Polyanions in Coagulation and Thrombosis: Focus on Polyphosphate and Neutrophils Extracellular Traps

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Abstract

Neutrophil extracellular traps (NETs) and polyphosphates (polyP) have been recognized as procoagulant polyanions. This review summarizes the activities and regulation of the two procoagulant mediators and compares their functions. NETs are composed of DNA which like polyP is built of phosphate units linked by high-energy phosphoanhydride bonds. Both NETs and polyP form insoluble particulate surfaces composed of a DNA/histone meshwork or Ca^{2+}-rich nanoparticles, respectively. These polyanionic molecules modulate coagulation involving an array of mechanisms and trigger thrombosis via activation of the factor XII-driven procoagulant and proinflammatory contact pathway. Here, we outline the current knowledge on NETs and polyP with respect to their procoagulant and prothrombotic nature, strategies for interference of their activities in circulation, as well as the crosstalk between these two molecules. A better understanding of the underlying, cellular mechanisms will shed light on the therapeutic potential of targeting NETs and polyP in coagulation and thrombosis.

Keywords
- polyanions
- contact activation
- NETs
- polyP

Physiological Polyanions

Biological polyanions are highly abundant, negatively charged molecules that exist ubiquitously in various forms in nature. For decades it has been established that polyanions participate in blood coagulation and exert either procoagulant or anticoagulant activities that contribute to normal hemostasis or pathological thrombosis, respectively. Polyanionic carbohydrates, glycosaminoglycans (GAGs) provide anticoagulant activities on the cell surface of most eukaryotic cells. Heparan-, chondroitin-, and dermatan-sulfate-type GAGs interfere with clot formation at the interface of blood and vascular cells by amplifying antithrombin and heparin cofactor II activities.[1] Mast cell-derived heparin shares structural similarity with heparan sulfate. Unfractionated heparin, low-molecular weight heparin, and heparin-derived agents are commonly used therapeutically as injectable anticoagulants.[2] In contrast to negatively charged polysaccharides, DNA, a key component of neutrophil extracellular traps (NETs), and polyphosphate (polyP) have procoagulant activities and promote blood clotting with implications for thrombosis (►**Fig. 1**).

Extracellular DNA

Circulating extracellular DNA in human plasma was described as early as 1948.[3] In response to stimulation, an array of cells, including leukocytes, mast cells, senescent cells, and tumor cells, release their DNA into the extracellular space either as chromatin (histones complexed with DNA), naked double-stranded DNA (dsDNA), or mitochondrial DNA.[4] In addition to actively released nucleic acids, DNA from disintegrating bacteria and viruses is also detectable in circulation.[5] Small amounts of extracellular DNA are present in plasma and serum of healthy individuals; however, levels are largely elevated in

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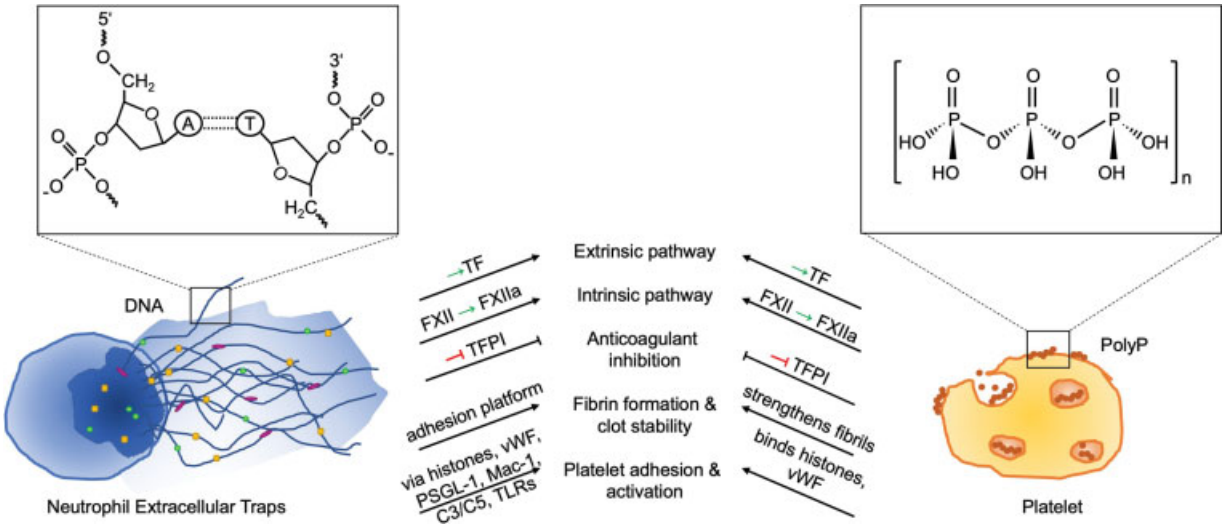

Fig. 1 Common mechanistic and structural features of NETs and platelet polyP. The lower part of the left image shows a neutrophil that is releasing NETs (depicted by long, dark blue DNA strands entangled with histones and other granular proteins) and the right-hand side shows a platelet decorated with polyP on its surface. PolyP can be composed of a few hundreds to thousands of phosphate units, which also make up the phosphate backbone of DNA. The phosphate backbone serves as a structural support and energy source for both of these molecules. NETs and polyP are polyanionic, immunomodulatory structures that can activate platelets, FXII, and other factors of the contact pathway, which will lead to further downstream events of the coagulation cascade. Eventually, NETs and polyP can interact with fibrin and fibrinogen, reinforcing the fibrin meshwork. C3/C5, complement components; FXII, factor XII; FXIIa, activated FXII; Mac-1: macrophage-1 antigen/CD11b/CD18; NET; neutrophil extracellular trap; polyP, polyphosphate; PSGL-1: P-selectin glycoprotein ligand-1; TF: tissue factor; TFPI: tissue factor pathway inhibitor; TLR: toll-like receptor; vWF, von Willebrand factor.

pathological conditions, suggesting the use of extracellular DNA as a prognostic biomarker.[6–10]

Neutrophils are the predominant leukocyte in human blood and present the major source of extracellular DNA. In response to various inflammatory stimuli, activated neutrophils cast out their DNA, forming NETs. NETs were originally described as components of the innate immune response to microbial infections that trap invading microorganisms, thus interfering with pathogen dissemination. Furthermore, it has been shown that inducers of phagocytosis trigger NET formation suggesting a cooperative effect of NETosis and phagocytosis in host defense.[11] NETs are composed of long DNA strands that are bound to histones and neutrophil granular-derived proteins.[12] DNA-intercalating dyes stain NETs; however, the signal is lost upon efficient digestion by deoxyribonuclease-1 (DNase1) indicating that polyanionic dsDNA is the major component of NETs.[13] Since their discovery, NETs have been implicated in a plethora of pathophysiologic conditions offering a novel link between inflammation and thrombosis in an emerging field in biomedicine.[14–16]

NET formation is a multistep process (►**Table 1**). Upon neutrophil activation, nuclear chromatin starts to decondense, leading to a loss of the typical lobulated morphology of the neutrophils' nucleus. During classical NET formation, the multimeric NADPH-oxidase assembles on cellular membranes and produces reactive oxygen species, which in turn activate the enzyme peptidyl-arginine deiminase 4 (PAD4).[17,18] PAD4 citrullinates histones, neutralizing their net positive charge and thus reducing their affinity for binding to the negatively charged DNA polyanion, thereby facilitating chromatin decondensation.[18] Additionally, neutrophil elastase (NE) and myeloperoxidase (MPO) are released from neutrophil granules and translocate to the nucleus, where they degrade histones and promote further unfolding of chromatin.[19] Consequently, the nuclear membrane breaks up, and chromatin is released into the cytosol, where it binds to granular and cytosolic proteins. The mechanism by which the plasma membrane ruptures to release NETs is not completely understood; however, recent studies indicate that the pore-forming protein gasdermin D might play a role.[20]

The extracellular DNA forms supramolecular web-like structures both in the vasculature and surrounding tissues.[17] High-resolution scanning electron microscopy (SEM) revealed that NETs are made of fine thread-like structures, composed of long and sticky DNA strands.[13]

Polyphosphate

In contrast to NETs, polyP is a purely inorganic polymer composed of linear chains of orthophosphates that are connected by energy-rich phosphoanhydride bonds (►**Table 1**). PolyP is abundant in the environment, synthetic polyP is used in multiple technical processes (e.g., as water softener, food ingredient, or fire extinguisher), and physiological polyP is found in every cell in nature. The polymer is evolutionarily conserved among bacterial, fungal, plant, and animal cells.[21] The high-energy phosphoanhydride bonds in the polyP chain are equivalent to those in ATP and bacteria and yeast use the polymer as a chemical energy storage pool during starvation and environmental stress.[22]

Prokaryotic and lower eukaryotic microorganisms have intracellular polyP molecules ranging in chain length from a few hundreds to thousands of phosphate units. The polymer is stored in subcellular organelles called acidocalcisomes, along

Table 1 Formation, binding partners, cellular origin, detection, and degradation of neutrophil extracellular traps and polyphosphate

	Neutrophil extracellular traps	Polyphosphate
Formation	• Microbial/inflammatory stimuli such as LPS, TLRs, cytokine, Fc, or complement receptors[13,112–114] • Synthetic compounds like phorbol myristate acetate (PMA), A23187, or ionomycin[114,115] • Platelet neutrophil interaction[113]	• Polyphosphate kinase 1 and 2 (PPK1, PPK2) and homologs, e.g., DdPPK[71,116] • Vacuolar transporter chaperone cleaves ATP γ-phosphate residues[117] • Formation and secretion are induced by agonists such as thrombin, thrombin receptor-activating peptide 6 (Trap6), collagen, and ADP[31]
Binding partners	• Binds platelets via glycoprotein Ibα, P-selectin, and high-mobility group box 1 (HMGB1)[62,118,119] • Extracellular histones, predominantly H3 and H4, cause platelet aggregation[120] and induce platelets to secrete short-chain polyP from α-granules[65,94] • DNA and histones individually promote thrombin generation; histones have shown to do so in a polyP-dependent manner[49,65,94] • NETs can bind and activate FXII, which then induces the activation of the kallikrein–kinin system[61] • Neutrophil elastase (NE) cleaves prothrombin, releasing small peptides that exert antibacterial and immunomodulatory effects[121] • TFPI and thrombomodulin can be inactivated by myeloperoxidase (MPO) and serine proteases[122] • NE and cathepsin G contribute to fibrin formation on NETs, also by degradation of TFPI[95] • Intertwined fibrin–NET fibrils may reinforce NETs to prevent pathogen spread[123] • NETs can amplify tissue factor[124,125] • vWF binds to isolated DNA in vitro, potentially acting as a linker for leukocyte adhesion to endothelial cells[126]	• Accelerates the generation of FXIa and thrombin[127] • Amplifies thrombin-mediated activation of FXI[128] • Accelerates FV activation by FXa and thrombin[128] • Enhances the binding of platelets to von Willebrand factor[129] • Activates FXII[127] thereby also triggering inflammation via FXIIa-mediated activation of the kallikrein–kinin system[52] • Inactivates TFPI, abrogating its anticoagulant function[130] • Integrates into the fibrin clot, making it more resistant to fibrinolysis[131] • Binds extracellular histones and activates platelets[132]
Cellular origin	• Leukocytes[13,133] • Mast cells[134] • Tumor cells[4]	• Ubiquitously found in various species including bacterial, plant, and mammalian cells[21] • Platelet dense granules[29] • Mast cells[34] • Astrocytes[135] • Tumor cells[27]
Detection	• Microscopy[13] • Flow cytometry[81] • Flow chamber[113] • ELISA[82] • Western blotting[19] • Sytox Green/PicoGreen staining[12]	• DAPI, Hoechst 33342, toluidine blue O, methylene blue, tetracycline, neutral red, malachite green[85–87] • Flow cytometry[79,87] • Urea-polyacrylamide gel electrophoresis[84] • Chromatography[84] • ^{32}P-NMR[84] • Fourier transform-infrared (FT-IR)[84] • Mass spectrometry[84] • Microscopy[84]
Degradation	• Endonucleases DNase1 and DNase1 like-3[59] • Human monocyte-derived macrophages and dendritic cells[69,70] • Opsonization by complement factors[70]	• Endopolyphosphatases, e.g., Ppn1, Ppn2, Ddp1[74,75,136] • Exopolyphosphatases, e.g., Ppx1[72,73] • Diphosphoinositol polyP phosphohydrolases (DIPPs) may degrade polyP in mammals[76]

Abbreviations: DAPI, 4′,6-diamidino-2-phenylindole; ELISA, enzyme-linked immunosorbent assay; LPS; lipopolysaccharides; NET; neutrophil extracellular trap; ^{32}P-NMR, phosphorus-31 nuclear magnetic resonance; polyP, polyphosphate; TFPI, tissue factor pathway inhibitor; TLR: toll-like receptor; vWF, von Willebrand factor.

with high concentrations (in the molar range) of divalent metal cations, mostly Ca^{2+} but also Mg^{2+} and Zn^{2+}.[21] Ca^{2+}-ions bind to the phosphate units in the polyP backbone with high affinity. In vivo, physiological polyP is complexed with metal ions. Ion-bound polyP has a different structure and biophysical properties. Ca^{2+}-polyP has little if any solubility in plasma, challenging the predictive value of coagulation studies based on soluble synthetic polyP. Despite detailed information on polyP metabolism in yeast, not much is known about polyP regulation in mammals. The polymer is enriched in various

subcellular compartments including lysosomes, mitochondria, and nuclei; however, it is also found in association with the cytoskeleton and in the cytoplasm. Some cells such as astrocytes, mast cells, tumor cells, and platelets have the capacity to actively release polyP from secretory vesicles.[23–28] Platelet dense granules are specialized secretory organelles similar to acidocalcisomes found in microorganisms. Dense granules appear as dark vesicles in electron microscopy images because of their high local concentration of polyP (~130mM) that is complexed with Ca^{2+}, Mg^{2+}, and Zn^{2+} ions.[29,30]

PolyP in Blood Coagulation

Patients with a defect in platelet dense granules show significantly lower polyP levels and defective factor XII (FXII)-dependent clotting in platelet-rich plasma (PRP; Hermansky–Pudlak syndrome, delta storage pool diseases, Chediak–Higashi syndrome).[24,31,32] The addition of exogenous polyP to PRP of Hermansky–Pudlak syndrome patients restores their clotting capacity, consistent with the notion that platelet polyP triggers coagulation in a FXII-dependent manner.[31] Yeast cells lacking inositol hexakisphosphate kinase (a key enzyme involved in polyP synthesis) are devoid of polyP. Consistently, platelets of inositol hexakisphosphate kinase-1-deficient (*Ip6k1*$^{-/-}$) mice have reduced polyP levels, compromised FXII-triggered coagulation, and are protected from platelet-driven lethal pulmonary embolisms.[33] In addition to defective polyP levels, *Ip6k1*$^{-/-}$ mice show an array of other severe phenotypes including infertility and heart problems making them a challenging model to study platelet polyP in vivo. Xenotropic and polytropic retrovirus receptor 1 (XPR1) is a transmembrane protein that was originally described as a cellular docking site for retroviruses but also functions as a phosphate exporter. Recent systems biology-based studies have identified XPR1 as the major, if not exclusive, phosphate exporter in platelets. Pharmacologic and genetic targeting of XPR1 activity increased intracellular phosphate levels and led to polyP accumulation. Conditional ablation of the *Xpr1* gene in mouse platelets accelerated arterial thrombosis and activated platelet-driven pulmonary embolism, but did not affect hemostasis.[34] The data identify XPR1 as the first specific regulator of polyP in platelets and possibly other cells and indicate a fundamental role of phosphate metabolisms for thromboembolic diseases.

For years, it was believed that platelets secrete soluble short-chain 50–100mer polyP upon activation. However, this hypothesis was based on polymer purifications from the supernatant of activated platelets using a phenol–chloroform extraction method that selects for short-chain water soluble molecules.[31] Follow-up studies using anion-exchange isolation methods from complete cell lysates confirmed the presence of small amounts of short-chain polyP in platelets. Additionally, it was revealed that, similar to other mammalian cells, the vast majority of platelet polyP consists of long-chain polymers. As platelets store polyP together with high concentrations of Ca^{2+} ions in dense granules, the released polyP is complexed with calcium.[35] Ca^{2+}–polyP has a very low solubility and readily precipitates into nanoparticles independent of its chain length.[36] PolyP nanoparticles are stable in physiologic buffers for several hours.[37] Real-time imaging using polyP-specific probes showed that only minor portions of the soluble polyanion fraction are released into the supernatant while the majority remains anchored to the platelet plasma membrane.[38,39] Flow cytometry-based methods have been established to quantify polyP on the surface of activated platelets suggesting a potential use of polyP as a biomarker in thrombotic diseases.[40] Platelet-bound polyP nanoparticles drive coagulation in a FXII-dependent manner, while soluble polymers have the capacity to drive other FXII-independent coagulation reactions. Consistent with the notion that polyP operates by activating FXII, a series of classical studies has shown the contribution of FXII in activated platelet-driven coagulation/clot formation.[41–44] Vice versa, ablation of FXII or polyP impairs platelet-driven thrombosis in murine models.[33,45,46]

NETs in Blood Coagulation

Similar to polyP, multiple in vivo studies have shown NETs to be implicated in thrombotic and inflammatory reactions.[47–54] Following vascular injury, neutrophils immediately migrate to the lesion site preceding platelets.[50] At the site of injury, activated platelets and endothelial cells activate neutrophils to induce NET formation (NETosis). NETs in turn stimulate platelet aggregation and trigger fibrin formation in vitro.[48] NETs are abundant in thrombi from experimental animal models and infusion of DNase interferes with thrombus formation.[48,55] NETs are also enriched in venous and arterial thrombi of patients who suffered from a heart attack,[56] stroke,[57] and peripheral vascular arterial occlusions.[58] Furthermore, it has been shown that NETs alone are sufficient for vascular occlusions under septic conditions in the absence of host enzymes DNase1 and DNase1L3.[59] High levels of NET biomarkers, such as DNA/histones complexes, MPO, and S100A8/A9, are detectable in plasma from patients with thrombotic microangiopathy, indicating that the ineffective clearance of NETs contributes to the mechanisms of the occlusive disease.[55,60] Various components of NETs have been identified as initiators or propagators of coagulation activity, including histones and granule proteins. Soluble DNA purified from neutrophils, as well as NETs (induced by glucose oxide or interleukin-8 [IL-8] stimulation), can assemble and activate FXII in vitro.[61] SEM of NETs induced by platelet-activated neutrophils showed that the DNA backbone of NETs binds FXII and its substrate of the intrinsic coagulation pathway, factor XI (FXI).[62] However, whether NETs directly trigger FXII contact activation or merely act as a scaffold for the assembly of FXII activators and coagulation factors is still unclear.[63] Thrombin generation triggered by the addition of NETs is reduced in FXII- and FXI-deficient plasma, indicating that the procoagulant activity of NETs is mediated by the FXII–FXI axis at least in vitro.[49] Besides contact-activating FXII, DNA acts as a surface in thrombin-dependent FXI activation.[64]

Many of the studies on the procoagulant nature of NETs examined purified NET DNA and the various components of NETs individually, and thus the overall procoagulant activity

of NETs was largely omitted. Recently it was shown that human neutrophil-purified DNA and recombinant histones H3 and H4 triggered coagulation in plasma individually, whereas intact NETs did not. Histone–histone and histone–DNA interactions within the nucleosome unit and supercoiled chromatin in NETs neutralize the negative charges of the polyanion and thereby dampen the procoagulant activity of NET–DNA.[65] The precise mechanisms of NETs in thrombus formation are the subject of ongoing studies; however, NETs appear to stimulate both platelets and the coagulation system.[49]

Degradation of NETs and polyP

Despite their functional and structural similarities, the degradation pathways of NETs and polyP seem to be quite different. Defective NET clearance triggers proinflammatory and autoimmune conditions; however, the underlying mechanisms are still under investigation. Degradation of NETs is an intricate process involving the activity of various enzymes. While endonucleases efficiently degrade extracellular DNA, other NET components such as histones and NE remain intact in a murine model of bacterial infection.[66] Although coagulation inhibitor activated protein C (APC) cleaves histones and interferes with their cytotoxic activity in a purified system, it has no effect on NET-induced cytotoxicity suggesting that histone-dependent cytotoxicity is protected from APC degradation.[67,68]

Complete degradation of NETs in vivo requires the concerted activity of two secreted host endonucleases, DNase1 and DNase1-like 3.[59] The reconstitution of either DNase1 or DNase1-like 3 was sufficient to rescue the lethal phenotype of a chronic inflammation model in *Dnase1*$^{-/-}$/*Dnase1-like3*$^{-/-}$ mice. In addition to extracellular DNases, the cytosolic exonuclease TREX1 (DNase III) has the capacity of clearing NETs in vitro.[69] Furthermore, NETs can be engulfed by monocyte-derived macrophages and dendritic cells in a cytochalasin D-dependent manner, implying a role of active endocytosis in NET clearance.[69,70] Following internalization by macrophages, NETs are degraded in lysosomal compartments in an immunologically silent manner. Hence, NET clearance does not evoke the release of proinflammatory cytokines, maintaining homeostasis in tissues.[70]

In contrast to NETs, not much is known about polyP metabolism in mammalian systems. In prokaryotes polyP is synthesized by polyP kinase (PPK), which reversibly transfers γ-phosphate units from ATP and guanosine diphosphate onto the polymer chain.[22,71] Depolymerization of polyP into free P_i residues is catalyzed by exopolyphosphatase (Ppx).[72] Three distinct polyP phosphatases have been described in *Saccharomyces cerevisiae*: exopolyphosphatase [Ppx1], endopolyphosphatases [Ppn1], and diadenosine and diphosphoinositol phosphohydrolase [Ddp1].[73–75] Mammalian homologs for these polyP phosphatases have not yet been identified; however, diphosphoinositol polyP phosphohydrolases seem to participate in polyP degradation under alkaline conditions.[75] Mammalian alkaline phosphatase (AP) from calf intestine is a potent exopolyphosphatase and cleaves polyP.[76] Ca^{2+}–polyP has a half-life in plasma of approximately 90 minutes, before it gets degraded by polyphosphatases, such as AP. Exopolyphosphatase (Ppx1)-mediated degradation of polyP improved cardiomyocyte function in cell culture[77] and alleviated Ca^{2+} accumulation in mitochondria and Ca^{2+}-induced cell death processes related to myocardial infarction and ischemia-reperfusion injury.

Extracellular RNA is considered to promote blood coagulation based on the fact that infusion of RNase interferes with arterial thrombosis in a murine $FeCl_3$-driven vascular injury model.[78] RNase readily hydrolyzes polyP, offering an alternative explanation for the thromboprotective effects conferred by the enzyme.[79]

Detection of polyP and NETs

NETs and polyP are detected by similar dyes and techniques. Imaging of NETs in vitro is mainly based on immunofluorescence microscopy, transmission electron microscopy, and SEM. The DNA-intercalating dyes SYTOX Green/PicoGreen and 4′,6-diamidino-2-phenylindole (DAPI), as well as antibodies against NET-specific structures such as citrullinated histones (H3cit) and histone–MPO complexes are typically used for microscopy.[13] In recent years, the occasional bias in microscopic imaging of NETs has been criticized, hence more automated software tools for image-based NET quantification are currently being developed.[80] Granular proteins and other NET components can also be targeted with flow cytometry, Western blotting, and enzyme-linked immunosorbent assays.[19,81,82] To further standardize quantification of NETs, especially in clinical settings, the ISTH (International Society on Thrombosis and Haemostasis) Vascular Biology Subcommittee has recently started a collaborative effort to investigate and harmonize NET quantification techniques. Despite successful imaging of NETs in vitro, visualization of the polyanion in vivo still poses significant hurdles. However, during the last few years, imaging by intravital microscopy has strongly facilitated the in vivo evaluation of NET formation and degradation.[64,83]

PolyP can be stained with dyes such as toluidine blue O or methylene blue to be visualized by phase-contrast, bright-field, and electron microscopy.[79] Because polyP is mainly stored in membrane-enclosed compartments in eukaryotes, the dyes neutral red and tetracycline can detect polyP with nondestructive methods, such as light microscopy and flow cytometry.[84] Similarly to NETs, DNA-intercalating dyes such as DAPI[85] and Hoechst 33342[86] stain polyP. However, DAPI bound to polyP emits a bright yellow-green fluorescence, distinct from the blue fluorescence emitted by DNA.[87] Toluidine blue O and DAPI only detect polyP with a chain length longer than 15-mers.[88,89] Sophisticated flow cytometry analyses using DAPI or tetracycline staining[87] or recombinant polyP-specific probes based on the polyP-binding domain of *Escherichia coli* exopolyphosphatase[40] are also being employed.

Malachite green dye binds free orthophosphates and can be used to quantify phosphate monomers in solution.[79]

Degradation of polyP with Ppx, allows for quantifying polyP concentration. The malachite green assay fails to detect the chain length of the polyanion; however, it has a high sensitivity and measures polyP up to the picomolar range. As Ppx only digests polyP with a chain length of greater than 38 phosphate subunits, the malachite green assay is insensitive for short-chain polyP. PolyP can furthermore be visualized by microscopy,[79] electrophoresis, chromatography, ^{32}P-NMR, Fourier transform-infrared, and mass spectrometry.[84]

Crosstalk of NETs and polyP

Inflammation and thrombosis are mediated by a complex interplay involving neutrophils and platelets. During coagulation, FXII is activated by a unique mechanism triggered by binding ("contact") to negatively charged polyanionic surfaces ("contact activation"). Activated FXII initiates the intrinsic pathway of coagulation and the bradykinin-producing kallikrein–kinin system, leading to coagulation and inflammation.[90–92] Extracellular DNA and polyP activate FXII and promote thrombosis by the intrinsic pathway of coagulation in vivo.[87,93,94]

While polyP initiates coagulation via FXII, NETs also contribute to the activity of the tissue factor (TF)-driven extrinsic coagulation pathway. NET-associated TF and granular protease NE and cathepsin G inhibit the TF pathway inhibitor (TFPI).[95,96] Activation of neutrophils with cytokines upregulates their TF mRNA expression and TF deposition on NETs.[97] Furthermore, NETs contribute to mechanical clot stability by slowing down plasminogen–plasmin conversion by tissue plasminogen activator (t-PA) on clot surfaces. They also bind fibrin degradation peptides and delay their release from fibrin clots, as well as intercalate into fibrin fibers and delay plasmin-mediated lysis of plasma clots.[98,99]

Neutrophils and platelets interact with each other via platelet glycoprotein Ibα binding to neutrophil MAC-1 and platelet P-selectin binding to neutrophil P-selectin glycoprotein ligand-1 (PSGL-1).[100–103] NETs promote coagulation in a platelet-dependent manner. High-resolution confocal intravital microscopy revealed that NET-triggered coagulation is a result of collaborative interaction between multiple components of NETs including DNA, histones and proteases with platelets, and platelet polyPs. Histone H4 on NETs perforates platelets causing the release of procoagulant polyP.[94] Neutralization of polyP with monoclonal blocking antibody (PP2055) significantly reduced NET-initiated thrombin formation in an experimental sepsis model.[64] Furthermore, the procoagulant effect of NETs in PRP was attenuated by addition of bovine AP, providing additional evidence that polyP plays a role in the procoagulant activity of NETs.[49] In an acute ST-segment elevation myocardial infarction model, platelet polyP led to NET formation by mTOR inhibition and autophagy induction. Treatment with IL-29 counteracted the effect of polyP on NET formation.[104] Together, these studies indicate that polyP interacts with NETs and that the polyP–NETs crosstalk is important in coagulation.

Purified platelet and bacterial polyP exert high procoagulant activity even in the presence of inhibitors of the TF-driven extrinsic pathway. However, in the absence of FXII, polyP fails to trigger procoagulant activities.[31] Consistent with polyP activities in human plasma, infusion of the polyanion into wild-type mice led to lethal pulmonary embolism, whereas FXII-deficient mice or mice treated with a FXII inhibitor were protected from polyP-triggered thrombosis. FXII, FXI, and FXII/FXI-double-deficient mice were similarly protected upon polyP-triggered thrombosis, indicating that polyP operates via the classical intrinsic coagulation pathway in vivo.[31]

Therapeutic Targeting of NETs and polyP in Thrombosis

NETs play a role in both arterial and venous thrombosis, making them an interesting target to reduce thrombosis or stimulate thrombolysis. There is a multitude of NET components (e.g., DNA, PAD4), cellular interactions (e.g., leukocyte–platelet/leukocyte–endothelium), and signaling pathways (e.g., leukocyte recruitment, NET formation/degradation), that are currently being investigated and that can be targeted pharmaceutically.[53] For instance, blocking platelet α-granules or Weibel–Palade body release would hamper tethering of platelets and neutrophils to the vessel wall and also reduce leukocyte and platelet recruitment upon activation.[105] Treating NET-containing thrombi from ischemic stroke patients ex vivo with t-PA resulted in partial thrombus dissolution, which was significantly accelerated upon the addition of DNase1.[105] A similar study showed that treating stroke thrombi with DNase1 alone does not efficiently resolve the thrombi.[106] Thus, a combination treatment with a fibrinolytic agent, e.g., t-PA and/or ADAMTS13 (the protease specifically cleaving vWF), and a nuclease is recommended to obtain a sufficient degree of thrombolysis. Besides the recombinant human DNase1 (Dornase α, Pulmozyme, Roche), which is approved for the treatment of cystic fibrosis, there are ongoing endeavors to develop improved NET-degrading nucleases.[59] Furthermore, ongoing preclinical studies investigate PAD4 inhibitors as potential treatment options for multiple myeloma (BMS-P5, Bristol Myers Squibb[107]), rheumatoid arthritis, lung fibrosis, and thrombosis (preclinical PAD4 inhibitors program, Jubilant Therapeutics).

Based on the structural homology of DNA and polyP, nucleic acid-binding polymers were analyzed for interference with polyP-mediated coagulation.[108] Polyamidoamine dendrimer, 1,4-diaminobutane core, generation 3 (PAMAM G-3) was shown to be the most effective polyP-binding molecule and reduced thrombus formation without increasing the risk of bleeding in both the $FeCl_3$-induced carotid artery injury and collagen/epinephrine-induced pulmonary thromboembolism models. The notion that targeting polyP interferes with thrombosis while sparing hemostasis confirms that polyP exerts its procoagulant activity via FXII. FXII is the only coagulation factor that critically contributes to thrombosis but has no role in hemostatic mechanisms (reviewed in Renné and Stavrou[109]). Due to concerns regarding the significant toxicities of anti-polyP agents including dendrimers and other cationic small molecules,[110,111] a new nontoxic, thromboprotective dendrimer-like cationic

polyP-blocking compound class was introduced in 2016. Two of these novel universal heparin reversal agents (UHRAs), UHRA-9 and -10, significantly reduced arterial thrombosis in vivo and did not indicate any signs of fibrinogen aggregates, inflammation, tissue damage, or necrosis. UHRA-9 and -10 also displayed a lower bleeding risk compared with therapeutic doses of heparin. In a more specific approach, recombinant *E. coli* Ppx was shown to specifically bind and degrade polyP. Targeting polyP with Ppx abolished polyP procoagulant activity in human plasma and in experimental thrombosis models in vivo while sparing hemostasis, demonstrating that polyP is procoagulant in a FXII-dependent manner in vivo.[79]

Summary and Conclusions

- NETs and polyP are physiologic polyanions with potent procoagulant activity.
- PolyP triggers coagulation by activating FXII, while both FXII- and TF-driven pathways contribute to NET-stimulated coagulation.
- The crosstalk between NETs and polyP plays an important role in coagulation and thrombosis.
- PolyP forms Ca^{2+}-rich nanoparticles independently of the polyanion chain lengths that are retained on procoagulant platelet surfaces in vivo.
- DNase1 digests NETs in vivo and provides a promising strategy to therapeutically target NETs during thrombosis.
- Cationic nucleic acid-binding molecules, recombinant exopolyphosphatase mutants, and universal heparin reversal agent (UHRA) target polyP-driven thrombosis while sparing hemostasis, indicating that polyP functions via FXII activation in vivo.

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Conflict of Interest

None declared.

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