Functional Behavior of Vessels from Pigs with von Willebrand Disease

Values of Platelet Deposition Are Identical to Those Obtained on Normal Vessels

Lina Badimon, Juan J. Badimon, Vincent T. Turitto, Jacob Rand, and Valentin Fuster

Vessels from normal pigs and pigs with severe von Willebrand disease were exposed for up to 30 minutes to both nonanticoagulated and heparinized blood from normal pigs in an ex vivo perfusion system. Shear rates at the vessel surface were varied over a broad physiological range, $\gamma_s = 212$ to $3380$ sec$^{-1}$. The deposition of $^{111}$In-labeled platelets was determined by radiometric counting. For all shear rates and exposure times investigated, the levels of platelet deposition on de-endothelialized thoracic aorta of normal and von Willebrand disease pigs were not significantly different. Thus, the functional activity of the vessels correlated with the results obtained previously by Immunofluorescence. Namely, the von Willebrand factor protein in the thoracic subendothelium of normal pigs is significantly diminished or absent and is comparable to the levels observed in von Willebrand disease pigs. (Arteriosclerosis 9:184-188, March/April 1989)

Pigs with von Willebrand disease (vWD), when maintained on a normal or cholesterol-rich diet, develop significantly fewer atherosclerotic lesions of the abdominal aorta than do normal pigs, a finding which may be related to the reduced levels of von Willebrand factor (vWF) in the plasma, platelets, and vessel wall of these animals. A major function of vWF has been related to its ability to support platelet adhesion and platelet-platelet interactions in flowing blood. We have observed reduced platelet deposition when blood from vWD pigs, compared with that from normal controls, is exposed in an ex vivo perfusion system to normal pig aorta. The mechanisms by which vWF helps support platelet adhesion are not entirely clear. Platelet adhesion has been shown to depend on the level of plasma vWF deposited on vessels perfused with plasma. The vascular elements to which plasma vWF attaches are currently unknown, but a role for endogenous vessel wall vWF in this process cannot be excluded. Endogenous vWF has been described in the subendothelium of various species, including humans. Blockage of endogenous vWF in the vessel wall with various antibodies has led to reduced levels of platelet adhesion on the treated vessels, even in the presence of normal amounts of plasma vWF. These studies have supported the idea that vWF in the vessel wall may contribute significantly to platelet adhesion.

Recent studies in our laboratory have revealed a deficiency of vWF in the endothelial cells and intima of most of the arterial system in normal pigs, as determined by immunofluorescent techniques in fresh and stored vessels; however, little is known about the functionality of normal and vWD porcine vessels. For example, it is conceivable that small quantities of active vWF available on normal vessels might support platelet adhesion and subsequent thrombus formation. In the present studies, we exposed de-endothelialized aortic vessel wall from normal and vWD pigs to normal pig blood in an ex vivo perfusion chamber. Values of platelet deposition on both types of vessels were not significantly different over a wide range of shear conditions ($212$ to $3380$ sec$^{-1}$). Thus, the results are consistent with the previous immunofluorescent studies, that significantly reduced or absent levels of vWF are characteristic of aortic wall in normal as in vWF pigs.

Methods

Experimental Model

All procedures performed in this study were approved by the appropriate institutional guidelines and followed the American Heart Association Guidelines for animal research. Swine with inherited homozygous vWD were used as vessel wall donors and were from the colony kept at the Mayo Clinic by Walter E. J. Bowie (Mayo Institute Hills Farm, Mayo Foundation). No vWF was present in the plasma, platelet granules, or the vessel wall in these pigs. Normal pigs were used as blood and vessel wall donors. Normal swine thoracic aorta did not show positive immunofluorescence to vWF. The pigs were housed at the Animal Research Center pig facilities of our institution. They were individually caged in a light-, temperature-, and humidity-controlled environment, with ad libitum access to water and...
jugular veins were catheterized by cutdown, and an in vivo
the chamber for 30 seconds under identical flow conditions.
jugular vein was established, as previously described. 18
the end of the perfusion period, buffer was passed through
substrate at a preselected flow rate and exposure time. At
37°C for 60 seconds. Blood was then perfused over the
wall were calculated from the expression of shear rate
extracorporeal circuit carotid artery-perfusion chamber-
nonanticoagulated blood.
Nonrecirculation Experiments Perfusing
Nonanticoagulated Blood

We used an original perfusion chamber that mimics the
tubular shape of the blood vessels. 4,7,18,19 In this chamber,
a circumferential portion of the tubular fluid channel is
replaced by the test substrate material, which becomes
directly exposed to the blood. Two chambers of different
internal diameters (1.0 and 2.0 mm) provide a broad
range of wall shear rates on the substrate with moderate
change in average blood flow rate.
The selected flow rates were 10 and 20 ml/min in the
small and large chamber. These flows gave theoretically
calculated average blood velocities from 5.3 to 42.3 cm/
sec and local shear rates from 212 to 3380 sec⁻¹. At these
shear rates, blood can be considered a Newtonian fluid
with constant viscosity. 20,21 Shear conditions at the vessel
wall were calculated from the expression of shear rate
given for a Newtonian fluid in tube flow. 22

Experimental Procedures

We studied platelet interaction to mildly damaged
normal thoracic aorta of normal and vWD pigs, as previously
reported. 4 In brief, the aorta of a deeply anesthe-
tized pig was exposed and all branches were ligated. The
animal was then euthanized by an overdose of anesthetic,
and simultaneously the aorta was perfused by cannulation
controlled food intake (3% wt/wt of the body weight, Purina
Laboratories). Table 1 shows the hemostatic parameters of
the normal animals used as blood donors in the study
determined by previously reported methods. 14–17

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Experimental Procedures

The pigs were sedated with intramuscular PromAze
(acepromazine maleate, Fort Dodge Lab, IA) 18 followed by
anesthesia with intravenous injection of sodium pentobar-
bital (Fort Dodge Lab). The carotid artery and contralateral
jugular veins were catheterized by cutdown, and an in vivo
extracorporeal circuit carotid artery-perfusion chamber-
jugular vein was established, as previously described. 18

Nonrecirculation Experiments Perfusing
Nonanticoagulated Blood

The carotid artery was connected to the input of the
chamber maintained at 37°C, and the output was connected
to a variable speed peristaltic pump (Masterflex model 7013)
with interchangeable heads calibrated to obtain selected
blood flow rates. Test specimens were mounted in the
chamber and were perfused with Vassar saline (pH 7.4) at
37°C for 60 seconds. Blood was then perfused over the
substrate at a presellected flow rate and exposure time. At
the end of the perfusion period, buffer was passed through
the chamber for 30 seconds under identical flow conditions.
Blood was discarded after exiting the chamber to prevent
re-infusion of potentially activated blood.

Recirculation Experiments

The animals were intravenously heparinized (300 U/kg,
Liquemin 10 000, Roche). The cannulated carotid artery
was connected to the input of the Plexiglas chamber; the
output of the chamber was connected to the peristaltic
pump. Blood that passed through the chamber was recirc-
ulated back into the animal by the contralateral jugular vein.
The specimens were processed as before. They were
perfused with Vassar saline solution at 37°C for 60
seconds. After the preperfusion period, blood at a
preselected flow rate entered the chamber for various
perfusion times. At the termination of the blood perfusion
period, the buffer was again passed for 30 seconds under
identical flow conditions through the chamber and dis-
carded. The changes from buffer to blood and vice versa
were achieved by a three-way valve without the introduc-
tion of stasis in the chamber. The extracorporeal circula-
tion produced no changes in hematocrit, platelet count,
platelet lysis, or radiolabel uptake by various organ sys-
tems during the duration of the experiment, compared with
experiments where blood was not recirculated.

Radioactive Labeling of Platelets

Approximately 24 hours before the perfusion experi-
ment, autologous platelets were labeled with 111ln (tro-
polone) by a modification 20 of our previously described
technique in pigs. 24 In brief, 111ln-tropolone was prepared
from 111ln-chloride (Medi-Physics, Incorporated, Emerville
Company), by the addition of 50 μg of tropolone dissolved
in 50 μl of saline to 500 μCl of 111ln-chloride. This solution
was mixed with 1 ml of platelet-poor plasma (PPP). Platelets
were harvested from 43 ml of blood collected by
venipuncture into 7 cc of modified ACD solution. The
isolated pellet of platelets was resuspended in 2 ml of
PPP. The 111ln-tropolone complex was added to the
platelet-rich plasma (2 cc) (PRP) solution, and the mixture
was incubated at 37°C for 20 minutes. Free 111ln-tropolone
was removed by washing with 4 ml of PPP. The final pellet
of labeled platelets was resuspended in 4.5 ml of PPP and
injected into the animal after a low-spin centrifugation to
remove any microaggregates. The labeling procedure
required approximately 2 hours. An average Indium plasma
activity of 3.7 ±0.7% (X±SE) was measured just before
injection of the platelet concentrate. The injected activity
was 212±12 μCi (X±SE), and 3×10⁶±2×10⁶ per μl of
111ln-labeled platelets (X±SE) were injected in a volume
of 4.5 ml of plasma.

The number of platelets deposited on each specimen
was calculated from the platelet count and the 111ln-
activity on the perfused area and in blood by using the
method we previously described. 18 Results were normal-
ized by area of exposed surface.

Vessel Wall Preparation

We have studied platelet interaction to mildly damaged
normal thoracic aorta of normal and vWD pigs, as previously
reported. 4 In brief, the aorta of a deeply anesthe-
tized pig was exposed and all branches were ligated. The
animal was then euthanized by an overdose of anesthetic,
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of the aortic arch and the abdominal trifurcation with phosphate-buffered saline, 0.2 M (pH 7.4) containing papaverine (120 mg/l). An air stream was subsequently passed through the aorta at a rate of 1000 ml/min for 10 minutes. The vessel was immediately removed and placed in ice-cold buffer. This procedure induces selective endothelial injury without damaging the basement membrane. Absence of endothelium was checked by en face staining with silver nitrate. The vessels stored in Tris buffer with antibiotics (penicillin and streptomycin) at 4°C were used within 1 to 3 weeks of harvesting. The residual release of prostacyclin by the vascular wall was assayed at the time of its exposure in the perfusion chamber and was similar in both types of vascular wall.

**Ultrastructural Analysis of Specimens**

Selected perfused specimens were fixed in a mixture of 3% glutaraldehyde in 0.2 M cacodylate buffer (pH 7.4) immediately after removal from the chamber. For scanning electron microscopy, specimens were dehydrated by processing through a series of ethanol solutions and were dried with carbon dioxide by the critical-point method. The dried tissue was coated with 100 Å of gold-palladium and carbon and was examined under a scanning electron microscope.

**Statistical Analysis**

The data were statistically analyzed for the best bivariate data model fitting and repeated measurement analysis of variance. Variance about the means is given as 1SE. The Cliniflo and SAS (City University of New York) computer systems were used for all statistical analysis (supported by Grant RR-71 from the Division of Research Resources, National Institutes of Health).

**Results**

Blood from normal pigs drawn directly from the carotid artery either without anticoagulation or after systemic heparinization was exposed to de-endothelialized aorta from normal or vWD pigs for a range of wall shear rate conditions (212 to 3380 sec⁻¹) and times (1 to 30 minutes). The deposition of ¹¹¹In-labeled platelets was determined by radiometric counting.

**Nonanticoagulated Blood Studies**

Platelet deposition with nonanticoagulated blood was not significantly different on normal or vWD aortas at a shear rate of either 212 sec⁻¹ or 1690 sec⁻¹ (Figure 1). Deposition increased with exposure time on both vessels, but comparable levels of deposition were observed.

**Heparinized Blood Studies**

**Wall Shear Rate of 212 Sec⁻¹**

Deposition values in heparinized blood increased with increasing exposure time and gradually approached an asymptotic value of deposition beyond 10 minutes (Figure 2). No significant differences between vessels from normal and vWD pigs were observed.
**Figure 2.** Mean values of platelet deposition (× 10⁶/cm²) (± 1 SE) are plotted vs. perfusion time (min). Heparinized pig blood was perfused at a wall shear rate of 212 sec⁻¹ (A), 424 sec⁻¹ (B), 1690 sec⁻¹ (C), and 3380 sec⁻¹ (D) over de-endothelialized vessel wall from normal (•) and vWD (△) pigs in an in vivo extracorporeal circulation.

**Discussion**

We have investigated the platelet response to normal and vWD aorta that was denuded of its endothelial lining over a broad range of shear conditions (212 to 3380 sec⁻¹) and exposure times (1 to 30 minutes) in both native and anticoagulated blood. No significant differences between the two types of vessel were seen for all experimental conditions utilized. These conditions included shear rates (212 to 3380 sec⁻¹) for which a defect in platelet-vessel wall interaction has been previously observed when vWD blood was perfused over normal vascular substrate. Thus, the functional activity of the normal vessel wall correlated with the results obtained previously by immunofluorescence; namely, vWF was significantly reduced or absent in the subendothelium of the normal pig, as it is in the vWD pig aorta. These findings do not reflect the relative importance of subendothelial vWF with respect to platelet deposition, since both sets of vessels contain little or no such protein; however, they do indicate that the vessel wall can support platelet adhesion and thrombus formation in the absence of endogenous vWF in the vessel wall.

Pigs develop atherosclerosis of the lower abdominal aorta either spontaneously or in response to a high-cholesterol diet, and we have reported that the vWD animals are protected from developing atherosclerotic lesions in this area of the vasculature. Since we previously found VWF in the abdominal aorta of normal pigs, it is possible that endogenous subendothelial vWF protein is involved in the vascular disease process that typically occurs in this area. Little disease is generally observed in the thoracic region of normal pigs, which also do not show detectable quantities of VWF in the subendothelium. Thus, our present findings do not rule out a role for vascular vWF in atherosclerosis.

The present findings are consistent with a major role for vWF in blood in the deposition of platelets on porcine aortic subendothelium and, presumably, in large vessel thrombosis. The importance of VWF in vessels in the normal pig that do show the presence of vWF by immunological methodology, such as in the microvasculature and the venous and pulmonary circulation, is not clear. Certainly, it is plausible that vascular VWF may play an important role in normal hemostatic function, which is primarily a microcirculatory event. However, its role in large vessels (pulmonary artery, veins, abdominal aorta), which do exhibit differences in the presence of vWF between vWD and normal pigs, is less certain.

**References**


Index Terms: von Willebrand disease • von Willebrand platelets • platelet-vessel wall interactions
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