* 2016;88:45–50. [PubMed: 27552115]
54. Fukuchi M, Ueki S, Saito H, Miyabe Y, Konno Y, Omokawa A, et al. Comparison of CD16-negative selection vs. MACSxpress system for isolation of blood eosinophils. *Allergol Int* 2019;68:S11–3.
55. Sollberger G, Tilley DO, Zychlinsky A. Neutrophil extracellular traps: the biology of chromatin externalization. *Dev Cel* 2018;44:542–53.
56. Brehmer-Andersson E, Kaaman T, Skog E, Frithz A. The histopathogenesis of the flame figure in Wells' syndrome based on five cases. *Acta Derm Venereol* 1986;66:213–9. [PubMed: 2426897]
57. McDonald B, Urrutia R, Yipp BG, Jenne CN, Kubes P. Intravascular neutrophil extracellular traps capture bacteria from the bloodstream during sepsis. *Cell Host Microbe* 2012;12:324–33. [PubMed: 22980329]
58. Brinkmann V, Zychlinsky A. Beneficial suicide: why neutrophils die to make NETs. *Nat Rev Microbiol* 2007;5:577–82. [PubMed: 17632569]
59. Rohrbach AS, Slade DJ, Thompson PR, Mowen KA. Activation of PAD4 in NET formation. *Front Immunol* 2012;3:360. [PubMed: 23264775]
60. Wang Y, Li M, Stadler S, Correll S, Li P, Wang D, et al. Histone hyper-citrullination mediates chromatin decondensation and neutrophil extracellular trap formation. *J Cel Biol* 2009;184:205–13.
61. Li P, Li M, Lindberg MR, Kennett MJ, Xiong N, Wang Y. PAD4 is essential for antibacterial innate immunity mediated by neutrophil extracellular traps. *J Exp Med* 2010;207:1853–62. [PubMed: 20733033]
62. Melo RCN, Weller PF. Contemporary understanding of the secretory granules in human eosinophils. *J Leukoc Biol* 2018;104:85–93. [PubMed: 29749658]
63. Spencer LA, Bonjour K, Melo RC, Weller PF. Eosinophil secretion of granule-derived cytokines. *Front Immunol* 2014;5:496. [PubMed: 25386174]
64. Weller PF, Wang H, Melo RCN. The Charcot-Leyden crystal protein revisited-A lysopalmitoylphospholipase and more. *J Leukoc Biol* 2020;108:105–12. [PubMed: 32272499]
65. Wilkerson EM, Johansson MW, Hebert AS, Westphall MS, Mathur SK, Jarjour NN, et al. The peripheral blood eosinophil proteome. *J Proteome Res* 2016;15:1524–33. [PubMed: 27005946]
66. Persson EK, Verstraete K, Heyndrickx I, Gevaert E, Aegerter H, Percier JM, et al. Protein crystallization promotes type 2 immunity and is reversible by antibody treatment. *Science* 2019;364:eaaw4295.
67. Dunican EM, Elicker BM, Gierada DS, Nagle SK, Schiebler ML, Newell JD, et al. and National Heart Lung and Blood Institute (NHLBI) Severe Asthma Research Program (SARP). Mucus plugs in patients with asthma linked to eosinophilia and airflow obstruction. *J Clin Invest* 2018;128:997–1009. [PubMed: 29400693]
68. Persson C, Uller L. Theirs but to die and do: primary lysis of eosinophils and free eosinophil granules in asthma. *Am J Respir Crit Care Med* 2014;189: 628–33. [PubMed: 24512466]

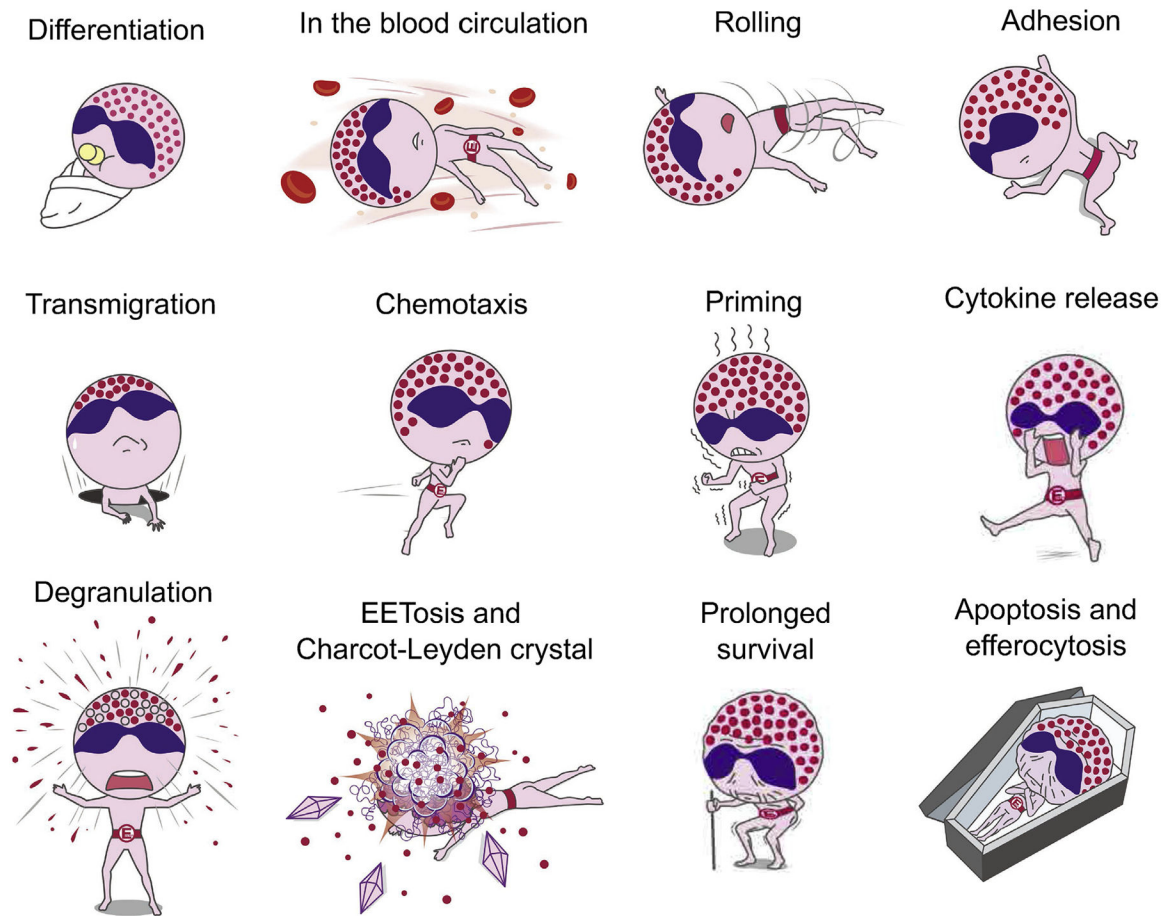
69. de Groot LES, van de Pol MA, Fens N, Dierdorp BS, Dekker T, Kulik W, et al. Corticosteroid withdrawal-induced loss of control in mild to moderate asthma is independent of classic granulocyte activation. *Chest* 2020;157:16–25. [PubMed: 31622588]
70. Ueki S, Mukherjee M, Nair P. Luminal eosinophil cell death as a biomarker for loss of asthma control? *Chest* 2020;157:1680–1. [PubMed: 32505311]

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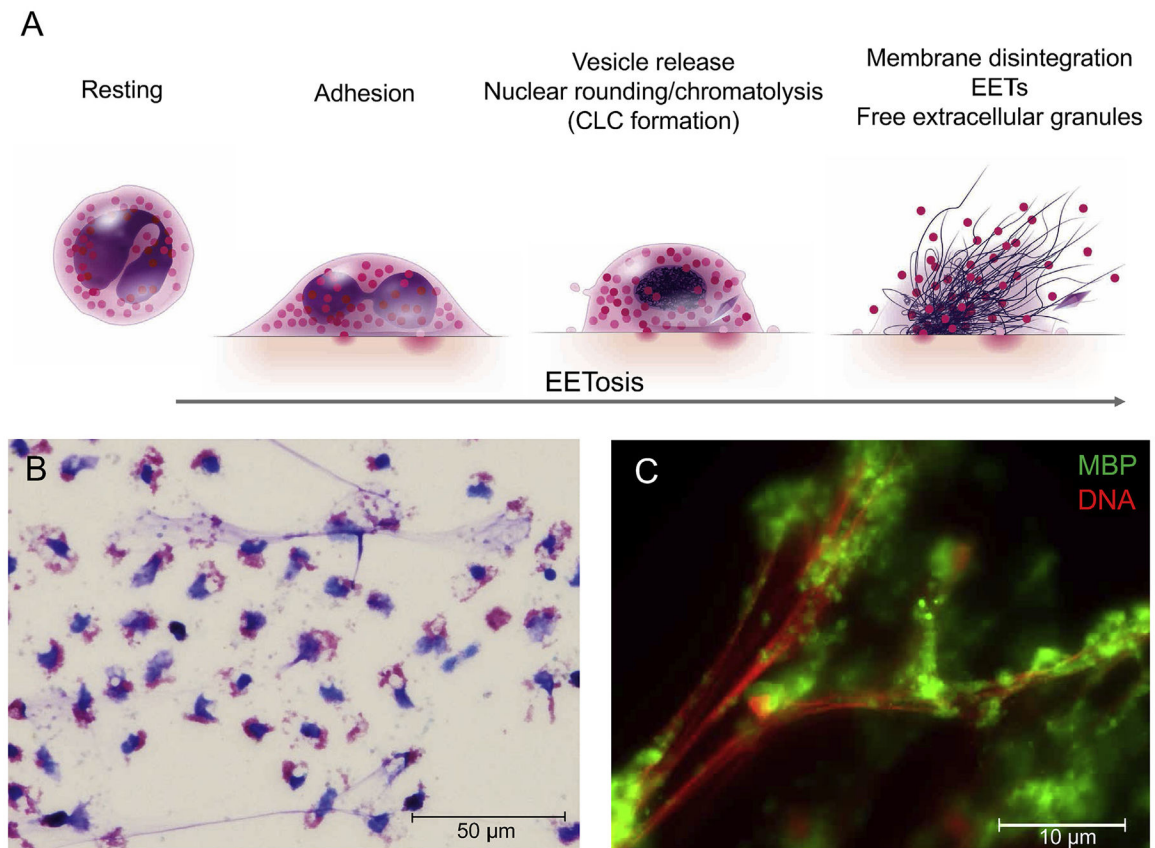
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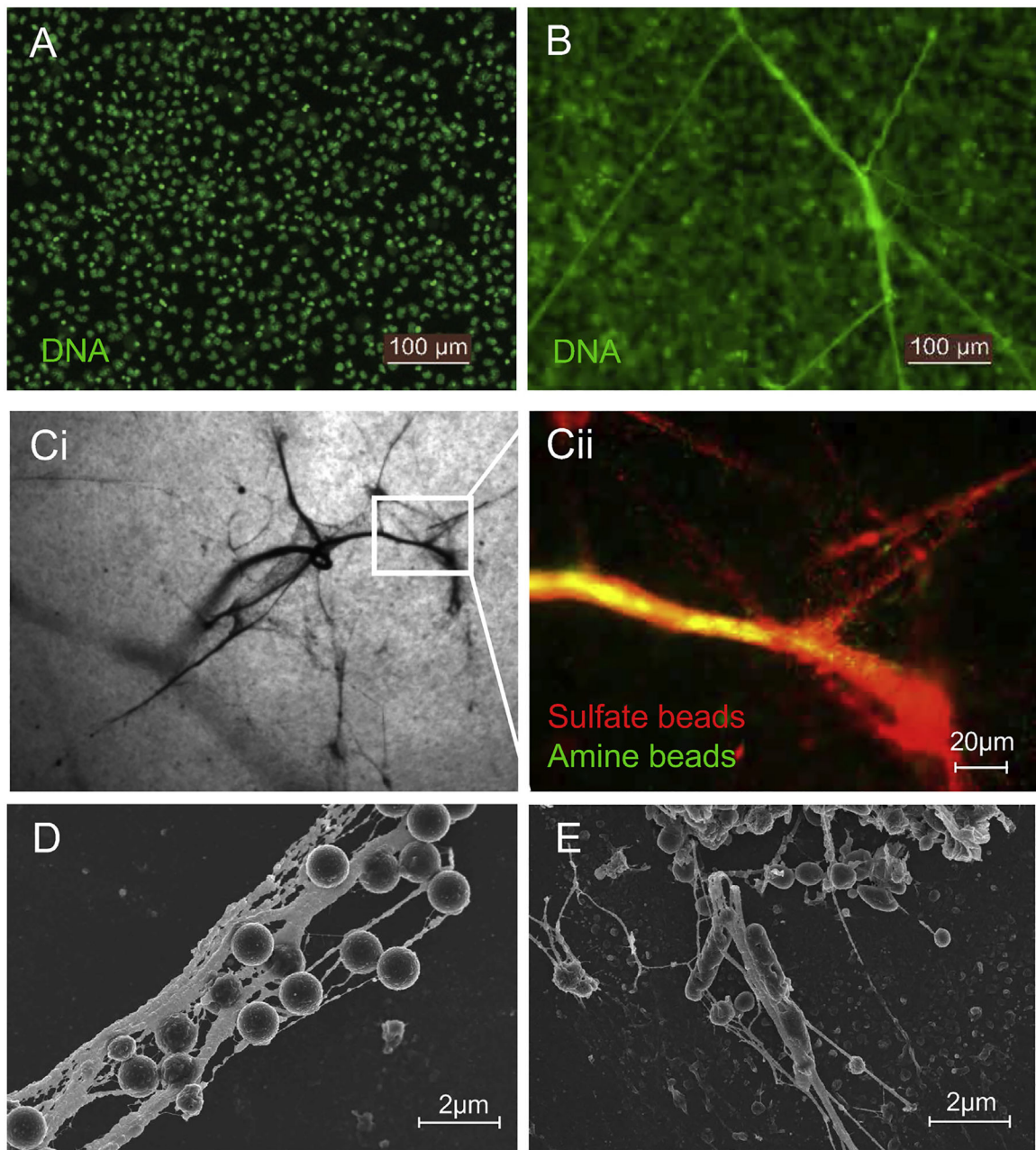
**Fig. 1.**

“EOSMAN” demonstrates eosinophil fates. Eosinophils normally comprise a small fraction of circulating blood leukocytes, although they can play critical roles in homeostasis and certain pathological conditions. Eosinophil biology includes production, longevity, accumulation, activation status, and secretory functions. We have created a cartoon character, EOSMAN, that might promote public awareness, research into eosinophil biology, and aid mutual understanding between physicians and patients with eosinophilic diseases.





**Fig. 2.** Cytolytic EETosis releases free granules and EETs. **(A)** Temporal course of EETosis. Human eosinophils activated by stimuli, initially attached to the culture plate, followed by nuclear rounding and chromatin decondensation. Extracellular vesicles are also released from plasma membrane protrusions and occasionally intracellular Charcot-Leyden crystals (CLCs) are formed before plasma membrane dissolution. Finally, nuclear and plasma membranes are both disintegrated and net-like chromatin structures are liberated. EETs can be spread by shear stress. **(B)** Diff-quick staining of EETosis. Plasma membrane disintegration, net-like nuclear contents, and extracellular granules are observed. Eosinophils were stimulated with 1 ng/ml of IL-5 and 1  $\mu$ M platelet-activating factor for 3 h in RPMI 1640 with 0.3% bovine serum albumin. (40 $\times$  objective; scale bar shows 50  $\mu$ m). **(C)** Immunostaining for granule proteins of released EETs. Purified human eosinophils were stimulated with A23187 for 60 min to induce EETosis, then stained with anti-MBP Ab (green) for granule proteins. Propidium iodide (PI; red) was used for staining DNA. The images were obtained using fluorescence microscopy (100 $\times$  objective; scale bar shows 10  $\mu$ m). Detailed methods are described in Reference.<sup>4</sup>



**Fig. 3.** Characteristics of EETs *in vitro*. **(A)** SYTOX staining and effect of shear stress. Eosinophils were stimulated with PMA for 3 h in the presence of cell-impermeable DNA dye SYTOX green dye (>90% of eosinophils were SYTOX positive). Under static culture conditions, net-like EETs were barely identified because of adherence to originating cells. **(B)** After overnight incubation (>99% of eosinophils were SYTOX positive), the culture plate was shaken using a plate shaker. Large aggregated EETs were then visualized. **(Ci)** Bright field image of microbeads trapped by EETs (4 × objective). After EETosis induction by stimulation with 2 μM A23187, 1 μm fluorescence beads (red, sulfate-modified beads; green, amine-modified beads) were added to the medium followed by induction of

aggregation using a plate shaker. **(Cii)** A fluorescence image is the boxed area seen at higher magnification. Hydrophobic sulfate beads bound preferentially to EETs. **(D)** Ultrastructure of sulfate bead-trapping EETs. **(E)** EETs bound to *E. coli*. Detailed methods are described in Reference.<sup>9</sup>

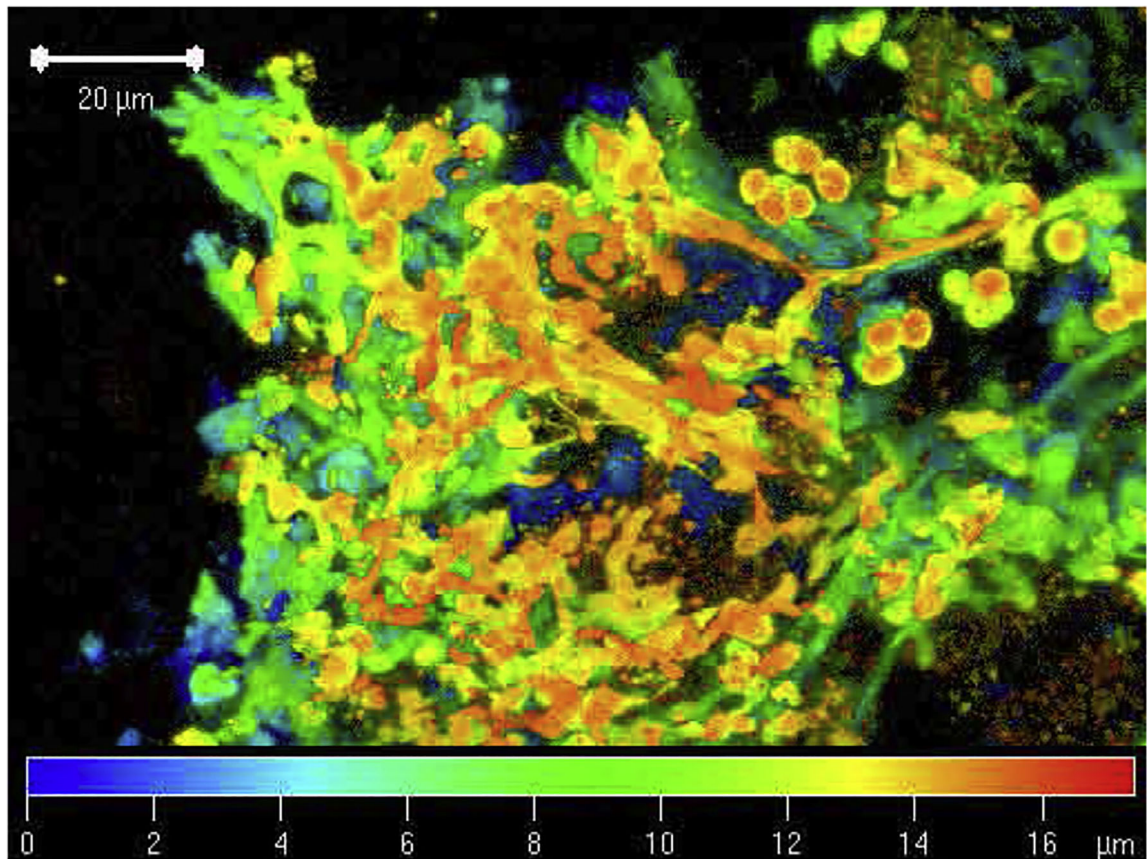
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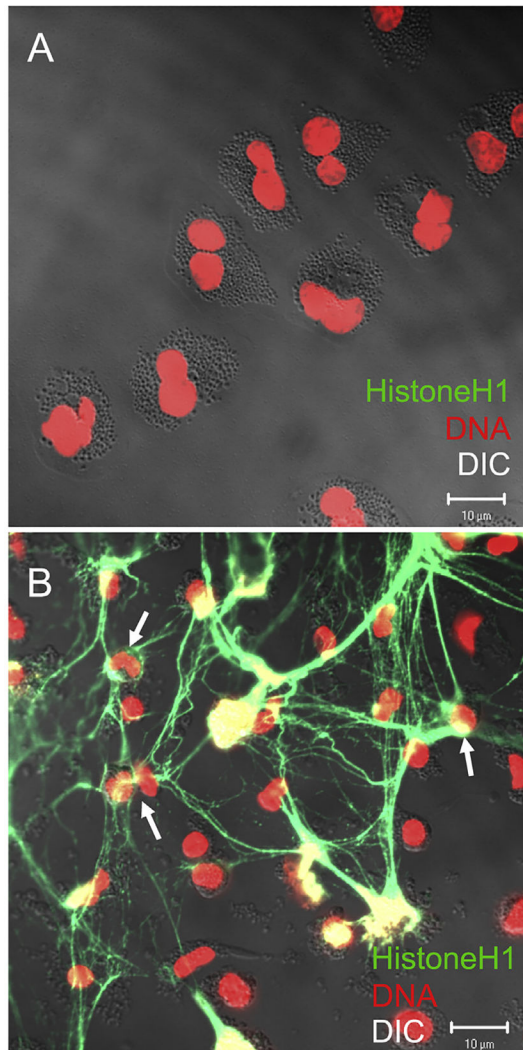
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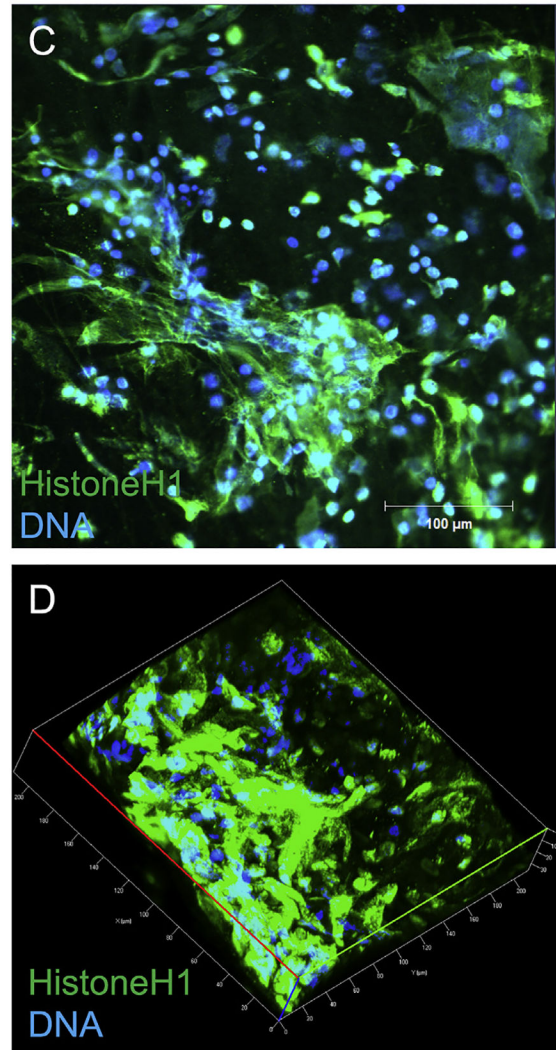


**Fig. 4.** Aggregated EETs in eosinophilic exudate. Pseudocolor representation of EETs evaluated throughout the depths of eosinophilic mucin obtained from a patient with eosinophilic chronic rhinosinusitis (chronic rhinosinusitis with nasal polyps). Fixed eosinophilic mucin was stained for DNA using SYTOX green. Depth-level serial Z-stack images were pseudocolored according to the indicated color depth scale and projected to 3D using Zeiss LSM software (60 × objective). Detailed methods are described in Reference.<sup>9</sup>

## Isolated eosinophils



## Bronchial secretion smear



**Fig. 5.** Extracellular histone staining. **(A)** Isolated eosinophils were stimulated with PMA for 15 min, followed by fixation (without permeabilization) and immunostained for histone H1 and DNA. Merged image of histone H1 (green), fluorescence DNA dye propidium iodine (red) and differential interference contrast (DIC) were obtained by confocal microscopy (100 × objective). Because anti-histone H1 antibodies do not penetrate intact nuclear and plasma membranes, cells were positive for DNA only. **(B)** After 120 min stimulation with PMA, eosinophils were similarly stained for histone H1 and DNA. Released EETs from lytic eosinophils were stained with anti-histone H1 antibodies. Note that EETs were only from lytic cells, but often attached to the neighboring intact cells (arrows). Detailed methods are described in Reference.<sup>9</sup> **(C)** Bronchial secretion smear obtained from a patient with allergic bronchopulmonary aspergillosis was fixed and stained with histone H1 (green) and DNA (Hoechst33342, blue). EETs and chromatolytic cells were stained with anti-histone H1 antibodies. The image was obtained with a fluorescence confocal microscope using a larger pinhole diameter because of the sample thickness (20 × objective). **(D)** 3D reconstructed

Z-stack confocal image of a bronchial secretion smear obtained from a patient with allergic bronchopulmonary aspergillosis.

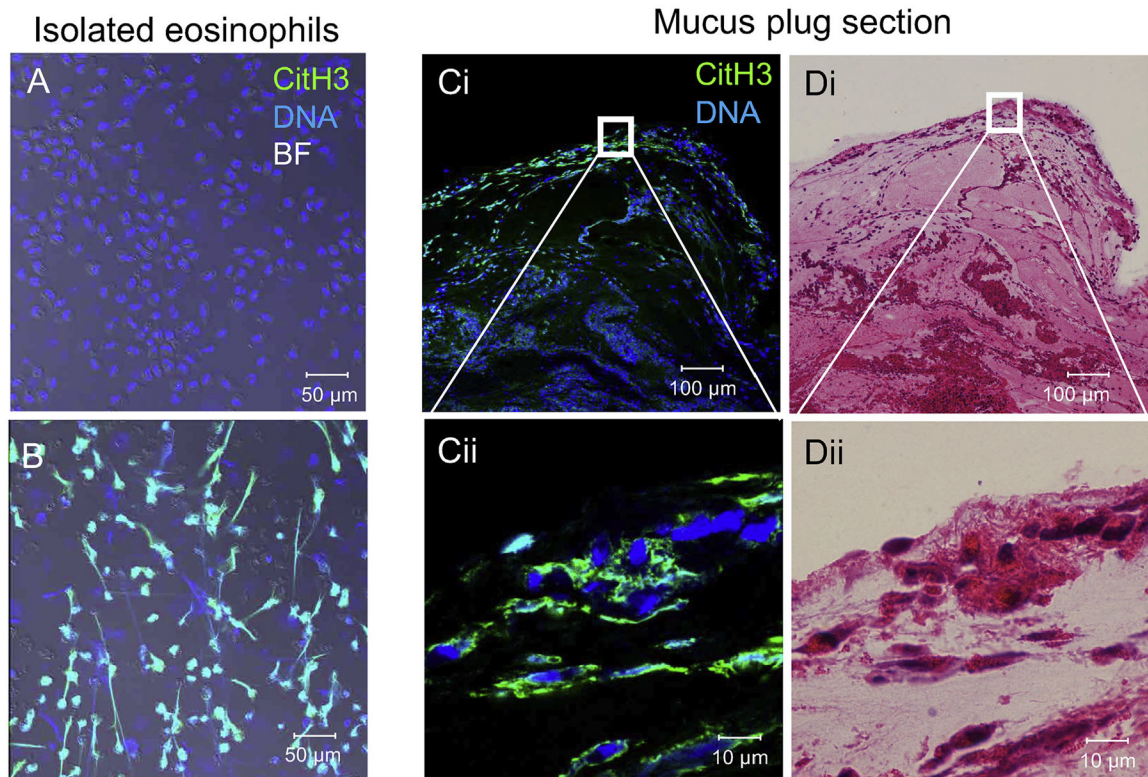
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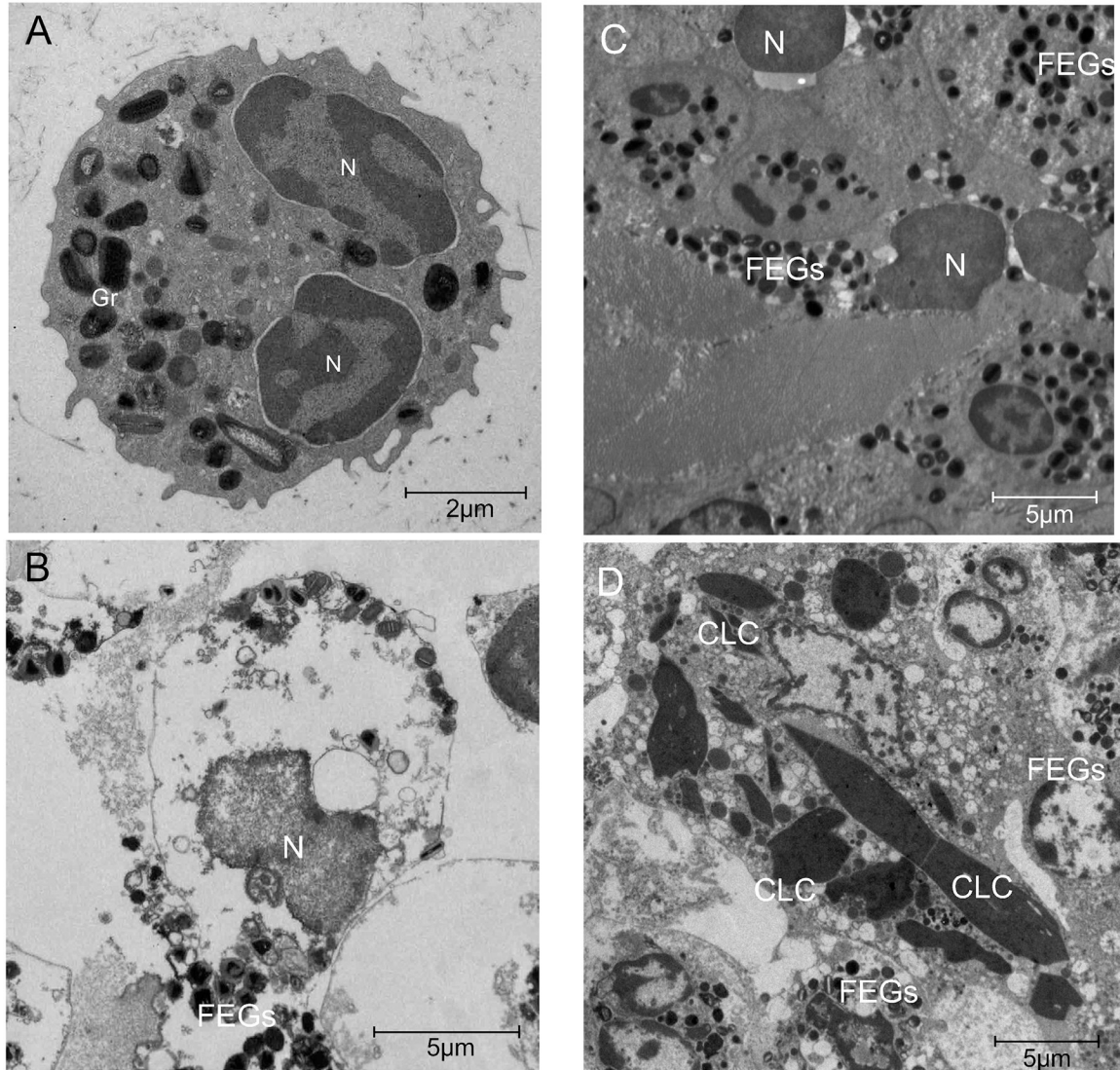




**Fig. 6.** Citrullinated histone staining. **(A)** Isolated eosinophils were stimulated with PMA for 15 min, followed by fixation (without permeabilization) and stained for citrullinated histone H3 (CitH3, green) and DNA (blue, Hoechst33342 DNA dye). The DIC image was merged ( $20 \times$  objective). **(B)** After 120 min stimulation with PMA, eosinophils were similarly stained for citrullinated histone H3 and DNA. **(Ci)** Section of a bronchial mucus plug obtained from a patient with allergic bronchopulmonary aspergillosis was stained for citrullinated histone H3 (green) and DNA (blue) ( $4 \times$  objective). **(Cii)** The boxed area in **(Ci)** was seen at higher magnification. **(Di, Dii)** A section identical to that in **(Ci, Cii)** was further stained with hematoxylin and eosin. Note that chromatolytic eosinophils and EETs were stained with citrullinated histone H3, but intact nuclei were not. Detailed methods are described in Reference.<sup>9</sup>

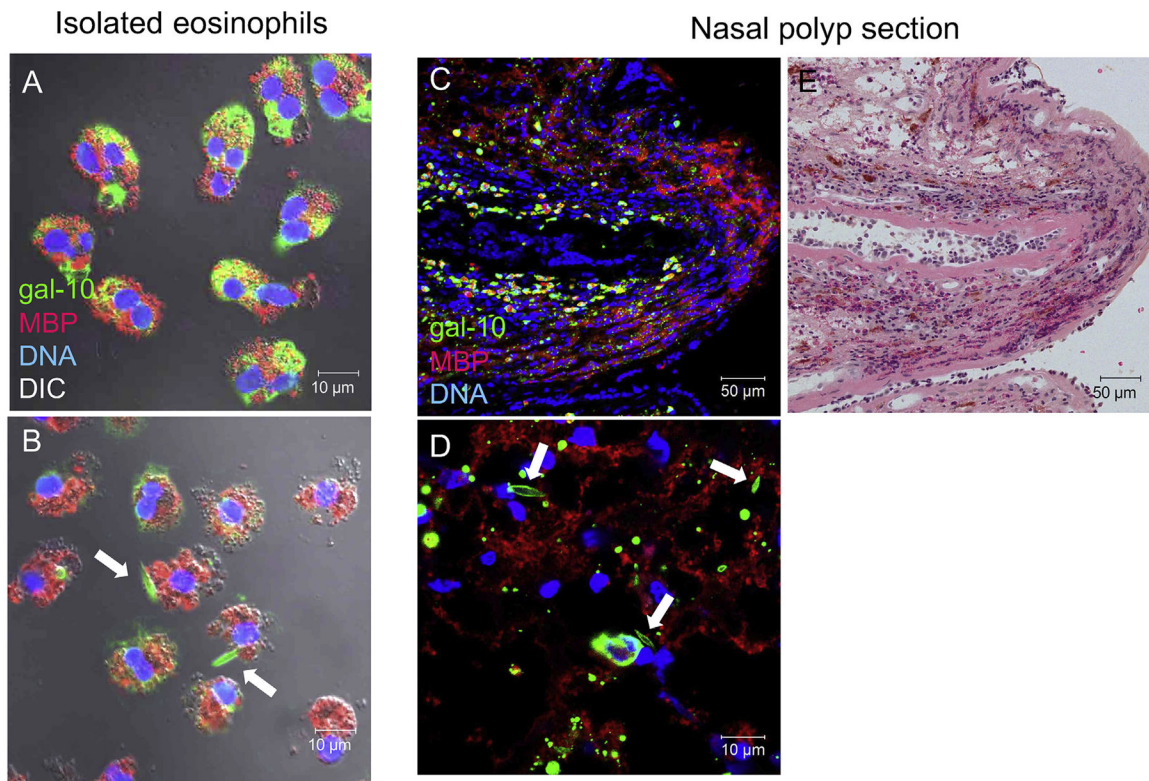
## Isolated eosinophils

## Tissue



**Fig. 7.** Ultrastructural morphologies of EETosis. **(A)** Isolated blood eosinophils were observed using transmission electron microscopy. Nucleus (N) showed heterochromatin and electron-dense granules (Gr). **(B)** Eosinophils were stimulated with a combination of IL-5 and platelet activating factor for 3 h. Chromatolytic nucleus (N) and free extracellular granules (FEGs) were evident. **(C)** Nerve tissue sample obtained from a patient with eosinophilic granulomatosis with polyangiitis. EETotic eosinophils with chromatolytic nucleus (N) and FEGs are indicated. **(D)** Electron micrograph for lymph node obtained from a patient with hypereosinophilic syndrome. Abundant CLCs and FEGs were present.





**Fig. 8.** Detection of lytic eosinophils using galectin-10 and MBP staining. **(A)** Isolated eosinophils were stimulated with PMA for 15 min, followed by fixation (with permeabilization) and stained for cytoplasmic galectin-10 (green), granular protein MBP (red), and DNA (blue). Merged immunofluorescence staining and DIC images were obtained by confocal microscopy. **(B)** After 120 min stimulation with PMA, eosinophils were similarly stained for galectin-10 and MBP. Notably, nuclear lobulation was lost in lytic galectin-10 negative cells and MBP were not co-localized with DNA. Bipyramidal Charcot-Leyden crystals were occasionally observed in EETotic cells (arrows). **(C)** Section of a nasal polyp obtained from a patient with eosinophilic chronic rhinosinusitis (chronic rhinosinusitis with nasal polyps) was stained for galectin-10 (green), MBP (red), and DNA (blue) (4 × objective). **(D)** At higher magnification (100 × objective), CLCs were associated with lytic eosinophils (arrows). **(E)** A section identical to that in (C) was further stained with H&E. Massive MBP deposition was observed even in eosinophils that were no longer recognizable.

Table 1

*In vitro* stimuli/conditions inducing “cytolytic” eosinophil cell death.

Inducers	Cell death	References
A23187	Cytolytic degranulation	Fukuda T, <i>et al.</i> <i>J Immunol</i> 1985;135 (2):1349–1356.
Immunoglobulin (IgG/IgA) coated beads	Cell lysis	Weiler CR, <i>et al.</i> <i>J Leukocyte Biol</i> 1996;60 (4):493–501.
<i>Staphylococcus aureus</i> supermatant	Necrosis	Prince LR, <i>et al.</i> <i>PLoS One</i> 2012;7 (2):e31506.
PMA	ETosis	Ueki S, <i>et al.</i> <i>Blood</i> 2013;121 (11):2074–83.
Immobilized IgG, Immobilized IgA		
IL-5/PAF co-stimulation		
GM-CSF/PAF co-stimulation		
A23187		
Anti-Siglec-8 antibody crosslinking/IL-5 co-stimulation	Necrotic cell death	Kano G, <i>et al.</i> <i>J Allergy Clin Immunol</i> 2013;132 (2):437–45.
Adherence to the glass in blood coagulation	Cytolysis	Muniz-Junqueira MI, <i>et al.</i> <i>Allergy</i> 2013;68 (7):911–20.
Anti-Siglec-8 antibody crosslinking/IL-5 co-stimulation	Cell death	Kano G, <i>et al.</i> <i>Immunobiology</i> 2017;222 (2): 343–349.
A23187	ETosis	
Immobilized intravenous immunoglobulin/inactive C3b co-stimulation	Cytolysis with DNA cloud	Radonjic-Hoesli S, <i>et al.</i> <i>J Allergy Clin Immunol</i> 2017;140 (6):1632–42.
Necrotic liver	Pyroptosis	Palacios-Macapagal D, <i>et al.</i> <i>J Immunol</i> 2017;199 (3):847–53.
Immobilized immunoprecipitation-immunoglobulins from asthmatic sputum	Cytolysis with EETs	Mukherjee M, <i>et al.</i> <i>J Allergy Clin Immunol</i> 2018;141 (4):1269–79.
<i>Aspergillus fumigatus</i>	ETosis	Muniz VS, <i>et al.</i> <i>J Allergy Clin Immunol</i> 2018;141 (2):571–85 e7.
Immobilized anti-neutrophil cytoplasmic antibody (ANCA) from EGPA sputum	Cytolysis with EETs	Mukherjee M, <i>et al.</i> <i>Am J Respir Crit Care Med</i> 2019;199 (2): p.158–170.
Fibrinogen	Cytolytic degranulation	Coden ME, <i>et al.</i> <i>J Immunol</i> 2020;204 (2):438–448.
PAF	Cytolysis with EETs	Kim HI, <i>et al.</i> <i>Allergy</i> 2020 (in press)
A23187		
Lysophosphatidylserine (LysoPS)		