Plasminogen activator inhibitor-1 and haemostasis in obesity

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The connection between obesity and disordered haemostasis is well established, but incompletely understood. There is a strong link between inhibition of fibrinolysis and obesity, and elevation of the plasma inhibitor, plasminogen activator inhibitor-1 (PAI-1), is regarded as a central factor. Here we explore the increased risk of atherothrombotic disorders in obese subjects, and the evidence for metabolic and genetic causes. There is a clear relationship between plasma PAI-1 and obesity, and adipose tissue synthesises PAI-1, as has been shown in mouse and rat models, and more recently in human material. This tissue also produces several effector molecules that can up regulate PAI-1. These molecules include transforming growth factor β, tumour necrosis factor α, angiotensin II and interleukin 6, all of which up regulate PAI-1 in various cell types. The issue of whether adipose tissue directly contributes to plasma PAI-1, or whether it primarily contributes indirectly, its products stimulating other cells to produce PAI-1 that feeds into the plasma pool, is not yet resolved. Finally, we briefly examine other proteins of haemostasis that are products of adipose tissue. Further studies are needed to define the regulation of these proteins, in adipose tissue itself and in other cells influenced by its products, in order to extend recent insights into the links between obesity and haemostasis.

Obesity: PAI-1: Thrombosis: Insulin resistance: Cardiovascular disease

Haemostasis describes the systems that prevent loss of blood from the organism by clotting at sites of injury. Many different components are active in this process, including the endothelium of the vessel wall, circulating blood cells, notably platelets and leucocytes, and plasma components. Two major protease cascades are involved, the coagulation and fibrinolytic pathways (Fig. 1), which consist primarily of inactive plasma precursors that are activated to become serine proteases.

Cell surfaces and/or fibrin provide sites for local activation of the haemostatic system; this process is not favoured in free solution. Coagulation is initiated primarily by cell surface expression of tissue factor, which acts as a focus for plasma coagulation factors, culminating in the formation of thrombin; it then converts fibrinogen to fibrin. Fibrinolysis depends on bringing together plasminogen, an inactive plasma protein, and its activators, tissue plasminogen activator and urokinase, on fibrin or cells, where plasmin is generated and degrades fibrin. The essential balance in plasma is between the proteolytic activities of tissue plasminogen activator and urokinase and the inhibitor, plasminogen activator inhibitor-1 (PAI-1). In general, PAI-1 is present in 4–5-fold excess over the activators, favouring the stabilization of fibrin. Fibrin formation is an essential defensive mechanism, protecting the body from bleeding. If it persists it can cause thrombosis. Deposition of excess fibrin in the vessel wall is also relevant to atherosclerosis. Obese subjects suffer many atherothrombotic diseases. The protein of the haemostatic system that is most disordered in obesity is PAI-1, an inhibitor of plasminogen activation, which stabilises fibrin (Fig. 1). The present review focuses on this inhibitor.

Plasminogen activator inhibitor-1

PAI-1 is produced by a variety of cells in culture and is widely distributed in tissues (Sawdey & Loskutoff, 1991; Simpson et al. 1991). In cultured cells PAI-1 production is stimulated by many agents, including thrombin, insulin, cytokines, lipoproteins, angiotensin II and bacterial lipopolysaccharide (Andreasen et al. 1990; Loskutoff, 1991). PAI-1 occurs at low concentrations in plasma, about 20 ng/ml or 400 pM, while platelets account for more than 90% of blood PAI-1 (Booth, 1999). PAI-1 activity is unstable, but is protected in plasma by its interaction with vitronectin (Declerck et al. 1988). There is good agreement

Abbreviations: PAI-1, plasminogen activator inhibitor-1; RAS, renin–angiotensin system; TGFβ, transforming growth factor β; TNF-α, tumour necrosis factor α.

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The early studies showed a coincidence between disease and elevations in plasma PAI-1. The possibility of a causal link between high PAI-1 and pathological conditions was then examined in large prospective studies, measuring either PAI-1 activity or antigen. These studies also sought a genetic basis for elevated plasma PAI-1. Several polymorphisms in the PAI-1 gene have been reported to be represented more frequently in patients than in healthy populations, but there are many conflicting reports, and no compelling data to connect the PAI-1 gene to disease (Lane & Grant, 2000). The problem of inconsistent results in these genetic studies has sometimes overshadowed the clear connection between elevated plasma PAI-1 and disease. PAI-1 in plasma is elevated in the insulin resistance syndrome (also termed syndrome X; Reaven, 1988), being associated strongly with plasma insulin, triacylglycerols and BMI (Juhan-Vague & Alessi, 1997). Once corrected for these other markers, the elevation in plasma PAI-1 becomes non-significant, leading to the conclusion that PAI-1 is a marker of the insulin resistance syndrome, and not an independent risk factor (Juhan-Vague et al. 1996). This lack of independence as a risk factor should not be regarded negatively; rather it signals the close connection between PAI-1 and metabolic disturbance, including obesity.

Obesity is an independent risk factor for atherosclerosis and cardiovascular disease, and a major contributor to mortality and morbidity (Rosenbaum et al. 1997). More than one mechanism may explain this increased risk, but impaired fibrinolysis has been strongly associated over several decades with obesity (Fearnley et al. 1963; Bennett et al. 1966). Increased plasma PAI-1 has emerged as the main cause of the decreased fibrinolytic activity (Vague et al. 1986, 1989; Landin et al. 1992; McGill et al. 1994). Importantly, energetic weight loss led to a decrease in plasma PAI-1 (Sundell et al. 1989, 1991; Folsom et al. 1993; Markmann et al. 1998), which rose again if weight was regained (Mavri et al. 1999). The same effect was achieved by surgical removal of fat (Primrose et al. 1992).

These clinical studies supported the possibility that adipose tissue contributed directly to elevated plasma PAI-1, a hypothesis that emerged strongly when it was observed that mouse adipose tissue expressed high levels of PAI-1 mRNA (Sawdewy & Loskutoff, 1991). A seminal finding was made in ob/ob mice, which cannot produce leptin, as a result of which they develop obesity and insulin resistance. These mice had plasma PAI-1 levels 5-fold higher than their lean counterparts, with overexpression of the PAI-1 gene in adipose tissue (Samad & Loskutoff, 1996; Loskutoff et al. 2000). Expression of PAI-1 mRNA was also demonstrated in visceral and subcutaneous fat of obese rats (Shimomura et al. 1996). These findings and the emerging role of adipose tissue as an organ secreting proteins such as adipin, leptin and adiponectin into blood (Spiegelman & Flier, 1996) suggested the importance of this tissue in the elevation of plasma PAI-1 (Fig. 2). The potentially large mass of adipose tissue in obese subjects would have a capacity to synthesise PAI-1 that could exceed that of other tissues.

PAI-1 activity in human plasma is correlated with adipin, itself a product of adipose tissue (Alessi et al. 1995), and it was shown later that human adipose tissue produced PAI-1 (Alessi et al. 1997). PAI-1 mRNA was...
detected in freshly-isolated stromal and adipocyte fractions of human adipose tissue. The weak signal in fresh tissue was greatly increased on culture, and the adipocytes were identified as the main source of PAI-1. The illustration of PAI-1 mRNA in human adipose tissue raised interest in adipose tissue as a source of PAI-1, and several studies went on to analyse PAI-1 and related factors. Adipose tissue explants released PAI-1 after 2 h incubation with significantly more released antigen from obese subjects than from non-obese subjects ($P < 0.0001$), consistent with a 2-fold difference ($P < 0.05$) in the steady-state level of PAI-1 mRNA (Eriksson et al. 1998). These authors expressed PAI-1 secretion per adipose tissue fat cell, which revealed a larger difference between obese and non-obese controls. They also illustrated that PAI-1 mRNA levels and adipocyte PAI-1 secretion were related to adipocyte volume and lipid content.

Studies on human subjects have revealed differences in PAI-1 release from different fat depots. A direct link has been shown between plasma PAI-1 and visceral fat area in obese and non-obese children and adults (Cigolini et al. 1996; Ferguson et al. 1998). PAI-1 secretion by human adipocytes has been reported to be more pronounced in visceral fat than in subcutaneous fat (Alessi et al. 1997), a phenomenon also reported in animal models. Analysis of rat adipose tissue suggested that both visceral and subcutaneous fat could synthesize PAI-1, but that the increased expression associated with obesity is related only to increases in visceral fat PAI-1 expression (Shimomura et al. 1996). An interesting study on obese men and women, in which visceral fat was measured by magnetic resonance imaging, showed that visceral fat was directly correlated with plasma PAI-1 antigen and activity in men but not in women (Kockx et al. 1999). This finding is consistent with men having more visceral fat. Plasma PAI-1 correlated well with PAI-1 produced in vitro by cultured subcutaneous and visceral adipose tissue, and there was good correlation between the two sources, with visceral fat producing about twice as much PAI-1 as subcutaneous fat (Morange et al. 1999).

Alessi et al. (2000) found that visceral and subcutaneous fat were comparable in their production of PAI-1, while Eriksson et al. (2000) found higher PAI-1 mRNA in subcutaneous fat compared with visceral fat, and a higher rate of synthesis of PAI-1 antigen. These authors also point out that the subcutaneous depot is the largest fat depot. Further studies are required to define the differences in PAI-1 production by these different fat sources, particularly in tissue of human origin, as animal body fat distribution differs from that in human subjects. Recent studies focus on the possible role of local depots of adipose tissue, such as the artery-associated fat, in the pathobiology of atherosclerosis (Chaldakov et al. 2000).

PAI-1 is up regulated by a number of hormones, cytokines and metabolic factors (Andreasen et al. 1990; Loskutoff, 1991). It was speculated that the general up regulation of cytokines and effector molecules in obesity would lead to increased PAI-1 synthesis. To address the question of whether adipose tissue expression of PAI-1 contributed directly to plasma PAI-1, Yudkin et al. (1999) measured arterio–venous differences across subcutaneous adipose tissue. No net increase in PAI-1 activity or antigen was observed in healthy subjects, leading to the conclusion that subcutaneous adipose tissue does not significantly contribute to circulating PAI-1. They found significant arterio–venous differences in the concentration of interleukin 6 ($P < 0.001$) and some difference in tumour necrosis factor α (TNF-α), again consistent with the idea that the effects of adipose tissue may be mediated through cytokines and growth factors (Yudkin et al. 2000). This finding would predict that synthesis of PAI-1 in other tissues would be increased, and indeed Pandolfi et al. (2000) found increased expression in the liver, adipose tissue and aorta wall of diabetic rats that were chronically hyperglycaemic.

**Cytokines, growth factors and other effector molecules**

Two cytokines that up regulate PAI-1 synthesis by various cells are TNF-α and transforming growth factor β (TGFβ) (Andreasen et al. 1990; Loskutoff, 1991). The influence of these cytokines on PAI-1 synthesis in adipose tissue, and that of other effector molecules, insulin and angiotensin II, will be addressed.

TNF-α is expressed in adipose tissue of both rodents (Hotamisligil et al. 1993) and human subjects (Perdidi & Spiegelman, 1997). Intraportal injection of TNF-α into lean mice caused up regulation and cellular expression of PAI-1 comparable with that observed in obese mice (Samad & Loskutoff, 1996; Samad et al. 1996). In ob/ob mice neutralization of TNF-α or deletion of the two TNF-α receptors (I and II) resulted in significantly decreased plasma PAI-1 antigen ($P < 0.02$) and adipose tissue PAI-1 ($P < 0.0001$; Samad et al. 1999). Similarly, treatment of human adipose tissue explants with TNF-α resulted in up regulation of PAI-1 mRNA, an effect that was abolished by antibodies to TNF-α (Cigolini et al. 1999). Adipose tissue PAI-1 and TNF-α mRNA levels produced by human adipocytes correlated well (Morange et al. 1999), suggesting a role for this cytokine in PAI-1 gene expression. However, a number of reports do not show a connection. Incubation of human adipose tissue with TNF-α failed to up regulate...
PAI-1 mRNA levels (Alessi et al. 1997) and no association was observed between PAI-1 antigen and TNF-α (Alessi et al. 2000). These results on human tissue are in agreement with those of Lundgren et al. (1996), who did not observe an effect of TNF-α in murine 3T3L1 differentiated adipocytes. There is no obvious reason for the discrepancies between studies, which appear not to reflect species differences. It may be that subtle differences in the cells, resulting from different experimental handling, affect their response to TNF-α. Further work is needed to clarify the relationship between TNF-α and PAI-1 synthesis by adipose tissue.

TNF-α is also a potent inducer of TGFβ in murine adipose tissue, and it contributes to the elevated TGFβ expression (Samad et al. 1999) that is observed in the adipose tissue of obese mice (Samad et al. 1997). Administration of TGFβ to mice resulted in an increase in plasma PAI-1 activity and PAI-1 mRNA expression in adipose tissue (Lundgren et al. 1996). Similarly, TGFβ treatment of human adipose tissue resulted in a 3-fold increase in PAI-1 antigen and a 2-fold increase in PAI-1 mRNA (Birgel et al. 2000). In agreement with these data, several reports have shown that PAI-1 mRNA is correlated with TGFβ mRNA (Morange et al. 1999) and PAI-1 antigen is correlated with TGFβ antigen in human adipose tissue explants (Alessi et al. 1997, 2000). Both PAI-1 mRNA and TGFβ mRNA were positively associated with BMI (Alessi et al. 2000). The data on TGFβ and PAI-1 in obesity suggest that the elevated plasma concentrations of PAI-1 may be due to the involvement of mediators in the regulation of PAI-1 gene expression, rather than a direct up regulation of adipose PAI-1. It may be that the effect of TNF-α can also be explained by its action on TGFβ and thus on PAI-1 synthesis.

Insulin has been shown to be correlated with PAI-1 in several studies, and indeed relationships between PAI-1 and BMI, triacylglycerol level and blood pressure are regarded as being secondary to this relationship (Juhan-Vague & Alessi, 1993). Efforts to explain this relationship by its up regulation of adipose tissue of obese mice (Samad et al. 1997). Administration of TGFβ to mice resulted in an increase in plasma PAI-1 activity and PAI-1 mRNA expression in adipose tissue (Lundgren et al. 1996). Similarly, TGFβ treatment of human adipose tissue resulted in a 3-fold increase in PAI-1 antigen and a 2-fold increase in PAI-1 mRNA (Birgel et al. 2000). In agreement with these data, several reports have shown that PAI-1 mRNA is correlated with TGFβ mRNA (Morange et al. 1999) and PAI-1 antigen is correlated with TGFβ antigen in human adipose tissue explants (Alessi et al. 1997, 2000). Both PAI-1 mRNA and TGFβ mRNA were positively associated with BMI (Alessi et al. 2000). The data on TGFβ and PAI-1 in obesity suggest that the elevated plasma concentrations of PAI-1 may be due to the involvement of mediators in the regulation of PAI-1 gene expression, rather than a direct up regulation of adipose PAI-1. It may be that the effect of TNF-α can also be explained by its action on TGFβ and thus on PAI-1 synthesis.

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The haemostatic system protease cascades can be affected by the products of other cascades such as the renin–angiotensin system (RAS), which plays an important role in the regulation of vascular and local fibrinolytic balance (Vaughan, 1998). Angiotensinogen is converted to angiotensin I by renin and to the potent vasoactive peptide angiotensin II by angiotensin converting enzyme. Angiotensin II stimulates PAI-1 production in a number of cells including endothelial cells and smooth muscle cells (Feener et al. 1995), mesangial cells in the glomerulus (Wilson et al. 1997) and in brain astrocytes (Olson et al. 1991). In human subjects infusion of physiological concentrations of angiotensin II exerted a rapid dose-dependent increase in plasma PAI-1 release (Ridker et al. 1993). The RAS system regulates neointimal PAI-1 expression, and angiotensin converting enzyme inhibitors decreased PAI-1 in the vessel wall in vivo (Hamdan et al. 1996). In a separate but complementary pathway angiotensin converting enzyme degrades bradykinin, resulting in decreased tissue plasminogen activator production (Brown et al. 1997).

Adipose tissue is an important source of angiotensinogen, and these cells can also process it to angiotensin II (Karlsson et al. 1998). Angiotensinogen expression in adipocytes is stimulated by a high-fat diet concurrent with enlargement of fat mass associated with insulin resistance (Zorad et al. 1995). In obese patients the involvement of angiotensin II as a consequence of increased plasma angiotensinogen secreted from adipose tissue has been proposed in the development of hypertension. The RAS is present both as a circulating hormone and as a local system. Recent evidence shows that a local RAS is present in human adipose tissue and may act as a distinct system from plasma RAS (Schling et al. 1999). Adipose tissue also has receptors for angiotensin II that are regulated by age and fat mass (Zorad et al. 1995). It is likely that angiotensin II stimulates PAI-1 synthesis in adipocytes, as it does in other cell types.

Locally-produced angiotensin II has been suggested to participate in the control of tissue growth and development. In adipose tissue angiotensin II stimulates the production of prostacyclin, which in turn converts preadipocytes to adipocytes and increases lipid synthesis and storage in adipocytes (Ailhaud, 1999). Thus, angiotensinogen-derived peptides produced in adipose tissue itself may affect adipogenesis and play a role in the pathogenesis of obesity.

An interesting report by Morange et al. (2000) investigated the possibility that PAI-1 is not only a marker of obesity, but also contributes to the development and modification of adipose tissue. Using the PAI-1 null mouse they showed that the absence of PAI-1 resulted in faster weight gain in the early weeks of life when animals were fed on a high-fat diet. They suggest that increased expression of PAI-1 in obesity could reflect effects of this protein in adipose development.

Other haemostatic proteins in obesity

Most of the present review has focused on PAI-1, but there are other proteins of the haemostatic system that are products of adipose tissue. Tissue factor, the initiator of the clotting cascade, is up regulated in obese mice (Samad et al. 1998). Elevated tissue factor mRNA was found in the adipose tissue of ob/ob mice compared with matched lean controls. The level of expression increased with both age and degree of obesity. Preliminary data suggest that this mechanism could also be regulated by TGFβ (Samad et al. 1997), which up regulates PAI-1 gene expression. It will be of interest to see if the data on tissue factor mRNA hold also at the protein level. Tissue factor expression in rabbit atheroma was decreased by lowering the lipid content of the diet. This effect was functional, in that it resulted in reduced cellular binding of coagulation factors and consequent fibrin deposition (Aikawa et al. 1999).
Adiponectin, another secreted product of adipose tissue, is an adhesion molecule that affects binding of monocytes to endothelial cells. It is found in plasma at high concentrations and seems to have a protective effect against atherogenesis, being decreased in obesity and in diabetes (Hotta et al. 2000).

Conclusion

Recent studies on the involvement of adipose tissue in haemostasis are beginning to dissect potential mechanisms for the long-established correlations between defective fibrinolysis and obesity. Adipose tissue is emerging as a secretory organ, and PAI-1 is among its products. The question of whether this tissue contributes directly to circulating PAI-1 is still not settled. Even if it does not, there is little doubt that its synthesis of cytokines and growth factors, which in turn up regulate PAI-1, contributes to local, and probably to circulating PAI-1 (Fig. 2). Questions remain on the depots that are most important for PAI-1 synthesis and on the subtleties of its regulation. Increasing efforts to study human adipose tissue are extending and corroborating the research in mouse models, which has been so important in opening up this field of study.

References


New perspectives on adipose tissue function


