Platelet Secretory Products May Contribute to Neuronal Injury

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Background: We do not fully understand the mechanisms for neuronal damage following cerebral arterial occlusion by a thrombus that consists mainly of platelets. The view that certain endogenous substances, such as glutamate, may also contribute to neuronal injury is now reasonably well established. Blood platelets are known to contain and secrete a number of substances that have been associated with neuronal dysfunction. Therefore, we hypothesize that a high concentration (approximately several thousand-fold higher than in plasma, in our estimation) of locally released platelet secretory products derived from the causative thrombus may contribute to neuronal injury and promote reactive gliosis.

Summary of Comment: We have recently been able to report some direct support for this concept. When organotypic spinal cord cultures were exposed to platelet and platelet products, a significant reduction in the number and the size of the surviving neurons occurred in comparison with those in controls. We further observed that serotonin, a major platelet product, has neurotoxic properties. There may be other platelet components with similar effect.

Conclusions: The hypothesis of platelet-mediated neurotoxicity gains some support from these recent in vitro findings. The concept could provide a new area of research in stroke, both at the clinical and basic levels. (Stroke 1991;22:1448-1451)

Our understanding of the platelet has evolved from a time when it was considered an artifact in a blood smear, to the present time, when so much is known of its role in hemostasis that some may view this as its only function. In carrying out its hemostatic function, the platelet can also contribute to in vivo propagation of thrombosis, often with devastating clinical consequences such as cerebral thrombosis. Platelets, despite their small size and anuclear status, have numerous metabolically active functions. Within their cytoplasm are storage organelles, such as dense and α-granules that contain a variety of biologically active substances, including serotonin (5HT) and calcium. The organelar contents of the platelet are secreted by an energy-dependent process without loss of other subcellular compartments and with simultaneous generation of thromboxane A2. During the platelet secretion process, a contractile wave of circumferential microtubules centralize the organelles so that their contents are secreted into a canalicular system for release to the exterior. The granule membrane is probably recycled by incorporation into the platelet plasma membrane. The platelet products released after stimulation with physiological agonists such as collagen cause local vasoconstriction, endothelial injury, and increased vascular permeability. Furthermore, platelet factor 4, an α-granule protein, has been shown to permeate the de-endothelized vessel wall. Many of the substances secreted by the platelet have either direct actions on cells, including the platelets themselves, or are converted into physiologically more active substances in plasma or on cell surfaces.

We and others have shown that platelets are the major cellular structure within an acute thrombus. The concentration of platelet secretory products at the site of thrombus formation may be several thousand-fold the concentration in plasma. For example, 50% of an occluding platelet plug is comprised of platelets, and the number of platelets in a unit volume of this plug is estimated to be about 190 times that in the same unit volume of whole blood. We have determined that the concentration of free 5HT in human whole blood before activation of platelets is 36 nM, and the total amount of 5HT after activation of platelets with collagen is 836 nM. Theoretically, the amount of 5HT released by one milliliter of platelet plug, assuming that all the platelets in the plug have been activated, is about 4,000 times the concentration of free 5HT in one milliliter of blood.
[190\times(836-36)/36=4,222]. Thus, we suspect an abundant secretion of platelet products at the site of an acute cerebral thrombosis. Conceivably, these products cause further neuron dysfunction upon diffusion into the surrounding neural tissue through a locally disrupted blood–brain barrier. This communication offers evidence in support of this hypothesis. We do recognize that the mechanism(s) of neuronal injury in thrombotic stroke may be more complex and that several other factors may be involved. For instance, glutamate, which has been shown to be neurotoxic, is released in large amounts by ischemic neurons. Other factors such as leukocytes, which contain potentially toxic substances, have been shown to concentrate in ischemic regions, although in smaller numbers.16

During the acute phase of ischemic stroke caused by cerebral thrombosis, the neurological deficit is often greater than can be explained by the size of the lesion delineated even by sophisticated imaging techniques.2,5 This is particularly true in patients with brain stem infarction and stroke-in-evolution, in which the clinical deficit during the acute phase is alarming although neuroimaging shows little or no abnormality.2,5 At present, there is no convincing explanation for this discrepancy. With the knowledge that the integrity of the blood–brain barrier is disrupted at the site of cerebral ischemia, it is conceivable that platelet secretory products released from the causative thrombus diffuse into the neighboring brain parenchyma. Experiments in gerbils have shown that during cerebral ischemia, the blood–brain barrier is disrupted at 5 hours (the earliest recorded time period) after induction of cerebral ischemia, is most pronounced at 72 hours, and returns to normal levels at 1 week.17 Therefore, the time course of blood–brain barrier disruption is compatible with the hypothesis that locally released platelet secretory products may have access to surrounding neurons under acute ischemic conditions. In this study, the authors also show that the blood–brain barrier, under ischemic conditions, becomes permeable to a number of biogenic amines, including 5HT. We have investigated the relation between the extent of platelet activation and acute cerebral infarction in stroke patients and have observed increased platelet activation based on platelet [Ca\textsuperscript{2+}] measurement;18 increased platelet secretion, determined by ATP release from dense granules; and a reduced α-granule content.19 Our finding of maximal platelet activation at 36–72 hours after the onset of stroke in these patients corresponded well with the initial clinical profile observed by others, who saw clinical worsening of stroke over a similar period of time.20

A consideration of thrombotic thrombocytopenic purpura also evokes further evidence for our concepts. This often life-threatening condition is characterized clinically by the presence of thrombocytopenia and neurological dysfunction. Central nervous system abnormalities occur in more than 90% of patients, and nearly half initially present with neurological complaints.21 Adams et al.,22 in their neuropathological study of thrombotic thrombocytopenic purpura, observed agglutinated platelets in cerebral microvessels, perivascular foci of nerve cell damage, and, in places, glial proliferation and petechial hemorrhages. Alteration of neurons in small foci around the thrombosed vessels was a common finding. The neurons were usually faintly stained and had pale bluish cytoplasm and nuclei suggestive of degeneration. Disruption of the blood–brain barrier in the cerebral vessels containing the platelet thrombi has also been observed.23 Although the rarity of cerebral infarction distal to an occluding thrombus in thrombotic thrombocytopenic purpura may be explained by good collaterization, this does not fully explain the perivascular neuronal changes. There remains the possibility that platelet secretory products derived from luminal thrombi cause the damage to the surrounding neurons.

In addition to the observations that platelet aggregates form the major part of an arterial thrombus,13-15 there is experimental evidence that platelets actually accumulate at the site of focal cerebral ischemia as a secondary phenomenon.24,25 This takes place even at focal areas of ischemia produced by air emboli.24 Thromboxane A\textsubscript{2}, a platelet-specific prostaglandin, is a major product released by platelets upon activation.26 The amount of thromboxane A\textsubscript{2} found at the site of thrombus formation is largely derived from the platelet. There is a specific increase in the amount of thromboxane A\textsubscript{2}, measured as its stable metabolite thromboxane B\textsubscript{2}, at the site of ischemic lesion in the spinal cord.27 The degree of neurological deficit in the acute phase and the extent of neuropathological damage correlated with the thromboxane concentration at the site of spinal cord ischemia.27 Similar findings of elevated thromboxane levels in models of focal29,30 and global31-33 cerebral ischemia provide some support for our hypothesis.

There is also convincing evidence from studies in baboons24,25 that 5HT, a major platelet product, can cause neuronal dysfunction. Platelets contain more than 90% of the total amount of 5HT present in blood30 and, like neurons, have 5HT\textsubscript{1} receptors that are blocked by specific antagonists.37 When 5HT was injected into a cerebral circulation with osmotically disrupted blood–brain barrier, there was suppression of neuronal metabolism and electroencephalographic activity.34 In vitro studies have confirmed 5HT suppression of neuronal activity by neuronal membrane hyperpolarization.38-40

Furthermore, there is evidence that platelets contain other substances that are toxic to neurons. Glutamate has been convincingly shown to produce damage to neurons in culture.41,42 This damage for the most part occurs through an interaction with N-methyl-d-aspartate receptors on neurons. It is believed that at least part of the neuronal damage seen in anoxia is due to the effect of glutamate released from ischemic neurons.43,44 It is probable that the major portion of glutamate that causes
neuronal injury comes from ischemic neurons, but intravascular infusion of glutamate apparently can result in similar damage. As an extension of this latter finding, one may speculate on the significance of glutamate in platelets. However, the calculated concentration that may be achieved by platelets in the vicinity of a thrombus appears small when compared with the concentration measured in ischemic brain tissue.

Recent studies indicate that platelets may also play a role in neurodegenerative conditions. Several groups of investigators have shown that platelet α-granules contain and secrete peptide fragments of the β-amyloid precursor protein, similar to that seen in Alzheimer's neuritic plaque. Furthermore, Yankner et al report that β-amyloid is directly toxic to differentiated neurons. Although, the source and the mechanism of β-amyloid deposition in Alzheimer's neuritic plaque are unknown, it is possible that the platelet α-granule is the source. Whether the β-amyloid in platelets has any role in the neuronal injury from ischemia is a question that deserves study.

In addition to possibly contributing to acute neuronal injury, platelet secretory products may be involved in stimulating gliosis. Platelet α-granules are known to contain several growth-promoting peptides such as platelet-derived growth factor and transforming growth factor-β that regulate mitosis in connective tissue cells. Of these factors, platelet-derived growth factor has been studied most extensively. This peptide is released from platelets during thrombus formation and has been convincingly shown to cause proliferation of fibroblasts and smooth muscle cells. In fact, specific receptors for platelet-derived growth factor are known to be present on connective tissue cells.

In the central nervous system, platelet-derived growth factor has been shown to stimulate metabolism and proliferation of human glial cells but not of neurons. Therefore, it is possible that a platelet-derived growth factor released at the time of thrombosis may trigger gliosis in thrombotic stroke.

To test our hypothesis, we have recently studied the direct effect of platelets and their secretory products on central nervous system neurons. We used the roller-tube method to maintain explants of rat spinal cord in culture and identified their neurons by acetylcholinesterase staining. The changes in number and size of the ventral horns were morphometrically quantified. Compared with the control cultures, there was a significant decrease in the number of neurons per ventral horn in the platelet-treated explants, and there was a shift toward smaller-sized surviving neurons. This effect was quantitatively and qualitatively similar with the platelet secretory product-treated explants. The results suggest that the neuronal damage from platelets is through their secretory products. Further, the results of our initial experiments with SHT suggest that it may be one of the neurotoxic constituents of platelet secretion. These studies may constitute the first demonstration of a toxic effect of platelet secretory products on neurons.

In summary, we have presented clinical and experimental evidence to support the hypothesis that platelet products might contribute to neurological dysfunction beyond that attributed to vessel occlusion. Considering the large number of platelets involved in thrombus formation, it is possible that their secretory products may enhance ischemic neuronal damage.

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