Tissue Factor in Coagulation
Which? Where? When?

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Abstract—Tissue factor (TF) is an integral membrane protein, normally separated from the blood by the vascular endothelium, which plays a key role in the initiation of blood coagulation. With a perforating vascular injury, TF becomes exposed to blood and binds plasma factor VIIa. The resulting complex initiates a series of enzymatic reactions leading to clot formation and vascular sealing. In some pathological states, circulating blood cells express TF as a result of exposure to an inflammatory stimulus leading to intravascular clotting, vessel occlusion, and thrombotic pathology. Numerous controversies have arisen related to the influence of structural features of TF, its presentation, and its function. There are contradictory reports about the synthesis and presentation of TF on blood cells and the presence (or absence) of functionally active TF circulating in normal blood either on microparticles or as a soluble protein. In this review we discuss TF structure-function relationships and the role of TF during various phases of the blood coagulation process. We also highlight controversies concerning the expression/presence of TF on various cells and in blood in normal and pathological states. (Arterioscler Thromb Vasc Biol. 2009;29:1989-1996.)

Key Words: tissue factor ■ monocytes ■ posttranslational modifications ■ platelets ■ thrombin generation

Structure-Function Relationships (Which?)
TF is a 263/261 amino acid transmembrane protein containing 3 domains (Figure 1): (1) an extracellular domain representing the NH2-terminal part of the molecule (residues 1 to 219) and composed of 2 fibronectin type III domains; (2) a transmembrane domain, which anchors TF to the membrane (residues 220 to 242); and (3) a cytoplasmic COOH-terminal domain (residues 243 to 263). The extracellular domain of TF is involved in complex formation with factor VIIa increasing, in a membrane-dependent fashion, the activity of the protease toward its natural substrates factor IX, factor X, and factor VII by several orders of magnitude. Thus, 2 of the 3 domains of TF (extracellular and transmembrane) play distinct roles in the blood coagulation process. The major role of the cytoplasmic domain is related to signal transduction. As a consequence, it has been generally accepted that TF lacking the cytoplasmic domain is functionally identical to the full-length protein in the initiation of thrombin generation. On the other hand, recombinant TF lacking both the cytoplasmic and transmembrane domains cannot bind to the membrane, and therefore, while forming a complex with factor VIIa, does not activate factor VII and has decreased catalytic efficiency toward factor IX and factor X.

More than 20 years ago, sufficient natural TF was isolated to identify, clone, and express the recombinant protein (rTF) in human kidney 293 cells and in E coli. Subsequently, various forms of rTF ranging from the full-length protein to...
the extracellular domain of TF with different levels of posttranslational modifications have been expressed in a variety of vectors including yeast and insect cells (Figure 1). Mutational studies\textsuperscript{23} have been performed, and an x-ray structure\textsuperscript{23} has been derived using these rTFs. Although these rTFs have been used extensively as surrogates for the natural protein, the limited availability of purified natural TF has not allowed certification of results obtained with rTF.

The contributions of various regions of the primary structure of TF on its activity are relatively well established. However, data related to the influence of posttranslational modifications on the TF function are scarce, if available at all. The amino acid sequence data related to the structure of rTF indicate that the extracellular domain of protein has potential glycosylation sites at Asn\textsuperscript{11}, Asn\textsuperscript{124}, and Asn\textsuperscript{137}\textsuperscript{16,24} There are also 2 disulfide bonds (Cys\textsuperscript{49}-Cys\textsuperscript{57} and Cys\textsuperscript{186}-Cys\textsuperscript{209}) located in this domain.\textsuperscript{25} The carboxyterminal cytoplasmic region of TF contains a single Cys\textsuperscript{245} residue and 3 Ser residues. The Cys\textsuperscript{245} residue is linked to a palmitate or stearate fatty acyl-chain,\textsuperscript{25} whereas one of the Ser residues can be phosphorylated by a protein kinase C–dependent mechanism.\textsuperscript{26} Although the sites of glycosylation of the extracellular domain are established and a partial identification of carbohydrates attached to those sites has been accomplished,\textsuperscript{24} a complete analysis of the carbohydrate side chain structure is lacking. In addition, no systematic analyses have been reported which examine the influence of glycosylation on TF affinity for factor VIIa, or on the affinity of the TF-factor VIIa complex for its natural substrates factor IX and factor X, or on its effects on TF-factor VIIa catalytic efficiency. The apparent lack of interest related to TF glycosylation may have been caused by 2 early publications addressing the subject. In the only reported activity comparison for glycosylated and nonglycosylated rTFs by Paborsky and coworkers,\textsuperscript{21} it was suggested that TF glycosylation is not required for procoagulant activity. However, because no data were provided in the report, it is not established whether glycosylation influences TF activity. Waxman et al reported that the activity of rTF\textsubscript{1–263} is identical with that of natural TF from brain,\textsuperscript{27} however this also was not supported by data included in the publication. Similarly, studies suggesting that glycosylation could be essential for TF activity do not provide experimental evidence to support this hypothesis.\textsuperscript{28,29} Thus the question whether the glycosylation of TF has an effect on its function remains open because of the absence of relevant data.

A controversial issue associated with the activity of TF is related to a hypothetical “encryption-decryption” process associated with TF activity presentation. It has been suggested that the majority of TF molecules located on the cell surface have low activity (are “encrypted”) and that “decryption” is essential for the expression of TF function.\textsuperscript{30} Several contradictory mechanisms have been hypothesized in attempts to explain the “encryption-decryption” and presentation of TF activity.

One established method for inducing TF activity on the cell surface consists of the treatment of quiescent TF-bearing cells with calcium ionophore.\textsuperscript{31–34} Ionophore treatment increases TF activity by 2- to 10-fold. Although some authors assign this increased TF activity to increased expression of TF protein,\textsuperscript{35} others suggest this arises from changes in the cell membrane environment, particularly in an increased expression of acidic phospholipids,\textsuperscript{31–34,36} sometimes related to cell death.\textsuperscript{32,37} Several studies hypothesize a role for cholesterol in cell lipid rafts contributing to the “encryption-decryption” of TF activity,\textsuperscript{38–40} although there is little agreement between the proposed mechanisms for this process. An increase in TF activity has been reported when lipopolysaccharide (LPS)-stimulated monocytes are treated with platelets.\textsuperscript{41–43} However, the observed increase in activity was quite limited (2- to 3-fold) and could be (in part) assigned to an increase in TF antigen expression by monocytes.\textsuperscript{43}

It has been suggested\textsuperscript{44} that an “encryption” of TF preexisting and residing on the cell membrane is related to the reduction status of the Cys\textsuperscript{186}-Cys\textsuperscript{209} bond, which leads to impaired TF activity. The presumed reformation of this bond using an oxidizing agent (HgCl\textsubscript{2}) appears to restore TF activity. Unfortunately, structural data have not been provided in support of the reformation of the disulfide bridge from a hypothesized reduced state. In addition the proposed mechanism is not supported by relevant studies that conclude that in general HgCl\textsubscript{2} will oxidize only a single thiol group.\textsuperscript{45,46} Moreover, an increase in TF activity on cell surfaces similar to that caused by HgCl\textsubscript{2} can be achieved by treating TF-bearing cells with other metal compounds, such as AgNO\textsubscript{3} and phenylmercuric acetate,\textsuperscript{47} with the authors concluding that this increase is related to the elevated exposure of phosphatidylserine.\textsuperscript{48,49} Similar controversy surrounds publications related to the putative role for protein disulfide isomerase (PDI) in TF activity. Ahamed et al\textsuperscript{40} postulate that PDI disrupts the Cys\textsuperscript{186}-Cys\textsuperscript{209} bond and, as a consequence, suppresses TF procoagulant activity. Reinhardt and coworkers, however, suggest in their study\textsuperscript{50} that PDI promotes TF activity, whereas Pendurthi et al\textsuperscript{41} reports that PDI plays no role in TF activity, and that the observed increase in TF activity is related to the contamination of PDI with phospholipids.\textsuperscript{52}
A soluble form of TF circulating in blood (alternatively spliced TF) was identified several years ago. It has been suggested that this form of TF is procoagulant and stimulates clot growth. However, subsequent studies showed that this form of TF has no procoagulant activity but could promote tumor growth and angiogenesis. The potential origin of this discrepancy could be assigned to the physiologically irrelevant conditions used for the detection of alternatively spliced TF activity and the lack of validated commercial assays for the detection of TF activity at its physiological concentrations. The role of soluble TF remains problematic.

Figure 2. TF titrations in contact pathway inhibited whole blood (A) and plasma (B) from healthy individuals. Black and white bars represent 2 healthy donors. Reproduced with permission from Butenas et al.

The Controversy Regarding Blood-Borne TF (Where?)

During the last several years, numerous conflicting studies related to the presence, concentration, and functional activity of TF circulating in blood as a soluble protein and on/in various blood cells and platelets have been published. Several groups of investigators reported the presence of TF antigen circulating in blood at the concentrations as high as 5 to 10 nmol/L and those of active protein reaching (sub)nanomolar concentrations. It has been reported that this blood-borne TF is located on blood cells, platelets, and microparticles or that it circulates as a soluble protein. Frequently, these reports have been developed using nonvalidated commercial assays. In contrast, data published by several other groups indicate that if there is TF-related activity either in blood or plasma from healthy humans, the concentration of active TF does not exceed 20 fmol/L (Figure 2). Additionally, based on the experience accumulated in our laboratory as well as on reports from other laboratories, blood or plasma activated with (sub)picomolar concentrations of functional TF clots within several minutes.

Another subject of controversy related to blood-borne TF is the location of this protein. It is generally agreed that TF can be expressed/exposed by monocytes on cytokine stimulation. In general, it has been accepted that the source of circulating TF in pathological conditions could be cell-derived microparticles. More controversial is a reported presence of TF in/on platelets. In some of those publications it has been suggested that TF is transferred to platelets from the cells, whereas others suggest that TF is synthesized by platelets. In contrast to these publications, it has been reported that neither TF activity nor antigen were detected on resting and calcium ionophore stimulated platelets. In that study, no TF antigen-related signal was observed in resting or ionophore treated platelets using flow cytometry (Figure 3A and 3B), although 91% of platelets were activated on treatment with the calcium ionophore (Figure 3C). Similarly, there is little agreement related to the presence of TF on granulocytes. Maugeri et al suggested in their publication that granulocytes produce TF on stimulation, whereas other authors have reported the expression of TF in neutrophils and eosinophils. However, data from Osterud’s laboratory show no evidence of TF expression in any granulocytic cells. The major causes for the discrepancies related to the presence and concentration of TF are, most likely, the lack of validated and reliable assays for TF antigen and activity. The majority of studies reporting high concentrations of TF in plasma and the presence of TF in platelets and blood cells use commercial assays. We developed and validated in-house assays for the quantitation of TF antigen and activity. Using our assays, we have reported that the TF antigen concentrations in plasmas from patients with acute coronary syndrome are at low picomolar levels, with an average functional concentration less than 0.4 pmol/L. In contrast, in a study by Bis et al, which used a commercial TF assay, nanomolar concentrations of TF in plasma from patients with a similar diagnosis were reported. Until there is agreement in the scientific community concerning the validity of the assays used by various laboratories, incongruent reports will continue to accumulate in the literature.
is presented, a full coagulant response follows; if the TF challenge is insufficient, the procoagulant response is arrested, primarily by the synergistic activities of the TF pathway inhibitor (TFPI), antithrombin, and the protein C pathway.89,90 A competing hypothesis of TF biology has been advanced in which the initiating TF stimulus requires constant supplementation to the ongoing reaction with newly available TF, providing a mechanistic rationale for blood-borne TF in normal hemostasis.

Eliminating one of these hypotheses requires resolving 2 basic areas of dispute: the constitutive presence of TF in blood, and the identity of the procoagulant catalysts required to propagate clot growth. As has been noted, the controversy concerning the presence and activity of TF species in blood and on blood cells continues, and ultimately has become an important debate about the rigor of the quantitative methods used. The mechanistic argument for a requirement for ongo-

**Figure 3.** Flow cytometric analyses of resting and calcium ionophore A23187-treated platelets. Resting (A) or A23187-treated platelets (B) were immunostained with anti–TF-5 monoclonal antibody. A23187-treated platelets were also treated with an anti–P-selectin antibody (C). An irrelevant isotype-matched mouse IgG was used in the control experiments. Reproduced with permission from Butenas et al.64

**Figure 4.** Termination of TF and factor VIIa activity in TF (5 pmol/L) initiated thrombin generation in synthetic coagulation proteome. Anti-TF and antifactor VIIa inhibitory antibodies were added at 0 s (◆), 10 s (●), 60 s (◆), and 240 s (●) after the initiation of the reaction or not added at all (○). Arrows indicate antibody addition time points. Reproduced with permission from Orfeo et al.98

**Figure 5.** Resupply of the synthetic coagulation proteome—the effect of factor VIII on the stability of response. A 5 nM TF-initiated reaction mixture was subdivided after 20 min (A), and the eight separate aliquots subsequently resupplied at different times with an equal volume of a mixture containing 1.4 µM antithrombin/2 µM phospholipids either without factor VIII (closed symbols) or with 0.7 nM factor VIII (open symbols) was conducted immediately (20 min → t=0, (◆) and 45 (◆), 90 (◆), and 110 (◆) min later). Resupply with the mixture supplemented with factor VIII was conducted at 15 (○), 55 (△), and 100 (○) min after the subdivision of the TF-initiated reaction. Thrombin levels for the final 5 min of the TF-initiated episode are also shown (○). Thrombin levels are expressed as total picomoles of active thrombin to normalize for the volume change. An arrow indicates the resupply time for each aliquot. Reproduced with permission from Orfeo et al.99
of a functioning TF-factor VIIa complex and becomes fully self-limiting in the absence of an ongoing supply of TF to the outer face of the thrombus. In this regard Panes et al recently reported that activation of platelets leads to rapid de novo synthesis of TF and its expression. In this model, thrombus growth is viewed as self-limiting in the absence of an ongoing supply of TF to the extravascular region.

Other data consistent with this overall view of how a coagulant response is propagated include immunochemical demonstrations of TF embedded in human and mouse thrombi, suggesting that some type of circulating TF in the growth of thrombi.

On the other hand, substantial evidence supports the view that in normal hemostasis TF functions primarily in the initial phase of the clotting process and that other catalysts are involved in the propagation and maintenance of fibrin–platelet clots. Our laboratory has explored the time dependence of the requirement for TF during the progress of a blood coagulation reaction using mathematical, synthetic coagulation proteome, and whole blood models. When TF activity was eliminated either using inhibitory antibodies for factor VII and TF or mathematically at various times during the initiation phase, the results in all 3 models indicated that the progress of the reaction rapidly loses an absolute dependence on the presence of a functioning TF-factor VIIa complex and becomes fully independent of TF by the onset of the propagation phase of thrombin generation. In addition these studies indicated that the catalysts generated by transient expression of TF cofactor activity were sufficient to maintain a TF-independent procoagulant response as long as reactants were available and that this catalyst pool could reinitiate coagulation without input from the TF-factor VIIa complex.

Figure 4 shows an example of this type of experiment using the synthetic coagulation proteome where inhibitory antibodies to TF and factor VIIa were added at the onset of the reaction or 10, 60, or 240 s post initiation. No thrombin generation is seen when antibodies are present at the beginning of the reaction. Conversely, addition of inhibitory antibodies at the onset of the propagation phase had no effect. However, when added 60 s after the start of the reaction, there is a slight prolongation of the initiation phase and almost no effect on other parameters of thrombin generation. Thus in several in vitro models of TF-initiated coagulation, the procoagulant response becomes independent of TF cofactor activity before the onset of clot formation, reflecting the emergence of the more efficient intrinsic factor Xase complex, and suggesting that transient expression of TF is sufficient to successfully achieve the first phase of hemorrhage control, formation of an impermeable platelet fibrin barrier.

Figure 5 shows a synthetic coagulation proteome experiment testing the stability of the procoagulant catalysts generated by an episode of TF-initiated thrombin generation. A TF-initiated reaction in which thrombin production had ceased and no detectable thrombin remained (because of inhibition by antithrombin) was subdivided after 20 minutes,
with individual aliquots then resupplied at various later times with mixtures containing prothrombin, antithrombin, phospholipid with or without factor VIII. In the absence of FVIII (closed symbols) thrombin generation by resupplied reactions was observed to decline slowly as the time period before resupply increased, reflecting a slow decline in the prothrombinase concentration. However, inclusion of factor VIII (open symbols) into the resupply mixture yielded time courses of thrombin generation that appeared unaltered even after an additional 100 minutes of incubation before resupply.

These studies indicate that prothrombinase and factor IXa formed during an episode of TF-initiated coagulation persist and also that they can function to restart thrombin generation. Complementary studies using our whole blood model have verified the importance of the prothrombinase complex in reinitiating coagulation. Numerous other studies have implicated fibrin bound thrombin as a relatively stable, localized, procoagulant product of TF-initiated coagulation, capable of activating procofactors, cleaving fibrinogen and activating platelets, and thus functioning to propagate thrombus growth. Thus, work from our laboratory and others has led us to propose a model of hemorrhage control (Figure 6). This model, 2 procoagulant compartments emerge as a consequence of the impermeable barrier formed by platelets and fibrin: an extravascular one, isolated from the blood of activating procofactors, cleaving fibrinogen and activating platelets, and thus functioning to propagate thrombus growth.

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Disclosures

None.

References


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