Chapter 7

Endothelial Cell von Willebrand Factor Secretion in Health and Cardiovascular Disease

Luiza Rusu and Richard D. Minshall

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.74029

Abstract

The main function of von Willebrand factor (vWF) is to initiate platelet adhesion upon vascular injury. The hallmark of acute and chronical inflammation is the widespread activation of endothelial cells which provokes excessive vWF secretion from the endothelial cell storage pool. The level of vWF in blood not only reflects the state of endothelial activation early on in the pathogenesis, but also predicts disease outcome. Elevation in the blood level of vWF occurs either by pathologic increase in the rate of basal vWF secretion or by increased evoked vWF release from dysfunctional/activated endothelial cells (ECs). The increase in plasma vWF is predictive of prothrombotic complications and multi-organ system failure associated with reduced survival in the context of severe inflammatory response syndrome, type II diabetes mellitus, stroke and other inflammatory cardiovascular disease states. This chapter focuses on the role of high circulating vWF levels in thrombotic and inflammatory disease while paying attention to the emerging vWF-related drug development strategies.

Keywords: cardiovascular disease, endothelial activation, von Willebrand factor, hemostasis, thrombosis, inflammation, ADAMTS-13, vWF-related therapeutical strategies

1. Introduction

Endothelial dysfunction, often as a result of chronic activation, is a primary determinant of the severity of disease states. Apart from other cell-specific defects, activation of endothelial cells (ECs) increases platelet binding to von Willebrand factor (vWF), a multimeric blood protein primarily synthesized, stored and secreted by ECs [1–6]. Under physiological conditions, vWF is secreted from ECs via two pathways that enable hemostasis; a continuous or basal secretory pathway that maintains a baseline blood vWF level, [7] and the other, a regulated secretory

pathway induced by agonists such as thrombin [8, 9]. Basal vWF secretion involves elements of regulated secretion, with vWF targeted to Weibel-Palade bodies (WPBs) after Golgi processing, but continuously secreted from the storage pool [7]. Release of WPB contents into the extracellular space upon thrombin stimulation of ECs, thought to be pathophysiologically relevant in inflammatory cardiovascular disease, occurs via several processes: (1) signaling via $[Ca^{2+}]$/Gαq and Gα12/α-soluble NSF attachment protein (α-SNAP) [10] that (2) promotes engagement and activation of vesicle (v) and target (t) membrane-associated v-SNARE and t-SNARE proteins (vesicle- and target-soluble NSF attachment protein receptors) [11, 12] and (3) energy-dependent fusion of WPB with plasma membrane that promotes the formation of a secretion pore through which the exocytosis of WPB contents occurs [13–15].

Once secreted from WPBs, vWF circulates in a globular conformation under resting conditions [16] and is a carrier for circulating coagulation factor VIII, thereby protecting it from degradation [17–19]. The blood vWF level in health and inflammatory disease is predominantly EC derived, while the contribution of platelets is rather minimal [20]. In response to high shear stress and inflammatory mediators [21], normally quiescent ECs secrete long vWF multimers in large quantities from the storage pool into systemic circulation. vWF multimers are then extracellularly cleaved by a metalloprotease ADAMTS-13 (A Disintegrin and Metalloproteinase with a thrombospondin type 1 motif, member 13), unfold in the circulation and self-associate into particularly linked concatemers to form ultra-large vWF strings [22]. Platelets spontaneously bind to activated vWF via glycoprotein Ibα (GpIbα) interaction with the exposed A1 domain, initiating the thrombogenic process [23–26]. In addition to its classical role in platelet binding, the vWF A1 domain also plays a role in vWF-dependent inflammatory responses [27–29]. In this chapter, we will discuss the most recent findings related to vWF secretion from ECs, the finely tuned balance of vWF level and activity in hemostasis and thrombosis, and the mechanisms by which vWF/ADAMTS-13 axis links inflammation and thrombosis. The potential of vWF as a target in antithrombotic therapies is also discussed.

2. Molecular mechanisms of vWF secretion

2.1. von Willebrand factor and Weibel-Palade bodies at a glance

WPBs are unique secretory granules in ECs, which were first discovered in the 1960s by transmission electron microscopy [30]. Later on, vWF was identified inside WPBs of cultured human ECs [4, 5, 31]. vWF synthesis and maturation trigger WPB biogenesis [32, 33]. vWF is the best example of a protein that drives its own organelle formation [5, 34, 35]. To date, the structure of vWF consists in domains arranged as follows: D1D2D'D3A1A2A3D4C1C2C3C4C5C6CK. Of these, D1D2 is the pro-peptide and, the rest, from D'-CK is the fully functional, mature vWF [36]. The high density of vWF in the secretory granules enables a bolus of fully functional vWF to be released at the site of vascular injury or inflammation, which will promote efficient platelet binding and hemostasis or lead to thrombosis [37]. The physiological importance of proper WPBs formation can be appreciated in the context of various disease states associated with the release of immature, defective or low levels of VWF due to altered Golgi multimerization or defective tubular packing in WPBs (i.e. type 2B von Willebrand disease (vWD)) [38, 39].

WPBs originate from clathrin and clathrin adaptor-protein1-coated vesicles, [35, 40] which, when loaded with vWF cargo, bud from the trans-Golgi network, continue to mature and vWF contained in them becomes densely pack and highly multimeric vWF [35]. Once the vesicles had formed, they lose the clathrin coat, and the interactions between WPBs and the actin cytoskeleton are thought to either tether WPBs to the perinuclear cytosolic compartment or to relocate WPBs in the proximity of the plasma membrane in preparation for fusion and exocytosis [41]. Upon secretion of its contents, WPBs dissociate from the membrane and are recycled and refilled [35].

Interestingly, vWF secretion is influenced by plasma sodium level [42]. In mice subjected to mild water restriction, elevated endothelial vWF protein levels correlated with increased number of micro thrombi in capillaries [42]. Hypernatremia causes up-regulation of vWF gene expression via nuclear factor of activated T-cells 5 (NFAT5) binding to the vWF promoter [42]. Another regulator of vWF was found to be autophagy [43]. Endothelial cell-specific ATG7 (critical factor in autophagy) deficient mice have prolonged bleeding times as compared to control, and decreased vWF secretion of immature vWF [43].

At least two different secretion mechanisms of WPB cargo have been reported so far: selective, time-dependent 'kiss-and-run' release [13] and differential release of the distinct components of these storage granules [8]. Apart from vWF, WPBs also contain other inflammatory and vasoactive mediators: P-selectin, Rab-27, coagulation factor XIIIa, tissue plasminogen activator, interleukin-8 (IL-8), eotaxin, endothelin-1, endothelin-converting enzyme, calcitonin-gene-related peptide, α1,3-fucosyltransferase VI and angiopoietin 2 [44]. vWF and the other components—stockpiled in and liberated as needed from WPBs—provide the ECs with the ability to react acutely to restore homeostasis; vWF plays a role in hemostasis and thrombosis, and also, in the regulation of inflammation [45], vascular permeability [27] and angiogenesis [46].

vWF is synthesized exclusively by ECs, megakaryocytes and platelets and stored in specialized secretory granules. EC WPBs and platelet α-granules share several characteristics, as both organelles contain vWF, P-selectin and CD63 [47, 48]. But, in platelets, vWF detection by immune-gold labeling is restricted to a subset of spherical α-granules [48]. In this vane, spherical secretory α-granules are quite distinct from WPBs. First, the vWF content of platelets is relatively low: 0.05–0.1 U per 3×10^8 platelets [49]. For comparison, plasma vWF concentration is 1–1.8 U/mL (10 μg/mL blood), of which only 15% of plasma vWF comes from platelets, while the majority 85% of the total vWF comes from ECs [4, 20, 34, 50]. Second, ECs combine basal and regulated vWF release, while platelets do not have a mechanism of basal secretion and, thus, substantial platelet activation would be needed for platelet vWF secretion to significantly contribute to the elevated blood vWF observed in different disease states. Finally, excessive secretion of EC-derived vWF in inflammation is attributed to the large capacity of ECs to make and store vWF in EC-specific storage pool, that is, in WPBs.

Thus, EC secretory granules supply the vasculature with circulating vWF to control hemostasis and thrombosis, while platelets play only a secondary role in this process [20, 49]. A balanced level of EC-derived vWF is critical to overcome the thrombotic complications in pathological settings, therefore it is important to understand the underlying endothelial constitutive and evoked exocytosis mechanisms which provide the bloodstream vWF in health and disease.

2.2. Basal versus regulated vWF secretion

Secretion of vWF occurs by one of the following three modes:

1. regulated secretion from WPBs, in response to a specific agonist (secretagogue) on-demand upon vascular injury [51, 52];
2. basal (constitutive-like or continuous) secretagogue-independent secretion of vWF from WPBs [7];
3. constitutive, secretagogue-independent release of vWF from non-WPB compartments [34, 40].

Over the years, there have been in the field opposite views about how much vWF is released through each of these three pathways and what determines the balance between basal (constitutive-like) and regulated vWF secretion is still under debate [34, 53, 54].

2.2.1. Basal vWF secretion

In resting ECs, secretion of vWF was thought to take place predominantly via conventional constitutive vWF secretion which is susceptible to protein synthesis inhibitor cycloheximide [34]. However, the importance of this pathway was exaggerated initially, as it could be drawn from the more recently published studies listed below. A vWF multimeric analysis in ECs challenged this view, indicating that highly multimeric vWF might be released solely from WPB storage pool [53]. Most recently, the issue was revisited when a study using metabolic labeling of vWF in human umbilical vein ECs (HUVECs) showed that most of the vWF secreted from unstimulated cells is not mediated by conventional constitutive secretion, but rather by basal release from the WPBs [7, 55]. Giblin and colleagues [7] recently brought more evidence to dismiss the belief that multimeric vWF passes uninterrupted from the Golgi to plasma membrane. They showed that freshly synthetized vWF is held for at least 24 h in WPBs before unstimulated release occurred, escaping cycloheximide-induced inhibition of protein synthesis, and, thus, consistent with release from the storage pool [7]. Similarly, Romani de Wit and coworkers [56] studied the dynamics of GFP-vWF-positive WPBs in resting HUVECs over time, and they were able to capture multiple image frames of WPBs traveling long distances toward the cell periphery. Intriguingly, resting ECs displayed membrane-apposed accumulation of GFP-vWF-containing vesicles [33, 56, 57]. It is worth mentioning here that only whenever a component of the cytoplasmic machinery is ablated the constitutive vWF secretion becomes predominant [40]. Taken together, these studies of WPBs behavior suggest that only the multimeric form of vWF is stored and that ECs secrete multimeric vWF via a continuous secretory pathway, which is a source of vWF in the bloodstream. If the WPB storage compartment is the source of the continuously secreted form of vWF that travels in the bloodstream, then the ability to regulate this constitutive vWF secretory route has significant clinical implications. Disruption of continuous vWF secretion may be implicated in the pathophysiology of type 2 vWD, which is due to both reduced vWF-dependent platelet function and reduced highly multimeric vWF in plasma.

2.2.2. Regulated vWF secretion

The release of vWF from the regulated pathway occurs only following stimulation of ECs with an appropriate agonist, providing the endothelium with the means to react to its microenvironment by finely tuning the rate of release.

The notion that blood collected under stress clots faster was known for a while. In the 1970s, it was found that desmopressin (a synthetic analog of vassopresin) can elevate vWF level twofolds in healthy individuals [58] The follow-up studies showed that desmopressin activates vasopressin receptor 2 (V2R) on ECs and triggers cyclic adenosine monophosphate (cAMP)-mediated release of vWF from EC WPBs [58]. A multitude of agonists have been reported to induce vWF release via regulated secretion. These include thrombin [51], calcium ionophores [34], hypoxia [59], vasopressin [58], histamine [14], complement [60], platelet-activating factor [61] and interleukins [62]. Importantly, high shear stress is modulating regulated vWF release [63].

2.3. G protein signaling in hemostasis and thrombosis

In order to understand how to control WPB secretion for therapeutic purposes, the signaling mechanisms of vWF secretion need to be elucidated.

The exocyst is a cytoplasmic protein complex which targets secretory granules from the trans-Golgi network to the plasma membrane; it facilitates docking and priming of the secretory granule to the plasma membrane, prior to SNARE-mediated fusion [64]. When WPBs are trafficked to the plasma membrane, the vesicles are aligned such that v-SNAREs from the vesicles and t-SNAREs from target membrane can assemble as α-helix zippers which pull the membranes together. This SNARE zipper model was studied in detail in synapses [65]. Interestingly, all major players of these complexes identified in neurons are also present in the endothelium, including SNAP23, syntaxin 2, 3 and 4, and vesicle-associated membrane protein 3 (VAMP3) complex which are thought to regulate vWF exocytosis [11].

Release of WPBs contents into the extracellular space is thought to occur via GTPase-dependent processes [10]. It has been postulated that G proteins mediate cell type and signaling microdomain-specific functions. According to the classic G protein signaling model, heterotrimeric G proteins are located in the proximity of the plasma membrane where they can be activated by seven transmembrane spanning receptors, the canonical G protein-coupled receptors (GPCRs), to provoke downstream signaling events. G proteins are GTPases that typically function through GTP hydrolysis and cycling between nucleotide free GDP-bound and GTP-bound forms. GTPases also control the timing and specificity of vesicle trafficking and the exocyst partners recognition events, without GTP hydrolysis [66, 67]; the distinction between cycling and non-cycling GTPases might be more obvious when examining the effect of GTP hydrolysis-deficient mutant proteins that would be expected to cause gain-of-function on non-cycling GTPases and loss-of-function on cycling GTPases [66]. Furthermore, several studies indicate heterotrimeric G proteins can rapidly shuttle between the plasma membrane and intracellular membranes to exercise their function upon cell-specific organelles, along the

secretory routes. Activation of GPCRs and G protein α and $\beta\gamma$ subunits of Gs, Gi, Gq/11 and G12/13 can stimulate secretory granule release [10, 68]. It has been shown, for example, by fluorescence polarization, that G protein i/o $\beta\gamma$ subunit competes with synaptotagmin for specific interaction sites on t-SNAREs, namely syntaxin 1 and SNAP25B (Synaptosomal-associated protein 25) [69]. G protein i/o binds to the SNARE at the plasma membrane, but in the presence of synaptotagmin and calcium, inhibits vesicle fusion with the plasma membrane, suggesting the G $\beta\gamma$-SNARE axis has an inhibitory role during synaptic exocytosis [69]. In the exocrine pancreas, G proteins have been shown to play a role in early transport events [68].

A role for G proteins Gαq/11 and Gα12/13 in hemostasis has been previously reported [70, 71]. Platelets from Gαq-deficient mice fail to respond to low doses of platelet-activating agonists and these mice have prolonged bleeding times and reduced thrombus formation after intravenous administration of adrenaline/collagen [71, 72]. Studies in megakaryocyte-restricted Gα12/13 double knockout mice reveal that these mice have prolonged bleeding time and reduced thrombus formation, suggesting that Gα13-dependent signaling in platelets is also relevant for hemostasis and thrombosis [70]. Interestingly, we found that, in addition to Gαs stimulatory-G protein [58, 73], Gα12 and Gαq/11 facilitate exocytosis of vWF from ECs [10]. Importantly, in Gα12 overexpression studies, Gα12 is able to localize to the plasma membrane because of its palmitoylation at cysteine 11 [74]. Palmitoylation targets Gα12 to lipid rafts fractions [75]. Both wild-type Gα12wt and Gα12QL (constitutive active) were observed in lipid rafts fractions, and therefore, the localization of Gα12 to discreet endothelial microdomains may be independent of Gα12 activation [76]. Other studies reported direct G protein-dependent regulation of the SNARE protein fusion machinery is required for secretory granule exocytosis [77], and Gα12 was shown by the yeast two-hybrid method to interact with a member of the exocytotic assembly, α-SNAP [66]. Using cultured human ECs and knockout mouse models, we showed that depletion of Gα12 or α-SNAP inhibited both basal and thrombin-induced vWF secretion and that G$\alpha 12^{-/-}$ mice exhibit mildly reduced blood levels of vWF, but intact vWF multimeric pattern, and impaired thrombus formation [10]. Our studies suggest that Gα12 may interact directly with α-SNAP to promote the docking and fusion of WPBs [10]. Furthermore, Gα12 and Gαq subunits, which are known to regulate actin cytoskeleton rearrangements in ECs via activation of RhoA GTPase, promote WPB docking on the plasma membrane, providing both direct and indirect mechanisms linking GPCR activation and SNARE complex fusion [10].

2.4. Kinetics of WPB secretion

Secretion of vWF from ECs is mediated by fusion of WPBs with the plasma membrane in a manner dependent on the ATPase N-ethylmaleimide-sensitive-factor (NSF), soluble-NSF-attachment protein alpha (α-SNAP) and SNAREs [78]. NSF binds to SNARE complexes to facilitate the disassembly of the zippered bundles [79]. Because NSF lacks a direct binding domain for members of the SNARE family, it connects via an adaptor, α-SNAP [80]. Six NSF proteins assemble together at the plasma membrane, and each NSF hexamer requires three α-SNAPs to mediate binding to the SNAREs [78]. Once the NSF/α-SNAP/SNARE complex is formed, NSF hydrolyses ATP, providing the energy necessary for the disassembly of the

SNARE complex [81]. Therefore, the rate of exocytosis depends on α-SNAP and NSF activity [78]. Using PC12 cells as an α-SNAP-regulated exocytosis model, it was shown that α-SNAP, in absence of NSF activity, can actually block exocytosis and that this α-SNAP-dependent event occurs by direct binding of α-SNAP to free syntaxin, thus preventing SNARE complex assembly [82]. It is documented that α-SNAP is activated in the exocyst complex by phosphorylation [83], that α-SNAP binds and stimulates NSF ATPase activity, [84] that Gα12 interacts with α-SNAP, [66] and that S-nitrosylation of NSF inhibits WPB exocytosis [85]. α-SNAP regulates exocytosis of granules from different types of cells [86]. α-SNAP binding to the SNARE complex in the fused membrane mediates recruitment and activation of NSF resulting of exocytosis from ECs [10, 87]. The Gα12 binding site for α-SNAP was recently identified by using a library of substitution mutants within myc-tagged Gα12QL in which regions of the cDNA encoding consecutive six aminoacids were replaced with a sequence encoding the following six aminoacids: asparagine-alanine-alanine-isoleucine-arginine-serine (NAAIRS) by oligonucleotide-directed mutagenesis and expressed in a cell line as described previously [88], followed by evaluation of direct binding between Gα12 NAAIRS mutants and α-SNAP by glutathione S-transferase (GST) pulldown [10]. Based on the evidence generated by the GST pulldown assay, we constructed an α-*S*NAP *B*inding *D*omain peptide to which we added a myristoyl group and micellar nanoformulation for cellular entry, to further assess the role of Gα12 interaction with α-SNAP in vWF secretion [89, 90].

2.5. Spatial and temporal regulators of the exocyst complex

Secretion of vWF from ECs is mediated by small GTPases via both second messengers Ca^{2+} and cAMP-dependent signaling pathways [91–93]. Small GTPases are the effectors of the exocyst complex, involved in temporal coordination, spatial segregation and proof-reading of membrane trafficking events [94]. Rab and Ral GTPases are thought to be involved in vesicle tethering, whereas RhoGTPases are spatial regulators of the exocyst complex [95].

RalA was the first GTPase found to co-sediment with WPBs in density gradients [96]. Ral A is activated by its exchange factor, Ral guanine-nucleotide dissociation stimulator (RalGDS) [97], which is kept inactive by β-arrestin under static conditions [98]. Upon GPCR activation, Ral GDS uncouples from β-arrestin and functions in its GTP-bound state. RalGDS downregulation with siRNA in thrombin-stimulated HUVECs leads to accumulation of WPBs in the proximity of the plasma membrane, but exocytosis is incomplete, suggesting RalGDS/ β-arrestin complex is necessary to link thrombin receptors to WPBs exocytosis [98]. Ral A facilitates WPBs trafficking and delivery to the plasma membrane [91]. Ral A has been implicated in actin cytoskeleton dynamic rearrangements through its direct interactions with effectors filamin A and RalBP1/RLIP76 (a RAC/CDC42 guanine-nucleotide activating protein (GAP) [99]. RalBP1 links RhoGTPases and RalGTPases, and, of note, RalBP1 GAP has an ATP binding domain, although it is not clear whether this domain is a motor required for assembly of the exocyst [99]. Studies conducted in our laboratory suggest that human pulmonary artery ECs treated with filamin A siRNA attenuates constitutive and thrombin-induced vWF secretion [100]. It has been proposed that Ral A/Ca^{2+}-dependent signaling might be a prerequisite for the exocytotic machinery [101].

The second point of intervention for the Rab and Ral GTPases is anchoring and fusion of WPBs with the plasma membrane [8]. Ral A also promotes exocytosis by increasing phospholipase D1 (PLD1) activity and subsequent phosphatidic acid (PA) production, thereby facilitating plasma membrane fusion as described in more detail in Section 2.6 of this chapter. The Rabs are a family of over 60 members of small GTPases that control membrane identity and the actions of the intracellular vesicles; each type of secretory vesicle in the cells has a unique set of Rab family members, as reviewed in [102]; of these, six Rab proteins were found in association with WPBs:Rab3 isoform b [103], Rab3 isoform d [104], Rab27a [105], Rab3 isoform a, Rab15, Rab33a, Rab37 [106] and Rab35 [107]. Rab 27a is located on the cytosolic face of WPBs, is used as a marker of organelle identity, and has multifunctional capacities: it could either mildly inhibit the secretion of WPBs by associating with its effector MyRIP (myosin VIIa and Rab-interacting protein), thus anchoring WPBs to actin filaments and keeping them from attaching to the plasma membrane until the right timing, [57] or it could strongly activate the secretion of WPBs by associating with an alternate effector, synaptotagmin-like protein 4 (or granuphilin) (Slp4-a), [108] which links the secretory granules to the plasma membrane via syntaxin-binding protein 1 and syntaxin 2 and 3 [108, 109]. The ratio of Rab27a occupancy by Slp4-a or MyRIP dictates whether Rab27a is stimulatory or inhibitory with regards to WPB exocytosis [103]. Furthermore, Rab27 was shown to work synergistically with Rab15 to control exocytosis; Zografou et al. recently showed that simultaneous knockdown of the two Rabs using siRNA in HUVEC leads to a greater reduction in vWF secretion compared with knockdown of either Rab alone [106]. Their experiments further showed that Munc13-4, a known effector of Rab27a, co-localized with Rab15 on WPBs. The three proteins, Rab27a, Rab15 and Munc13-4, thus form a complex and work in tandem to help regulate exocytosis of vWF [106]. Rab 33b has an inhibitory effect on vWF secretion [106].

A recent genome-wide screen identified a completely new signaling pathway associated with WPB exocytosis. Rab 35, which is controlled by Rab GAP TBC1D10A, promotes ACAP2 (ArfGAP with coiled-coil, Ank repeat and pleckstrin homology domain-containing protein) activation, which inhibits histamine-induced Ca^{2+}-dependent vWF and P-selectin expression in human ECs. This study used constitutively active mutants of Rab35, downregulation with siRNA and a fluorescence activated cell sorting (FACS)-based vWF secretory assay to prove that Rab35 promotes histamine-induced vWF secretion in a TBC1D10A- and ACAP2-dependent manner [107]. Of note, ACAP2 GAP targets Arf 6 which is a positive regulator of vWF secretion from human ECs, as shown by total internal reflection fluorescence (TIRF) microscopy and FACS-based vWF secretory essay [107]. Arf 6 GTPase activity at the plasma membrane elevates phosphatidylinositol 4,5-bisphosphate (PI (4,5) P_2) levels via PI (4)P5-kinase activation, acting antagonistically to Rab35 through TBC1D10A Rab GAP [107]. Finally, among the Rabs found to be in association with WPBs, only Rab27 is known to be involved in basal secretion [57, 108].

2.6. Endothelial cell secretory microdomains

GTPase-mediated exocyst activity of the SNARE assembly occurs in specific regions of the plasma membrane with distinct lipid profiles [110]. Namely, we know there is an increase in

PA production in HUVECs upon stimulation with histamine, which is a known agonist to induce exocytosis of WPB contents [111]. The increase in PA production is mediated by recruitment and activation of PLD1, an enzyme that hydrolyses phosphatidylcholine to produce PA [111]. PLD1 downregulation using shRNA resulted in a reduced secretion of vWF upon histamine stimulation [111]. PLD1 is commonly thought of as a general promoter of membrane fusion because of its role in producing fusogenic conical lipids such as PA [112]. PLD1 requires activation by one or more factors specific to the cell type and activation pathway, including small GTPases such as those of the ADP-ribosylation factor/Rho families as well as RalA, RalGDS or protein kinase C [113]. Thus, RalA and RalGDS not only play a role in the exocytosis process itself, as discussed in Section 2.5, but are also directly associated with the cytosolic face of WPBs. Therefore, it has been suggested that RalA could serve as an upstream activator of PLD1, promoting PLD1 movement to the membrane and subsequent generation of PA-enriched membrane microdomains important for membrane fusion [97].

2.7. Zyxin and other proteins that regulate vWF release from endothelial cells

Data published by Han et al. show that zyxin, a focal adhesion LIM domain-containing protein, is involved in thrombin-mediated remodeling of the actin cytoskeleton [114]. The molecular structure of zyxin predicts its function in cytoskeletal dynamics [115]. Zyxin has proline-rich repeats at the N terminus followed by a leucine-rich nuclear export signal (NES) and three copies of a cysteine- and histidine-rich motif called the LIM domain at the C terminus [115]. Regulators of cytoskeletal dynamics, such as Enap/vasodilator-stimulated phosphoprotein (VASP) family members and α-actinin interact with the proline-rich region of zyxin. Zyxin can generate new actin structures in a VASP-dependent manner, independently of the Arp2/3 complex that cooperates with members of the Wiskott-Aldrich syndrome family of proteins (WASP) to nucleate actin filaments [114, 116]. Zyxin is a VASP-dependent actin polymerization machine in cells [117], and Han et al. showed zyxin binds to the C-terminal domain of protease-activated receptor 1 (PAR-1) [114]. Upon disruption of PAR-1-zyxin interaction, thrombin-induced formation of actin stress fibers was inhibited further supporting the hypothesis that zyxin functions as a signal transducer in PAR-1 signaling. In contrast, downregulation of zyxin did not affect thrombin-induced activation of RhoA or Gi, Gq and G12/13 heterotrimeric G proteins, implicating a novel signaling pathway regulated by PAR-1 that is not mediated by G proteins. Depletion of zyxin using siRNA inhibited thrombin-induced actin stress fiber formation and serum response element (SRE)-dependent gene transcription. In addition, depletion of zyxin resulted in delay of endothelial barrier restoration after thrombin treatment. In 2017, Han et al. reported that downregulation of zyxin in HUVECs with shRNA inhibits cAMP-dependent secretion of vWF [116]. In zyxin shRNA-expressing cells, formation of the actin framework around exocytic WPBs was scarce. Moreover, phosphorylation of zyxin at serines 142 and 143 (S142/S143) is critical for vWF secretion since the zyxin mutant could not rescue the defect in zyxin shRNA-treated cells [116]. They showed that a protein kinase A (PKA)-specific inhibitor blocked zyxin phosphorylation at S142/S143 and concluded that zyxin acts downstream of PKA [116]. Han et al. thus proposed a novel model for cytoskeleton reorganization around WPBs undergoing exocytosis. Upon epinephrine stimulation, pre-existing filaments are reorganized to form actin frameworks

around exocytotic granules, limiting granule movement and promoting their localization in close proximity to the plasma membrane [116]. Then, actin monomers are recruited from the cytosol to form coat structures around granules within actin frameworks that promote fusion [116]. It was postulated that ECs use this synergistic strategy for effective and precise exocytosis. Under their experimental conditions, zyxin downregulation with shRNA had no effect on vWF release upon thrombin or histamine stimulation, whereas these mice exhibited impaired epinephrine-stimulated vWF release, prolonged bleeding time and thrombosis. Live cell super-resolution microscopy allowed visualization of zyxin-dependent reorganization of pre-existing actin filaments around WPBs before fusion. Using the total internal reflection fluorescence structured illumination microscopy (TIRF-SIM) technique, it was possible to achieve simultaneous visualization of the dynamics of fine cortical actin filaments and the behavior of the exocytotic granule in close proximity of the plasma membrane. Zyxin promotes the recruitment of the actin regulatory protein α-actinin; α-actinin is an actin crosslinking protein [114]. To prove the co-localization of zyxin with its interacting partners, they co-expressed zyxin construct tagged with mCherry for fluorescence microscopy detection (zyxin-mCherry) and Lifeact tagged with green fluorescence protein (GFP-Lifeact) (Life act is an actin binding peptide used in microscopy to monitor the behavior of actin filaments). Interestingly, the assembly of the pre-existing filaments started when WPBs were still tubular, so the formation of the actin framework appeared as a pre-fusion event by TIRF-SIM. Alexa Fluor 647-G actin incorporation assay indicated that pre-existing actin filaments reorganize to form the actin framework around the tubular WPBs, and G-actin was also recruited to form the actin coat structure in proximity to WPBs fused to the membrane and connected with the actin frameworks. Once WPBs became spherical and fluorescently-labeled, vWF was expulsed and fluorescence intensity declined in the expulsed area. The authors explain that the exocytotic events shown by variable-angle TIRF are mediated by the contraction of the actin coat which squeezes out WPB contents, followed by retraction of the depleted WPBs in the cytoplasm [116].

3. Dynamics of vWF reactivity in acute diseases

3.1. vWF as a surrogate marker of endothelial dysfunction

Association between vascular dysfunction and increased vWF levels is well established. The first study found a correlation between factor VIII antigen (another name for vWF) and kidney vascular damage in the context of glomerulonephritis in the 1970s [118]. Since this time, there have been many reports of inflammatory diseases associated with elevated vWF, that is, in acute systemic inflammation disorders such as sepsis, acute respiratory distress syndrome or systemic inflammatory response syndrome [73], T2DM [119] and TTP [120].

Upon activation of ECs, vWF acts as an acute phase reactant and correlates with serum C-reactive protein (CRP) level, another acute phase reactant [121, 122]. Other hemostatic proteins also behave in this way (i.e. factor VIII, fibrinogen and plasminogen inhibitor 1). Active vWF corresponds to the form of vWF required for platelet receptor GpIb binding [123–125].

Detection of active vWF is now possible using an assay based on a nanobody AU/vWF a11 which allows investigators to distinguish between the active and latent conformations of the vWF A1 domain [123]. Several pathological conditions are associated with a disturbed balance in vWF activation and inactivation kinetics and thereby increased levels of active vWF and thrombotic complications [126]. The same active vWF assay revealed that levels of circulating active vWF increased approximately twofold in patients with acquired and congenital TTP [123, 126]. More and more evidence indicates that vWF is a biomarker of EC activation, but there are numerous discrepancies among the various clinical studies [127, 128]. In a more recent effort to advance the use of plasma vWF as a clinical marker of vascular inflammation, Hyseni et al. measured plasma concentrations of active vWF in a cohort of 275 patients with systemic inflammatory response syndrome [45]. They reported that patients with an elevated level of active vWF on admission had a twofold higher mortality rate [45]. In contrast, despite strongly elevated vWF levels, no predictions of mortality could be obtained based on total vWF [45]. Elevated active vWF is thus now regarded as an independent biomarker of poor outcome in patients with acute lung injury [129]. Mechanical ventilation is necessary to support the critical ill, but it also exacerbates injury through mechanical stress-activated signaling pathways, therefore it is expected to affect the disease outcome [130]. Consistent with these findings, an earlier 28-day study of 50 patients van der Heijden et al. reported that high vWF levels correlated with pulmonary compliance [Vt/(Pplat –PEEP)], where Vt = tidal volume, Pplat = plateau pressure, PEEP = positive end-expiratory pressure throughout the course of septic shock while patients were mechanically ventilated [131].

3.2. vWF/ADAMTS13 axis in vascular health and disease

In order to fulfill its functions, vWF remodels in a few distinct ways [16, 132–136]. In ECs, vWF forms tubular structures inside acidic WPBs secretory granules [137]. The switch that converts highly packed vWF tubules into ultra-large vWF strings in the blood stream is critically important but poorly understood. Recently, more insight has been gained into the mechanism of rapid transition from tightly packed vWF tubules into intraendothelial granules to vWF strings that function at physiological pH. It is likely that distal to the fused end of the WPB, alkalinisation induces a rapid conformational change in the structure of vWF, which propagates causing vWF to unfurl in a concerted manner at the site of secretion, resulting in the loss of the storage conformation [132].

The highly multimeric, elongated form of vWF is not present in healthy plasma, but it is found in various pathological settings. This observation can be explained by the fact that vWF senses shear forces and remodels accordingly [134]. Atomic force micrographs have demonstrated at the single molecule level that under static conditions, vWF assumes a globular conformation, whereas, under high shear flow, vWF turns into an extended chain format [16] that forms ultra-large strings to which platelets bind to initiate clot formation at sites of vascular damage [25] and, when shear stress is above 30.000 s^{-1}, factor VIII is released from its carrier protein to provide factor VIII to the coagulation cascade [138]. We now realize that, while ultra-large MW (molecular weight) vWF is essential for the normal hemostasis, this multimeric array should not become too large because it alters the thrombotic propensity [15, 16, 133, 134, 138–147].

The last biosynthetic step required for the formation of normal vWF is the limited proteolysis of the multimeric array by the circulating metalloprotease ADAMTS13 [126, 135]. ADAMTS-13 is produced mainly by the hepatic stellate cells [148]. Secondarily, the enzyme is synthesize in other cell type (ECs, podocytes, platelets and glial cells), but the physiological importance of these other sources was not yet established [149]. ADAMTS-13 plasma concentration is in the range of 0.7–1.4 μg/mL [150]. Interestingly, ADAMTS-13 is secreted into the circulation as an active enzyme and has a plasma half-life of approximately 2–4 days [151]. The mechanism of ADAMTS-13 clearance is not completely elucidated. It has been suggested that the hepatic asialoglycoprotein receptor could be involved in ADAMTS-13 clearance [152]. It is believed that newly released multimeric forms of vWF become tethered to the EC surface through the interaction with P-selectin [153, 154] and become partially unfolded [16], allowing for ADAMTS13 cleavage of the multimeric arrays [136]. The physiological proteolytic processing of vWF by ADAMTS13 occurs between Tyr1605-Met1606 in the central A2 domain of vWF, and is facilitated by partially unfolding vWF by flow conditions in the microcirculation [124, 126, 155–162].

Too little cleavage of the newly released vWF produces a tendency for microvascular thrombotic occlusion, as in TTP [120], and too much cleavage by ADAMTS13 results in type 2 like vWD and a bleeding phenotype [38]. Cleavage is dramatically increased during systemic inflammation [45] and other prothrombotic conditions, and there is an inverse relationship between plasma levels of vWF and ADAMTS-13; under high shear stress/inflammatory conditions, the circulating vWF can acquire autoimmune resistance to proteolysis by ADAMTS-13 or ADAMTS-13 is quickly exhausted as there is more vWF to cleave than available cleaving enzyme for consumption [45]. Additionally, a decrease in the vWF-inactivating protease ADAMTS13 is dependent on the severity of the disease and organ dysfunction [163].

In mice models, vWF-deficiency abrogates the ADAMTS13-deficient prothrombotic state [164] and endotoxemia-induced thrombosis in mice [165], consistent with the observation that vWF-deficient mice subjected to the polymicrobial model of sepsis exhibit increased survival [29]. It has been recently reported that neutrophil-derived small peptides or human neutrophil peptides (HNPs) also known as α-defensins can inhibit cleavage of vWF by ADAMTS13 [166]; these peptides [167] have sequence similarities with the ADAMTS-13 spacer domain RRY motif and can bind to the cleavage site for ADAMTS-13 on the vWF A2 domain. It was shown that HNPs levels are high in TTP patients [166]. Pro-inflammatory cytokine IL-6 limits ADAMTS-13 function [168, 169], while IL-8 and TNF-α stimulate further the release of vWF from WPBs [168].

In conclusion, excessive levels of the highly prothrombotic and multimeric form of vWF and/or ADAMTS13 deficiency constitute a unifying pathologic mechanism linking inflammation to thrombosis [170].

3.3. vWF role in ischemic stroke

Stroke remains a major health concern and a leading cause of death in the adult population. As a result of intracerebral thrombosis, cerebral ischemia/reperfusion injury causes brain tissue

damage [171]. vWF promotes intracerebral thrombo-inflammatory response in the context of acute stroke [167, 172–175] and the vWF/ADAMTS13 axis was found to be involved in acute and chronic ischemic cerebrovascular events in patients [175]. vWF-deficient mice are protected from ischemic stroke [174]. It is well known that circulating vWF originates primarily from the endothelium, with a minor contribution from platelets [20]. Our current understanding of the role of different pools of vWF in the pathophysiology of acute stroke is based on mouse models [176]. EC-vWF mice are chimeric mice that express vWF only in ECs. Irradiated mice transplanted with bone marrow from vWF−/− mice to repopulate myeloid cells lack vWF in platelets but express vWF in ECs. Plt-mice are chimeric $vWF^{-/-}$ mice transplanted with normal bone marrow, and therefore have vWF in platelets [176]. The wild-type (WT), $vWF^{-/-}$, Plt-vWF and EC-vWF mice were subjected to 1 h ischemia followed by 23 h reperfusion and the outcome was compared [176]. The infarct volume and neurological outcome were comparable in WT and EC-vWF mice and decreased in $vWF^{-/-}$ mice. The stroke outcome in EC-vWF mice was documented using triphenyl-tetrazolium chloride-stained serial brain sections after 1 h transient middle cerebral artery occlusion. Also, it was observed in EC-VWF mice that there was a reduced local cerebral blood flow as assessed by Doppler flowmeter and a higher rate of thrombus formation in comparison to $vWF^{-/-}$ mice assessed by intravital microscopy. Stroke, infarction, vascular spasm and iatrogenic thrombotic events cause ischemia, which has a dramatic impact on vital organs. Post-ischemic reperfusion changes the pH, and extracellular alkalinization stimulates the physiological mechanisms that directly promote EC activation and can double vWF release in a $[Ca^{2+}]$-dependent manner [171]. Delaying the pH recovery with a Na^+/H^+ exchange subtype I pump inhibitor (applied in the perfusion media) [171] might prove to be a promising new way of inhibiting EC activation upon reperfusion injury. Taken together, EC-vWF seems to be the primary determinant of vWF-dependent ischemic stroke [171, 176], while platelet vWF plays a minor role [20, 176]. The ability to control vWF secretion from dysfunctional endothelium might be a valuable therapeutic target in stroke prone patients.

3.4. vWF role in sepsis

Apart from its primary role in hemostasis, vWF has a dual role in the pathophysiology of severe sepsis. On the one hand, vWF is involved in host-defense with a possible initial protective role in preventing complement activation [121]. In addition to its classical role in platelet binding, the vWF A1 domain also plays a role in vWF-dependent inflammatory responses. vWF and platelets promote leukocyte diapedesis, downstream of leukocyte tethering, rolling and adhesion in a mouse model of thioglycollate-induced peritonitis [177]. Polymorphonuclear leukocytes seem to directly interact with vWF via P-selectin glycoprotein ligand-1 and β2-integrins [178] As shown in mice in which inflammation was provoked by two different methods, [27] vWF-regulated leukocyte recruitment can be blocked by administration of a blocking anti-vWF llama nanobody, KB-VWF-006, which has picomolar affinity for the vWF A1 domain [27].

On the other hand, sepsis is not only a systemic inflammatory condition, it is also a state of dysfunctional endothelium and coagulation. One of the early on signs of systemic endothelial

activation is sepsis-induced elevation of plasma vWF levels [121, 129, 163, 179]. Sepsis can promote DIC, which is common in critically ill patients. When unfolded, highly multimeric sepsis-induced vWF interacts with platelets [26] and generates small clots in the microvasculature [45, 124]. Microvascular thrombosis appears to be a major pathological mechanism in sepsis pathology resulting in multi-organ dysfunction syndrome (MODS) [124]. Hence, sepsis-induced vWF secretion in excess in DIC and MODS are inevitably linked. In addition, sepsis-induced ultra-large high molecular weight multimeric vWF permits complement activation, [121] leading to a positive feedback cycle of inflammation and thrombosis.

In murine model of sepsis, mice subjected to cecal ligation and puncture (CLP) have increased circulating levels of vWF that promote a procoagulant phenotype and poor outcome [29]. vWF-deficient mice subjected to the CLP model of sepsis exhibit increased survival [180]. For the purpose of testing whether Gα12 modulates vWF secretion in sepsis pathological setting, we subjected G$\alpha12^{-/-}$ mice and WT control mice to the CLP model of polymicrobial sepsis and monitored survival [181]. Our preliminary results indicate that 80% of the G$\alpha12^{-/-}$ mice survived, while all WT mice succumbed in the first 96 h [182]. To further determine whether decreased vWF was responsible for the protective effect of G12 deficiency, we restored circulating vWF level in G$\alpha12^{-/-}$ mice, by intravenous administration of purified vWF [10], to the level observed in WT mice. This procedure resulted in the loss of the protective effect of G12 deletion [182]. Furthermore, we employed a pharmacological G12 inhibition approach to prove G12 involvement in sepsis-induced vWF secretion [183]. We hypothesized that a synthetic peptide derived from Gα12 would inhibit α-SNAP-dependent WPB priming and fusion with the plasma membrane [89, 182], thereby inhibiting vWF secretion from activated ECs, and reducing the risk of thrombotic microangiopathy during sepsis [182].

3.5. vWF role in other inflammatory diseases

Transient elevations of plasma vWF level were also observed after epinephrine infusion [184], and chronic elevation of circulating vWF (2–3-fold) was reported in hyperthyroidism, which is thought to be due to β-adrenergic receptor stimulation. In contrast, hypothyroidism is associated with a 15% decrease in vWF level, although this is reversible with appropriate treatment [185].

vWF secretion from ECs might play a role in sickle cell disease pathogenesis [186, 187]. Erythrocytes bind specifically to vWF [186] and stasis, or the reduction of blood flow and shear, promotes binding of erythrocytes to vWF which form fibrin-rich regions in venous thrombi [186].

4. vWF-related antithrombotic treatment strategies

Despite recent major advances in the vascular biology of thrombosis, we face unmet treatment needs which warrant search for novel antithrombotic medication. Inhibition of vWF secretion constitutes an attractive therapeutic strategy to counteract thrombus initiation and propagation as the plasma concentration of vWF increases in high risk populations and predicts cardiovascular disease outcome. In this section, we review the drugs with the potential of

vWF antagonism, illustrating how they might become an option to overcome current limitations of antithrombotic therapy.

Most of the studies involving anti-vWF antibodies were conducted in animal models. Monoclonal antibodies have been widely tested in murine, monkey and rabbit models of cardiovascular disease, including coronary thrombosis, stroke and in-stent stenosis: GPG-290, 6B4-Fab, AJW200, 82D6A6 and SZ-123 [188, 189]. These are all agents with antithrombotic and anti-inflammatory effects which do not prolong bleeding time and do not provoke thrombocytopenia. However, to date, none of these have made it into clinical trials. Hillgruber and colleagues recently published a study that found a massive accumulation of vWF in skin biopsies of patients suffering from leukocytoclastic vasculitis, an immune complex (IC)-mediated vasculitis (ICV) frequently encountered in dermatology that is caused by IC precipitation in the vessel wall followed by recruitment of neutrophils [28]. These results were confirmed in a murine model of vasculitis [28], and importantly, they identified ICs as possible vWF secretagogues. Of note, polyclonal anti-vWF blocking antibodies had an anti-inflammatory effect, reducing leukocyte recruitment and edema formation in a murine model of vascular inflammation [28]. Although the physiological implications of elevated vWF levels (increasing up to 400% of the normal level in various conditions [190, 191]) require additional investigation, it is currently believed that plasma vWF level is a surrogate marker of increased risk of vascular complications in septic patients and in those with vascular disease, which makes vWF antagonism a promising therapeutic target in thrombosis and inflammation.

Aptamers and nanobodies have been demonstrated to directly interfere with the vWF pathway, suggesting their powerful antithrombotic properties and acceptable level of safety may prove to be useful strategies. Aptamers are oligonucleotides that have similar characteristics with monoclonal antibodies and with small molecules. ARC1779 is an aptamer that binds to the A1 domain of vWF, blocking its interaction with GpIb and thereby inhibiting vWF-dependent platelet function. Clinical trials with ARC1779 were conducted and completed, but until truly meaningful clinical endpoints can be obtained that indicate effective inhibition of thrombosis without increasing bleeding, the utility of aptamers will remain unclear. Before the clinical trial was prematurely closed by the sponsor, the clinical and laboratory data after 14 days of dosing in nine patients with TTP aged 18–75 were very promising, and the authors optimistically proposed the study continuation (www.clinicaltrials.com; [192]) suggesting further development may be in order.

Nanobodies have the advantage of being highly specific therapeutic agents. Caplacizumab (ALX-0081) is an anti-vWF humanized nanobody that selectively targets vWF A1 domain, locking platelets launching on VWF A1 domain via interaction with their receptor GPIb. TITAN phase II trial concluded that caplacizumab administration in 75 patients with acquired TTP lead to a rapid resolution of the acute TTP episode, but it was adversely seconded by mild bleeding when compared to placebo group [193–195].

Unlike the vWF aptamer or antibodies, a pharmacological inhibitor of vWF secretion would have the advantage of acting from the inside of ECs, thereby limiting the amount of vWF available to support binding of platelets and thrombus formation. Studies thus far from our group suggest inhibition of Gα12-dependent activation of vWF secretion from WPBs may in

fact be one such option [89, 90, 181, 182, 196]. Ongoing studies are demonstrating that inhibition of vWF secretion from ECs, using a novel peptide inhibitor to block Gα12/α-SNAP-dependent WPB exocytosis [89], reduces DIC and mortality in septic mice [89, 90, 182, 183, 196].

5. Conclusions

The development of antithrombotic drugs continues to be an active area of research. As there is not a straightforward relationship between therapeutic intervention and improvement of endothelial function, but rather a complicated interrelation between multiple subcellular "targets", research has focused on understanding the underlying mechanisms leading to vWF elevation in the circulation. Development of novel non-invasive diagnostic methods that facilitate early detection of endothelial damage and dysfunction and expand our knowledge of the etiology of cardiovascular disease are aggressively being pursued. In this overview, we present currently available literature concerning the contribution of endothelial cell activation/dysfunction to the increase in the level of plasma vWF in the context of inflammatory cardiovascular disease. While differential diagnosis of infectious and non-infectious organ damage associated with high vWF levels is not possible using vWF as a marker, elevated levels of vWF correlate very well with organ failure and poor survival and thus encourage further pursuit of this line of research toward novel drug therapy.

Author details

Luiza Rusu* and Richard D. Minshall

*Address all correspondence to: luizarusu123@gmail.com

Ohio State University, University of Illinois at Chicago, USA

References

[1] Vlot AJ, Koppelman SJ, Bouma BN, Sixma JJ. Factor VIII and von Willebrand factor. Thrombosis and Haemostasis. 1998;**79**(3):456-465

[2] Borchiellini A, Fijnvandraat K, ten Cate JW, Pajkrt D, van Deventer SJ, Pasterkamp G, et al. Quantitative analysis of von Willebrand factor propeptide release in vivo: Effect of experimental endotoxemia and administration of 1-deamino-8-D-arginine vasopressin in humans. Blood. 1996;**88**(8):2951-2958

[3] Blann AD. How a damaged blood vessel wall contibutes to thrombosis and hypertenasion. Pathophysiology of Haemostasis and Thrombosis. 2003;**33**(5–6):445-448

[4] Sadler JE, Shelton-Inloes BB, Sorace JM, Harlan JM, Titani K, Davie EW. Cloning and characterization of two cDNAs coding for human von Willebrand factor. Proceedings of the National Academy of Sciences of the United States of America. 1985;**82**(19): 6394-6398

[5] Wagner DD, Saffaripour S, Bonfanti R, Sadler JE, Cramer EM, Chapman B, et al. Induction of specific storage organelles by von Willebrand factor propolypeptide. Cell. 1991; **64**(2):403-413

[6] Nishio K, Anderson PJ, Zheng XL, Sadler JE. Binding of platelet glycoprotein Ibalpha to von Willebrand factor domain A1 stimulates the cleavage of the adjacent domain A2 by ADAMTS13. Proceedings of the National Academy of Sciences of the United States of America. 2004;**101**(29):10578-10583

[7] Giblin JP, Hewlett LJ, Hannah MJ. Basal secretion of von Willebrand factor from human endothelial cells. Blood. 2008;**112**(4):957-964

[8] Cleator JH, Zhu WQ, Vaughan DE, Hamm HE. Differential regulation of endothelial exocytosis of P-selectin and von Willebrand factor by protease-activated receptors and cAMP. Blood. 2006;**107**(7):2736-2744

[9] Borissoff JI, Spronk HM, Heeneman S, ten Cate H. Is thrombin a key player in the 'coagulation-atherogenesis' maze? Cardiovascular Research 2009;**82**(3):392-403

[10] Rusu L, Andreeva A, Visintine DJ, Kim K, Vogel SM, Stojanovic-Terpo A, et al. G protein-dependent basal and evoked endothelial cell vWF secretion. Blood. 2014;**123**(3): 442-450

[11] Pulido IR, Jahn R, Gerke V. VAMP3 is associated with endothelial weibel-palade bodies and participates in their Ca(2+)-dependent exocytosis. Biochimica et Biophysica Acta. 2011;**1813**(5):1038-1044

[12] Fu J, Naren AP, Gao X, Ahmmed GU, Malik AB. Protease-activated receptor-1 activation of endothelial cells induces protein kinase Calpha-dependent phosphorylation of syntaxin 4 and Munc18c: Role in signaling p-selectin expression. The Journal of Biological Chemistry. 2005;**280**(5):3178-3184

[13] Babich V, Meli A, Knipe L, Dempster JE, Skehel P, Hannah MJ, et al. Selective release of molecules from Weibel-Palade bodies during a lingering kiss. Blood. 2008;**111**(11):5282-5290

[14] Erent M, Meli A, Moisoi N, Babich V, Hannah MJ, Skehel P, et al. Rate, extent and concentration dependence of histamine-evoked Weibel-Palade body exocytosis determined from individual fusion events in human endothelial cells. The Journal of Physiology. 2007;**583**(Pt 1):195-212

[15] Goerge T, Niemeyer A, Rogge P, Ossig R, Oberleithner H, Schneider SW. Secretion pores in human endothelial cells during acute hypoxia. The Journal of Membrane Biology. 2002;**187**(3):203-211

[16] Seyfried BK, Friedbacher G, Rottensteiner H, Schwarz HP, Ehrlich H, Allmaier G, et al. Comparison of plasma-derived and recombinant von Willebrand factor by atomic force microscopy. Thrombosis and Haemostasis. 2010;**104**(3):523-530

[17] Gralnick HR, Coller BS. Studies of the human factor VIII/von Willebrand's factor protein. II. Identification and characterization of the von Willebrand protein. Blood. 1975; **46**(3):417-430

[18] Nogami K, Shima M, Nishiya K, Hosokawa K, Saenko EL, Sakurai Y, et al. A novel mechanism of factor VIII protection by von Willebrand factor from activated protein C-catalyzed inactivation. Blood. 2002;**99**(11):3993-3998

[19] Nachman RL, Jaffe EA. The platelet-endothelial cell–VIII axis. Thrombosis and Haemostasis. 1976;**35**(1):120-123

[20] Kanaji S, Fahs SA, Shi Q, Haberichter SL, Montgomery RR. Contribution of platelet vs. endothelial VWF to platelet adhesion and hemostasis. Journal of Thrombosis and Haemostasis. 2012;**10**(8):1646-1652

[21] Lazzari MA, Sanchez-Luceros A, Woods AI, Alberto MF, Meschengieser SS. Von Willebrand factor (VWF) as a risk factor for bleeding and thrombosis. Hematology. 2012;**17**(Suppl 1):S150-S152

[22] Chen J, Ling M, Fu X, Lopez JA, Chung DW. Simultaneous exposure of sites in von willebrand factor for glycoprotein Ib binding and ADAMTS13 cleavage: Studies with Ristocetin. Arteriosclerosis, Thrombosis, and Vascular Biology; **32**(11):2625-2630

[23] Andre P, Denis CV, Ware J, Saffaripour S, Hynes RO, Ruggeri ZM, et al. Platelets adhere to and translocate on von Willebrand factor presented by endothelium in stimulated veins. Blood. 2000;**96**(10):3322-3328

[24] Ruggeri ZM. Von Willebrand factor. Current Opinion in Hematology. 2003;**10**(2):142-149

[25] Ruggeri ZM. Von Willebrand factor, platelets and endothelial cell interactions. Journal of Thrombosis and Haemostasis. 2003;**1**(7):1335-1342

[26] Ruggeri ZM, De Marco L, Gatti L, Bader R, Montgomery RR. Platelets have more than one binding site for von Willebrand factor. The Journal of Clinical Investigation. 1983; **72**(1):1-12

[27] Ayme G, Adam F, Legendre P, Bazaa A, Proulle V, Denis CV, et al. A novel single-domain antibody against von Willebrand factor A1 domain resolves leukocyte recruitment and vascular leakage during inflammation-brief report. Arteriosclerosis, Thrombosis, and Vascular Biology. 2017;**37**(9):1736-1740

[28] Hillgruber C, Steingraber AK, Poppelmann B, Denis CV, Ware J, Vestweber D, et al. Blocking von Willebrand factor for treatment of cutaneous inflammation. The Journal of Investigative Dermatology. 2014;**134**(1):77-86

[29] Lerolle N, Dunois-Larde C, Badirou I, Motto DG, Hill G, Bruneval P, et al. Von Willebrand factor is a major determinant of ADAMTS-13 decrease during mouse sepsis induced by cecum ligation and puncture. Journal of Thrombosis and Haemostasis. 2009; **7**(5):843-850

[30] Weibel ER, Palade GE. New cytoplasmic components in arterial endothelia. The Journal of Cell Biology. 1964;**23**:101-112

[31] Zimmerman TS, Ratnoff OD, Powell AE. Immunologic differentiation of classic hemophilia (factor 8 deficiency) and von Willebrand's dissase, with observations on combined deficiencies of antihemophilic factor and proaccelerin (factor V) and on an acquired circulating anticoagulant against antihemophilic factor. The Journal of Clinical Investigation. 1971;**50**(1):244-254

[32] van Mourik JA, Romani de Wit T, Voorberg J. Biogenesis and exocytosis of Weibel-Palade bodies. Histochemistry and Cell Biology 2002;**117**(2):113-122

[33] Voorberg J, Fontijn R, Calafat J, Janssen H, van Mourik JA, Pannekoek H Biogenesis of von Willebrand factor-containing organelles in heterologous transfected CV-1 cells. The EMBO Journal 1993;**12**(2):749-758

[34] Sporn LA, Marder VJ, Wagner DD. Inducible secretion of large, biologically potent von Willebrand factor multimers. Cell. 1986;**46**(2):185-190

[35] Zenner HL, Collinson LM, Michaux G, Cutler DF. High-pressure freezing provides insights into Weibel-Palade body biogenesis. Journal of Cell Science. 2007;**120**(Pt 12):2117-2125

[36] Zhou YF, Eng ET, Zhu J, Lu C, Walz T, Springer TA. Sequence and structure relationships within von Willebrand factor. Blood. 2012;**120**(2):449-458

[37] Wagner DD, Marder VJ. Biosynthesis of von Willebrand protein by human endothelial cells: Processing steps and their intracellular localization. The Journal of Cell Biology. 1984;**99**(6):2123-2130

[38] Scaglione GL, Lancellotti S, Papi M, De Spirito M, Maiorana A, Baronciani L, et al. The type 2B p.R1306W natural mutation of von Willebrand factor dramatically enhances the multimer sensitivity to shear stress. Journal of Thrombosis and Haemostasis. 2013;**11**(9): 1688-1698

[39] Valentijn KM, Eikenboom J. Weibel-Palade bodies: A window to von Willebrand disease. Journal of Thrombosis and Haemostasis. 2013;**11**(4):581-592

[40] Lui-Roberts WW, Collinson LM, Hewlett LJ, Michaux G, Cutler DF. An AP-1/clathrin coat plays a novel and essential role in forming the Weibel-Palade bodies of endothelial cells. The Journal of Cell Biology. 2005;**170**(4):627-636

[41] Rondaij MG, Bierings R, Kragt A, Gijzen KA, Sellink E, van Mourik JA, et al. Dynein-dynactin complex mediates protein kinase A-dependent clustering of Weibel-Palade

bodies in endothelial cells. Arteriosclerosis, Thrombosis, and Vascular Biology. 2006; **26**(1):49-55

[42] Dmitrieva NI, Burg MB. Secretion of von Willebrand factor by endothelial cells links sodium to hypercoagulability and thrombosis. Proceedings of the National Academy of Sciences of the United States of America. 2014;**111**(17):6485-6490

[43] Torisu T, Torisu K, Lee IH, Liu J, Malide D, Combs CA, et al. Autophagy regulates endothelial cell processing, maturation and secretion of von Willebrand factor. Nature Medicine. 2013;**19**(10):1281-1287

[44] Rondaij MG, Bierings R, Kragt A, van Mourik JA, Voorberg J. Dynamics and plasticity of Weibel-Palade bodies in endothelial cells. Arteriosclerosis, Thrombosis, and Vascular Biology. 2006;**26**(5):1002-1007

[45] Hyseni A, Kemperman H, de Lange DW, Kesecioglu J, de Groot PG, Roest M. Active von Willebrand factor predicts 28-day mortality in patients with systemic inflammatory response syndrome. Blood. 2014

[46] Xiao J, Feng Y, Li X, Li W, Fan L, Liu J, et al. Expression of ADAMTS13 in normal and abnormal placentae and its potential role in angiogenesis and placenta development. Arteriosclerosis, Thrombosis, and Vascular Biology. 2017;**37**(9):1748-1756

[47] van Nispen tot Pannerden H, de Haas F, Geerts W, Posthuma G, van Dijk S, Heijnen HF. The platelet interior revisited: Electron tomography reveals tubular alpha-granule subtypes. Blood. 2010;**116**(7):1147-1156

[48] Sehgal S, Storrie B. Evidence that differential packaging of the major platelet granule proteins von Willebrand factor and fibrinogen can support their differential release. Journal of Thrombosis and Haemostasis. 2007;**5**(10):2009-2016

[49] Howard MA, Montgomery DC, Hardisty RM. Factor-VIII-related antigen in platelets. Thrombosis Research. 1974;**4**(5):617-624

[50] Nichols WL, Hultin MB, James AH, Manco-Johnson MJ, Montgomery RR, Ortel TL, et al. Von Willebrand disease (VWD): Evidence-based diagnosis and management guidelines, the National Heart, Lung, and Blood Institute (NHLBI) expert panel report (USA). Haemophilia. 2008;**14**(2):171-232

[51] Levine JD, Harlan JM, Harker LA, Joseph ML, Counts RB. Thrombin-mediated release of factor VIII antigen from human umbilical vein endothelial cells in culture. Blood. 1982; **60**(2):531-534

[52] Nightingale T, Cutler D. The secretion of von Willebrand factor from endothelial cells; an increasingly complicated story. Journal of Thrombosis and Haemostasis. 2013;**11**(Suppl 1): 192-201

[53] Tsai HM, Nagel RL, Hatcher VB, Seaton AC, Sussman II. The high molecular weight form of endothelial cell von Willebrand factor is released by the regulated pathway. British Journal of Haematology. 1991;**79**(2):239-245

[54] van den Biggelaar M, Hernandez-Fernaud JR, van den Eshof BL, Neilson LJ, Meijer AB, Mertens K, et al. Quantitative phosphoproteomics unveils temporal dynamics of thrombin signaling in human endothelial cells. Blood. 2014;**123**(12):e22-e36

[55] Johnsen J, Lopez JA. VWF secretion: What's in a name? Blood. 2008;**112**(4):926-927

[56] Romani de Wit T, Rondaij MG, Hordijk PL, Voorberg J, van Mourik JA. Real-time imaging of the dynamics and secretory behavior of Weibel-Palade bodies. Arteriosclerosis, Thrombosis, and Vascular Biology. 2003;**23**(5):755-761

[57] Nightingale TD, White IJ, Doyle EL, Turmaine M, Harrison-Lavoie KJ, Webb KF, et al. Actomyosin II contractility expels von Willebrand factor from Weibel-Palade bodies during exocytosis. The Journal of Cell Biology. 2011;**194**(4):613-629

[58] Kaufmann JE, Oksche A, Wollheim CB, Gunther G, Rosenthal W, Vischer UM. Vasopressin-induced von Willebrand factor secretion from endothelial cells involves V2 receptors and cAMP. The Journal of Clinical Investigation. 2000;**106**(1):107-116

[59] Pinsky DJ, Naka Y, Liao H, Oz MC, Wagner DD, Mayadas TN, et al. Hypoxia-induced exocytosis of endothelial cell Weibel-Palade bodies. A mechanism for rapid neutrophil recruitment after cardiac preservation. The Journal of Clinical Investigation. 1996;**97**(2): 493-500

[60] Hattori R, Hamilton KK, McEver RP, Sims PJ. Complement proteins C5b-9 induce secretion of high molecular weight multimers of endothelial von Willebrand factor and translocation of granule membrane protein GMP-140 to the cell surface. The Journal of Biological Chemistry. 1989;**264**(15):9053-9060

[61] Hashemi S, Palmer DS, Aye MT, Ganz PR. Platelet-activating factor secreted by DDAVP-treated monocytes mediates von Willebrand factor release from endothelial cells. Journal of Cellular Physiology. 1993;**154**(3):496-505

[62] Denis CV, Kwack K, Saffaripour S, Maganti S, Andre P, Schaub RG, et al. Interleukin 11 significantly increases plasma von Willebrand factor and factor VIII in wild type and von Willebrand disease mouse models. Blood. 2001;**97**(2):465-472

[63] Galbusera M, Zoja C, Donadelli R, Paris S, Morigi M, Benigni A, et al. Fluid shear stress modulates von Willebrand factor release from human vascular endothelium. Blood. 1997;**90**(4):1558-1564

[64] Datta YH, Ewenstein BM. Regulated secretion in endothelial cells: Biology and clinical implications. Thrombosis and Haemostasis. 2001;**86**(5):1148-1155

[65] Jahn R, Fasshauer D. Molecular machines governing exocytosis of synaptic vesicles. Nature. 2012;**490**(7419):201-207

[66] Andreeva AV, Kutuzov MA, Vaiskunaite R, Profirovic J, Meigs TE, Predescu S, et al. G alpha12 interaction with alphaSNAP induces VE-cadherin localization at endothelial junctions and regulates barrier function. The Journal of Biological Chemistry. 2005; **280**(34):30376-30383

[67] Andreeva AV, Kutuzov MA, Voyno-Yasenetskaya TA. Scaffolding proteins in G-protein signaling. Journal of Molecular Signaling. 2007;**2**:13

[68] Sassmann A, Gier B, Grone HJ, Drews G, Offermanns S, Wettschureck N. The Gq/G11-mediated signaling pathway is critical for autocrine potentiation of insulin secretion in mice. The Journal of Clinical Investigation. 2010;**120**(6):2184-2193

[69] Zurawski Z, Page B, Chicka MC, Brindley RL, Wells CA, Preininger AM, et al. Gbetagamma directly modulates vesicle fusion by competing with synaptotagmin for binding to neuronal SNARE proteins embedded in membranes. The Journal of Biological Chemistry. 2017;**292**(29):12165-12177

[70] Moers A, Nieswandt B, Massberg S, Wettschureck N, Grüner S, Konrad I, et al. G13 is an essential mediator of platelet activation in hemostasis and thrombosis. Nature Medicine. 2003;**9**(11):1418-1422

[71] Offermanns S, Toombs CF, Hu YH, Simon MI. Defective platelet activation in G alpha (q)-deficient mice. Nature. 1997;**389**(6647):183-186

[72] Moers A, Wettschureck N, Gruner S, Nieswandt B, Offermanns S. Unresponsiveness of platelets lacking both Gaq and Ga13. The Journal of Biological Chemistry. 2004;**279**: 45354-45359

[73] Mannucci PM. Desmopressin (DDAVP) in the treatment of bleeding disorders: The first 20 years. Blood. 1997;**90**(7):2515-2521

[74] Ponimaskin E, Harteneck C, Schultz G, Schmidt MF. A cysteine-11 to serine mutant of G alpha12 impairs activation through the thrombin receptor. FEBS Letters. 1998;**429**(3):370-374

[75] Vaiskunaite R, Kozasa T, Voyno-Yasenetskaya TA. Interaction between the G alpha subunit of heterotrimeric G(12) protein and Hsp90 is required for G alpha(12) signaling. The Journal of Biological Chemistry. 2001;**276**(49):46088-46093

[76] Waheed AA, Jones TL. Hsp90 interactions and acylation target the G protein Galpha 12 but not Galpha 13 to lipid rafts. The Journal of Biological Chemistry. 2002;**277**(36):32409-32412

[77] Blackmer T, Larsen EC, Bartleson C, Kowalchyk JA, Yoon EJ, Preininger AM, et al. G protein betagamma directly regulates SNARE protein fusion machinery for secretory granule exocytosis. Nature Neuroscience. 2005;**8**(4):421-425

[78] Barnard RJ, Morgan A, Burgoyne RD. Stimulation of NSF ATPase activity by alpha-SNAP is required for SNARE complex disassembly and exocytosis. The Journal of Cell Biology. 1997;**139**(4):875-883

[79] Zhao C, Smith EC, Whiteheart SW. Requirements for the catalytic cycle of the N-ethylmaleimide-sensitive factor (NSF). Biochimica et Biophysica Acta. 2012;**1823**(1):159-171

[80] Clary DO, Griff IC, Rothman JE. SNAPs, a family of NSF attachment proteins involved in intracellular membrane fusion in animals and yeast. Cell. 1990;**61**(4):709-721

[81] Whiteheart SW, Rossnagel K, Buhrow SA, Brunner M, Jaenicke R, Rothman JE. N-ethylmaleimide-sensitive fusion protein: A trimeric ATPase whose hydrolysis of ATP is required for membrane fusion. The Journal of Cell Biology. 1994;**126**(4):945-954

[82] Barszczewski M, Chua JJ, Stein A, Winter U, Heintzmann R, Zilly FE, et al. A novel site of action for alpha-SNAP in the SNARE conformational cycle controlling membrane fusion. Molecular Biology of the Cell. 2008;**19**(3):776-784

[83] Hirling H, Scheller RH. Phosphorylation of synaptic vesicle proteins: Modulation of the alpha SNAP interaction with the core complex. Proceedings of the National Academy of Sciences of the United States of America. 1996;**93**(21):11945-11949

[84] Morgan A, Dimaline R, Burgoyne RD. The ATPase activity of N-ethylmaleimide-sensitive fusion protein (NSF) is regulated by soluble NSF attachment proteins. The Journal of Biological Chemistry. 1994;**269**(47):29347-29350

[85] Matsushita K, Morrell CN, Cambien B, Yang SX, Yamakuchi M, Bao C, et al. Nitric oxide regulates exocytosis by S-nitrosylation of N-ethylmaleimide-sensitive factor. Cell. 2003; **115**(2):139-150

[86] Rodríguez F, Bustos MA, Zanetti MN, Ruete MC, Mayorga LS, Tomes CN. α-SNAP prevents docking of the acrosome during sperm exocytosis because it sequesters monomeric syntaxin. PLoS One. 2011;**6**(7):e21925

[87] Niles WD, Malik AB. Endocytosis and exocytosis events regulate vesicle traffic in endothelial cells. The Journal of Membrane Biology. 1999;**167**(1):85-101

[88] Meigs TE, Juneja J, DeMarco CT, Stemmle LN, Kaplan DD, Casey PJ. Selective uncoupling of G alpha 12 from rho-mediated signaling. The Journal of Biological Chemistry. 2005; **280**(18):18049-18055

[89] Minshall RD, Rusu L. Compositions and method for treating thrombosis. Google Patents; 2014

[90] Rusu L, Schlapfer M, Offermanns S, Du X, Minshall RD. Abstract 659: Inhibition of vWF secretion with novel G alpha12 N-terminal alpha-SNAP binding domain peptide increases survival in septic rodents. Arteriosclerosis, Thrombosis, and Vascular Biology. 2015;**35**(Suppl 1):A659-A65A

[91] Rondaij MG, Sellink E, Gijzen KA, ten Klooster JP, Hordijk PL, van Mourik JA, et al. Small GTP-binding protein Ral is involved in cAMP-mediated release of von Willebrand factor from endothelial cells. Arteriosclerosis, Thrombosis, and Vascular Biology 2004;**24**(7): 1315-1320

[92] Birch KA, Ewenstein BM, Golan DE, Pober JS. Prolonged peak elevations in cytoplasmic free calcium ions, derived from intracellular stores, correlate with the extent of thrombin-stimulated exocytosis in single human umbilical vein endothelial cells. Journal of Cellular Physiology. 1994;**160**(3):545-554

[93] Klarenbach SW, Chipiuk A, Nelson RC, Hollenberg MD, Murray AG. Differential actions of PAR2 and PAR1 in stimulating human endothelial cell exocytosis and permeability: The role of rho-GTPases. Circulation Research. 2003;**92**(3):272-278

[94] Wu H, Rossi G, Brennwald P. The ghost in the machine: Small GTPases as spatial regulators of exocytosis. Trends in Cell Biology. 2008;**18**(9):397-404

[95] Roumanie O, Wu H, Molk JN, Rossi G, Bloom K, Brennwald P. Rho GTPase regulation of exocytosis in yeast is independent of GTP hydrolysis and polarization of the exocyst complex. The Journal of Cell Biology. 2005;**170**(4):583-594

[96] de Leeuw HP, Wijers-Koster PM, van Mourik JA, Voorberg J. Small GTP-binding protein RalA associates with Weibel-Palade bodies in endothelial cells. Thrombosis and Haemostasis. 1999;**82**(3):1177-1181

[97] Rondaij MG, Bierings R, van Agtmaal EL, Gijzen KA, Sellink E, Kragt A, et al. Guanine exchange factor RalGDS mediates exocytosis of Weibel-Palade bodies from endothelial cells. Blood. 2008;**112**(1):56-63

[98] Bhattacharya M, Anborgh PH, Babwah AV, Dale LB, Dobransky T, Benovic JL, et al. Beta-arrestins regulate a Ral-GDS Ral effector pathway that mediates cytoskeletal reorganization. Nature Cell Biology. 2002;**4**(8):547-555

[99] Mott HR, Owen D. RLIP76 (RalBP1): The first piece of the structural puzzle. Small GTPases. 2010;**1**(3):157-160

[100] Rusu L. Molecular Mechanisms of vWF Secretion [Doctoral]. Indigo: University of Illinois at Chicago; 2013

[101] Xie L, Kang Y, Liang T, Dolai S, Xie H, Parsaud L, et al. RalA GTPase tethers insulin granules to L- and R-type calcium channels through binding α2 δ-1 subunit. Traffic. 2013;**14**(4):428-439

[102] Stenmark H. Rab GTPases as coordinators of vesicle traffic. Nature Reviews. Molecular Cell Biology. 2009;**10**(8):513-525

[103] Bierings R, Hellen N, Kiskin N, Knipe L, Fonseca AV, Patel B, et al. The interplay between the Rab27A effectors Slp4-a and MyRIP controls hormone-evoked Weibel-Palade body exocytosis. Blood. 2012;**120**(13):2757-2767

[104] Knop M, Aareskjold E, Bode G, Gerke V. Rab3D and annexin A2 play a role in regulated secretion of vWF, but not tPA, from endothelial cells. The EMBO Journal. 2004;**23**(15): 2982-2992

[105] Hannah MJ, Hume AN, Arribas M, Williams R, Hewlett LJ, Seabra MC, et al. Weibel-Palade bodies recruit Rab27 by a content-driven, maturation-dependent mechanism that is independent of cell type. Journal of Cell Science. 2003;**116**(Pt 19):3939-3948

[106] Zografou S, Basagiannis D, Papafotika A, Shirakawa R, Horiuchi H, Auerbach D, et al. A complete Rab screening reveals novel insights in Weibel-Palade body exocytosis. Journal of Cell Science. 2012;**125**(Pt 20):4780-4790

[107] Biesemann A, Gorontzi A, Barr F, Gerke V. Rab35 protein regulates evoked exocytosis of endothelial Weibel-Palade bodies. The Journal of Biological Chemistry. 2017;**292**(28): 11631-11640

[108] Mizuno K, Fujita T, Gomi H, Izumi T. Granuphilin exclusively mediates functional granule docking to the plasma membrane. Scientific Reports. 2016;**6**:23909

[109] van Breevoort D, van Agtmaal EL, Dragt BS, Gebbinck JK, Dienava-Verdoold I, Kragt A, et al. Proteomic screen identifies IGFBP7 as a novel component of endothelial cell-specific Weibel-Palade bodies. Journal of Proteome Research. 2012;**11**(5):2925-2936

[110] Ammar M, Kassas N, Chasserot-Golaz S, Bader M-F, Vitale N. Lipids in regulated exocytosis: What are they doing? Frontiers in Endocrinology. 2013;**4**(125)

[111] Disse J, Vitale N, Bader MF, Gerke V. Phospholipase D1 is specifically required for regulated secretion of von Willebrand factor from endothelial cells. Blood. 2009;**113**(4):973-980

[112] Roth MG. Molecular mechanisms of PLD function in membrane traffic. Traffic. 2008;**9**(8): 1233-1239

[113] Jenkins GM, Frohman MA. Phospholipase D: A lipid centric review. Cellular and Molecular Life Sciences. 2005;**62**(19–20):2305-2316

[114] Han J, Liu G, Profirovic J, Niu J, Voyno-Yasenetskaya T. Zyxin is involved in thrombin signaling via interaction with PAR-1 receptor. The FASEB Journal. 2009;**23**(12):4193-4206

[115] Macalma T, Otte J, Hensler ME, Bockholt SM, Louis HA, Kalff-Suske M, et al. Molecular characterization of human zyxin. The Journal of Biological Chemistry. 1996;**271**(49): 31470-31478

[116] Han X, Li P, Yang Z, Huang X, Wei G, Sun Y, et al. Zyxin regulates endothelial von Willebrand factor secretion by reorganizing actin filaments around exocytic granules. Nature Communications. 2017;**8**:14639

[117] Fradelizi J, Noireaux V, Plastino J, Menichi B, Louvard D, Sykes C, et al. ActA and human zyxin harbour Arp2/3-independent actin-polymerization activity. Nature Cell Biology. 2001;**3**(8):699-707

[118] Boneu B, Abbal M, Plante J, Bierme R. Letter: Factor-VIII complex and endothelial damage. Lancet. 1975;**1**(7922):1430

[119] Berk KA, Oudshoorn TP, Verhoeven AJM, Mulder MT, Roks AJM, Dik WA, et al. Diet-induced weight loss and markers of endothelial dysfunction and inflammation in treated patients with type 2 diabetes. Clinical Nutrition ESPEN. 2016;**15**:101-106

[120] Bianchi V, Robles R, Alberio L, Furlan M, Lammle B. Von Willebrand factor-cleaving protease (ADAMTS13) in thrombocytopenic disorders: A severely deficient activity is specific for thrombotic thrombocytopenic purpura. Blood. 2002;**100**(2):710-713

[121] Feng S, Liang X, Kroll MH, Chung DW, Afshar-Kharghan V. Von Willebrand factor is a cofactor in complement regulation. Blood. 2015;**125**(6):1034-1037

[122] Pottinger BE, Read RC, Paleolog EM, Higgins PG, Pearson JD. Von Willebrand factor is an acute phase reactant in man. Thrombosis Research. 1989;**53**(4):387-394

[123] Groot E, de Groot PG, Fijnheer R, Lenting PJ. The presence of active von Willebrand factor under various pathological conditions. Current Opinion in Hematology. 2007; **14**(3):284-289

[124] De Filippis V, Lancellotti S, Maset F, Spolaore B, Pozzi N, Gambaro G, et al. Oxidation of Met1606 in von Willebrand factor is a risk factor for thrombotic and septic complications in chronic renal failure. The Biochemical Journal. 2012;**442**(2):423-432

[125] Lancellotti S, De Filippis V, Pozzi N, Oggianu L, Rutella S, Scaglione GL, et al. Oxidized von Willebrand factor is efficiently cleaved by serine proteases from primary granules of leukocytes: Divergence from ADAMTS-13. Journal of Thrombosis and Haemostasis. 2011;**9**(8):1620-1627

[126] Crawley JT, de Groot R, Xiang Y, Luken BM, Lane DA. Unraveling the scissile bond: How ADAMTS13 recognizes and cleaves von Willebrand factor. Blood. 2011;**118**(12): 3212-3221

[127] Paulus P, Jennewein C, Zacharowski K. Biomarkers of endothelial dysfunction: Can they help us deciphering systemic inflammation and sepsis? Biomarkers. 2011;**16**(Suppl 1): S11-S21

[128] Reinhart K, Bayer O, Brunkhorst F, Meisner M. Markers of endothelial damage in organ dysfunction and sepsis. Critical Care Medicine. 2002;**30**(Suppl 5):S302-S312

[129] Ware LB, Conner ER, Matthay MA. Von Willebrand factor antigen is an independent marker of poor outcome in patients with early acute lung injury. Critical Care Medicine. 2001;**29**(12):2325-2331

[130] Hepokoski M, Englert JA, Baron RM, Crotty-Alexander LE, Fuster MM, Beitler JR, et al. Ventilator-induced lung injury increases expression of endothelial inflammatory mediators in the kidney. American Journal of Physiology. Renal Physiology. 2017;**312**(4):F654-FF60

[131] van der Heijden M, Pickkers P, van Nieuw Amerongen GP, van Hinsbergh VW, Bouw MP, van der Hoeven JG, et al. Circulating angiopoietin-2 levels in the course of septic shock: Relation with fluid balance, pulmonary dysfunction and mortality. Intensive Care Medicine. 2009;**35**(9):1567-1574

[132] Zhou YF, Eng ET, Nishida N, Lu C, Walz T, Springer TA. A pH-regulated dimeric bouquet in the structure of von Willebrand factor. The EMBO Journal. 2011;**30**(19):4098-4111

[133] Muller JP, Lof A, Mielke S, Obser T, Bruetzel LK, Vanderlinden W, et al. pH-dependent interactions in dimers govern the mechanics and structure of von Willebrand factor. Biophysical Journal. 2016;**111**(2):312-322

[134] Muller JP, Mielke S, Lof A, Obser T, Beer C, Bruetzel LK, et al. Force sensing by the vascular protein von Willebrand factor is tuned by a strong intermonomer interaction. Proceedings of the National Academy of Sciences of the United States of America. 2016; **113**(5):1208-1213

[135] Furlan M, Robles R, Lammle B. Partial purification and characterization of a protease from human plasma cleaving von Willebrand factor to fragments produced by in vivo proteolysis. Blood. 1996;**87**(10):4223-4234

[136] Dong JF, Moake JL, Nolasco L, Bernardo A, Arceneaux W, Shrimpton CN, et al. ADAMTS-13 rapidly cleaves newly secreted ultralarge von Willebrand factor multimers on the endothelial surface under flowing conditions. Blood. 2002;**100**(12):4033-4039

[137] Michaux G, Abbitt KB, Collinson LM, Haberichter SL, Norman KE, Cutler DF. The physiological function of von Willebrand's factor depends on its tubular storage in endothelial Weibel-Palade bodies. Developmental Cell. 2006;**10**(2):223-232

[138] Bonazza K, Rottensteiner H, Schrenk G, Frank J, Allmaier G, Turecek PL, et al. Shear-dependent interactions of von Willebrand factor with factor VIII and protease ADAMTS 13 demonstrated at a single molecule level by atomic force microscopy. Analytical Chemistry. 2015;**87**(20):10299-10305

[139] Aponte-Santamaria C, Huck V, Posch S, Bronowska AK, Grassle S, Brehm MA, et al. Force-sensitive autoinhibition of the von Willebrand factor is mediated by interdomain interactions. Biophysical Journal. 2015;**108**(9):2312-2321

[140] Davydovskaya P, Janko M, Gaertner F, Ahmad Z, Simsek O, Massberg S, et al. Blood platelet adhesion to printed von Willebrand factor. Journal of Biomedical Materials Research. Part A. 2012;**100(**(2):335-341

[141] Lippok S, Kolsek K, Lof A, Eggert D, Vanderlinden W, Muller JP, et al. Von Willebrand factor is dimerized by protein disulfide isomerase. Blood. 2016;**127**(9):1183-1191

[142] Lof A, Muller JP, Benoit M, Brehm MA. Biophysical approaches promote advances in the understanding of von Willebrand factor processing and function. Advances in Biological Regulation. 2017;**63**:81-91

[143] Papi M, Maulucci G, De Spirito M, Missori M, Arcovito G, Lancellotti S, et al. Ristocetin-induced self-aggregation of von Willebrand factor. European Biophysics Journal. 2010; **39**(12):1597-1603

[144] Posch S, Aponte-Santamaria C, Schwarzl R, Karner A, Radtke M, Grater F, et al. Mutual a domain interactions in the force sensing protein von Willebrand factor. Journal of Structural Biology. 2017;**197**(1):57-64

[145] Siedlecki CA, Lestini BJ, Kottke-Marchant KK, Eppell SJ, Wilson DL, Marchant RE. Shear-dependent changes in the three-dimensional structure of human von Willebrand factor. Blood. 1996;**88**(8):2939-2950

[146] Tobimatsu H, Nishibuchi Y, Sudo R, Goto S, Tanishita K. Adhesive forces between A1 domain of von Willebrand factor and N-terminus domain of glycoprotein Ibalpha measured by atomic force microscopy. Journal of Atherosclerosis and Thrombosis. 2015; **22**(10):1091-1099

[147] Wu T, Lin J, Cruz MA, Dong JF, Zhu C. Force-induced cleavage of single VWFA1A2A3 tridomains by ADAMTS-13. Blood. 2010;**115**(2):370-378

[148] Zhou W, Inada M, Lee TP, Benten D, Lyubsky S, Bouhassira EE, et al. ADAMTS13 is expressed in hepatic stellate cells. Laboratory Investigation. 2005;**85**(6):780-788

[149] Plaimauer B, Fuhrmann J, Mohr G, Wernhart W, Bruno K, Ferrari S, et al. Modulation of ADAMTS13 secretion and specific activity by a combination of common amino acid polymorphisms and a missense mutation. Blood. 2006;**107**(1):118-125

[150] Rieger M, Ferrari S, Kremer Hovinga JA, Konetschny C, Herzog A, Koller L, et al. Relation between ADAMTS13 activity and ADAMTS13 antigen levels in healthy donors and patients with thrombotic microangiopathies (TMA). Thrombosis and Haemostasis. 2006;**95**(2):212-220

[151] Furlan M, Robles R, Morselli B, Sandoz P, Lammle B. Recovery and half-life of von Willebrand factor-cleaving protease after plasma therapy in patients with thrombotic thrombocytopenic purpura. Thrombosis and Haemostasis. 1999;**81**(1):8-13

[152] Barrett AJ, Rawlings ND, Woessner JF. Handbook of Proteolytic Enzymes. 2nd ed. Amsterdam, Boston: Elsvier Academic Press; 2004

[153] Padilla A, Moake JL, Bernardo A, Ball C, Wang Y, Arya M, et al. P-selectin anchors newly released ultralarge von Willebrand factor multimers to the endothelial cell surface. Blood. 2004;**103**(6):2150-2156

[154] Datta YH, Romano M, Jacobson BC, Golan DE, Serhan CN, Ewenstein BM. Peptidoleukotrienes are potent agonists of von Willebrand factor secretion and P-selectin surface expression in human umbilical vein endothelial cells. Circulation. 1995;**92**(11):3304-3311

[155] Lancellotti S, De Cristofaro R. Structure and proteolytic properties of ADAMTS13, a metalloprotease involved in the pathogenesis of thrombotic microangiopathies. Progress in Molecular Biology and Translational Science. 2011;**99**:105-144

[156] Lancellotti S, Dragani A, Ranalli P, Petrucci G, Basso M, Tartaglione R, et al. Qualitative and quantitative modifications of von Willebrand factor in patients with essential thrombocythemia and controlled platelet count. Journal of Thrombosis and Haemostasis. 2015;**13**(7):1226-1237

[157] Lynch CJ, Lane DA, Luken BM. Control of VWF A2 domain stability and ADAMTS13 access to the scissile bond of full-length VWF. Blood. 2014;**123**(16):2585-2592

[158] Xiang Y, de Groot R, Crawley JT, Lane DA. Mechanism of von Willebrand factor scissile bond cleavage by a disintegrin and metalloproteinase with a thrombospondin type 1 motif, member 13 (ADAMTS13). Proceedings of the National Academy of Sciences of the United States of America. 2011;**108**(28):11602-11607

[159] Xu AJ, Springer TA. Calcium stabilizes the von Willebrand factor A2 domain by promoting refolding. Proceedings of the National Academy of Sciences of the United States of America. 2012;**109**(10):3742-3747

[160] Zander CB, Cao W, Zheng XL. ADAMTS13 and von Willebrand factor interactions. Current Opinion in Hematology. 2015;**22**(5):452-459

[161] Zhang J, Ma Z, Dong N, Liu F, Su J, Zhao Y, et al. A conformation-sensitive monoclonal antibody against the A2 domain of von Willebrand factor reduces its proteolysis by ADAMTS13. PLoS One. 2011;**6**(7):e22157

[162] Zhou M, Dong X, Baldauf C, Chen H, Zhou Y, Springer TA, et al. A novel calcium-binding site of von Willebrand factor A2 domain regulates its cleavage by ADAMTS13. Blood. 2011;**117**(17):4623-4631

[163] Claus RA, Bockmeyer CL, Sossdorf M, Losche W. The balance between von-Willebrand factor and its cleaving protease ADAMTS13: Biomarker in systemic inflammation and development of organ failure? Current Molecular Medicine. 2010;**10**(2):236-248

[164] Chauhan AK, Walsh MT, Zhu G, Ginsburg D, Wagner DD, Motto DG. The combined roles of ADAMTS13 and VWF in murine models of TTP, endotoxemia, and thrombosis. Blood. 2008;**111**(7):3452-3457

[165] Patel KN, Soubra SH, Bellera RV, Dong JF, McMullen CA, Burns AR, et al. Differential role of von Willebrand factor and P-selectin on microvascular thrombosis in endotoxemia. Arteriosclerosis, Thrombosis, and Vascular Biology. 2008;**28**(12):2225-2230

[166] Pillai VG, Bao J, Zander CB, McDaniel JK, Chetty PS, Seeholzer SH, et al. Human neutrophil peptides inhibit cleavage of von Willebrand factor by ADAMTS13: A potential link of inflammation to TTP. Blood. 2016;**128**(1):110-119

[167] Kraft P, Drechsler C, Gunreben I, Nieswandt B, Stoll G, Heuschmann PU, et al. Von Willebrand factor regulation in patients with acute and chronic cerebrovascular disease: A pilot, case-control study. PLoS One. 2014;**9**(6):e99851

[168] Bernardo A, Ball C, Nolasco L, Moake JF, Dong JF. Effects of inflammatory cytokines on the release and cleavage of the endothelial cell-derived ultralarge von Willebrand factor multimers under flow. Blood. 2004;**104**(1):100-106

[169] Nguyen TC, Liu A, Liu L, Ball C, Choi H, May WS, et al. Acquired ADAMTS-13 deficiency in pediatric patients with severe sepsis. Haematologica. 2007;**92**(1):121-124

[170] Nguyen TC, Gushiken F, Correa JI, Dong JF, Dasgupta SK, Thiagarajan P, et al. A recombinant fragment of von Willebrand factor reduces fibrin-rich microthrombi formation in mice with endotoxemia. Thrombosis Research. 2015;**135**(5):1025-1030

[171] Huck V, Niemeyer A, Goerge T, Schnaeker EM, Ossig R, Rogge P, et al. Delay of acute intracellular pH recovery after acidosis decreases endothelial cell activation. Journal of Cellular Physiology. 2007;**211**(2):399-409

[172] Bongers TN, de Maat MP, van Goor ML, Bhagwanbali V, van Vliet HH, Gomez Garcia EB, et al. High von Willebrand factor levels increase the risk of first ischemic stroke: Influence of ADAMTS13, inflammation, and genetic variability. Stroke. 2006;**37**(11):2672-2677

[173] Khan MM, Motto DG, Lentz SR, Chauhan AK. ADAMTS13 reduces VWF-mediated acute inflammation following focal cerebral ischemia in mice. Journal of Thrombosis and Haemostasis. 2012;**10**(8):1665-1671

[174] Kleinschnitz C, De Meyer SF, Schwarz T, Austinat M, Vanhoorelbeke K, Nieswandt B, et al. Deficiency of von Willebrand factor protects mice from ischemic stroke. Blood. 2009;**113**(15):3600-3603

[175] Denorme F, Kraft P, Pareyn I, Drechsler C, Deckmyn H, Vanhoorelbeke K, et al. Reduced ADAMTS13 levels in patients with acute and chronic cerebrovascular disease. PLoS One. 2017;**12**(6):e0179258

[176] Dhanesha N, Prakash P, Doddapattar P, Khanna I, Pollpeter MJ, Nayak MK, et al. Endothelial cell-derived von willebrand factor is the major determinant that mediates von Willebrand factor-dependent acute ischemic stroke by promoting postischemic thromboinflammation. Arteriosclerosis, Thrombosis, and Vascular Biology. 2016;**36**(9):1829-1837

[177] Petri B, Broermann A, Li H, Khandoga AG, Zarbock A, Krombach F, et al. Von Willebrand factor promotes leukocyte extravasation. Blood. 2010;**116**(22):4712-4719

[178] Pendu R, Terraube V, Christophe OD, Gahmberg CG, de Groot PG, Lenting PJ, et al. P-selectin glycoprotein ligand 1 and beta2-integrins cooperate in the adhesion of leukocytes to von Willebrand factor. Blood. 2006;**108**(12):3746-3752

[179] Bockmeyer CL, Reuken PA, Simon TP, Budde U, Lösche W, Bauer M, et al. ADAMTS13 activity is decreased in a septic porcine model. Significance for glomerular thrombus deposition. Thrombosis and Haemostasis. 2011;**105**(1):145-153

[180] Kasuda S, Matsui H, Ono S, Matsunari Y, Nishio K, Shima M, et al. Relevant role of von Willebrand factor in neutrophil recruitment in a mouse sepsis model involving cecal ligation and puncture. Haematologica. 2016;**101**(2):e52-e54

[181] Rusu L, Bae M, Castellon M, Stojanovic-Terpo A, Christman JW, Du X, et al., editors. Novel G alpha12 N-terminal alpha-SNAP Binding Domain Peptide Inhibits vWF secretion, Prevents Microvascular Thrombosis, and Increases Survival in Septic Mice. AHA Scientific Sessions; 2016 November 2016; New Orleans

[182] Rusu L, Bae M, Castellon M, Stojanovic-Terpo A, Christman JW, Du X, et al. Abstract 20799: Novel G alpha 12 N-terminal alpha-SNAP binding domain peptide inhibits vWF secretion, prevents microvascular thrombosis and increases survival in septic mice. Circulation. 2016;**134**(Suppl 1):A20799-A

[183] Rusu L, Christman JW, Du X, Minshall RD. Inhibition of vWF Secretion with Novel Gα12 N-terminal α-SNAP Binding Domain Peptide Increases Survival in Septic Mice. Experimental Biology 2016 Meeting; April 2016; San Diego: The FASEB Journal; 2016. p. S943.8

[184] Vischer UM, Wollheim CB. Epinephrine induces von Willebrand factor release from cultured endothelial cells: Involvement of cyclic AMP-dependent signalling in exocytosis. Thrombosis and Haemostasis. 1997;**77**(6):1182-1188

[185] Liu L, Wang X, Lin Z, Wu H. Elevated plasma levels of VWF:Ag in hyperthyroidism are mediated through beta-adrenergic receptors. Endocrine Research. 1993;**19**(2–3):123-133

[186] Smeets MWJ, Mourik MJ, Niessen HWM, Hordijk PL. Stasis promotes erythrocyte adhesion to von Willebrand factor. Arteriosclerosis, Thrombosis, and Vascular Biology. 2017;**37**(9):1618-1627

[187] Sparkenbaugh E, Pawlinski R. Interplay between coagulation and vascular inflammation in sickle cell diseas. British Journal of Haematology. 2013;**162**(1):3-14

[188] Ji S, Jiang M, Yan B, Shen F, He Y, Wan A, et al. The chimeric monoclonal antibody MHCSZ-123 against human von Willebrand factor A3 domain inhibits high-shear arterial thrombosis in a rhesus monkey model. Journal of Hematology & Oncology. 2017; **10**(1):111

[189] Zhao YM, Jiang M, Ji SD, He Y, Shen F, Li XM, et al. Anti-human VWF monoclonal antibody SZ-123 prevents arterial thrombus formation by inhibiting VWF-collagen and VWF-platelet interactions in rhesus monkeys. Biochemical Pharmacology. 2013;**85**(7): 945-953

[190] Clark P, Brennand J, Conkie JA, McCall F, Greer IA, Walker ID. Activated protein C sensitivity, protein C, protein S and coagulation in normal pregnancy. Thrombosis and Haemostasis. 1998;**79**(6):1166-1170

[191] Bender M. High VWF, low ADAMTS13 puts women at risk. Blood. 2012;**119**(6):1329-1330

[192] Cataland SR, Scully MA, Paskavitz J, Maruff P, Witkoff L, Jin M, et al. Evidence of persistent neurologic injury following thrombotic thrombocytopenic purpura. American Journal of Hematology. 2011;**86**(1):87-89

[193] Peyvandi F, Callewaert F. Caplacizumab for acquired thrombotic thrombocytopenic Purpura. The New England Journal of Medicine. 2016;**374**(25):2497-2498

[194] Peyvandi F, Scully M, Kremer Hovinga JA, Cataland S, Knobl P, Wu H, et al. Caplacizumab for acquired thrombotic thrombocytopenic Purpura. The New England Journal of Medicine. 2016;**374**(6):511-522

[195] Peyvandi F, Scully M, Kremer Hovinga JA, Knobl P, Cataland S, De Beuf K, et al. Caplacizumab reduces the frequency of major thromboembolic events, exacerbations and death in patients with acquired thrombotic thrombocytopenic purpura. Journal of Thrombosis and Haemostasis. 2017;**15**(7):1448-1452

[196] Rusu L, Schlapfer M, Atkinson J, Du X, Minshall RD. Abstract 20277: Inhibition of vWF secretion prevents microvascular thrombosis in CLP rodent models of sepsis. Circulation. 2014;**130**(Suppl 2):A20277-A

IntechOpen