Review

The importance of endothelin-1 for vascular dysfunction in cardiovascular disease

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Abstract

Endothelin (ET)-1 is a potent vasoconstrictor peptide originally isolated from endothelial cells. Its production is stimulated in a variety of different cell types under the influence of risk factors for cardiovascular disease and during the development of cardiovascular disease. Based on these observations and the biological effects induced by ET-1, including profound vasoconstriction, pro-inflammatory actions, mitogenic and proliferative effects, stimulation of free radical formation and platelet activation, ET-1 has been implicated as an important factor in the development of vascular dysfunction and cardiovascular disease. In the following the pathogenic role of ET-1, the mechanisms underlying the involvement of ET-1 for the development of vascular dysfunction and the potentially beneficial therapeutic effects of selective ETA and dual ETA/ETB receptor antagonists will be discussed. In particular the changes of pathophysiological importance mediated by ET-1 in clinical studies are reviewed. These changes may be of significance for the development of various cardiovascular diseases beyond pulmonary arterial hypertension which is the currently approved indication for ET receptor antagonists.

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Keywords: Atherosclerosis; Coronary disease; Endothelins; Endothelial function; Endothelial receptors

1. Introduction

1.1. Vascular function

The endothelium plays an important role in the regulation of vascular function by producing a large number of biologically active substances that participate in the regulation of vascular tone, cell growth, inflammation, and thrombosis/haemostasis. Dysfunction of the vascular endothelium is an early finding in the development of cardiovascular disease and is closely related to clinical events in patients with atherosclerosis and hypertension [1]. Therefore, knowledge regarding the mechanisms behind the development of endothelial dysfunction and pharmacological strategies targeting endothelial dysfunction is of great importance. Endothelial dysfunction often refers to a situation of reduced bioavailability and consequently impaired vasodilator effect of endothelium-derived relaxing factors such as nitric oxide (NO), prostacyclin or endothelium-derived hyperpolarizing factor. One additional important alteration in endothelial dysfunction is an increased production and biological activity of the potent vasoconstrictor and pro-inflammatory peptide endothelin (ET)-1. In the present review the pathogenic role of the altered expression and biological actions of ET-1 and its receptors in vascular dysfunction and the development of cardiovascular disease are summarized. In particular the changes of pathophysiological importance mediated by ET-1 in clinical studies and the possible mechanisms behind these changes are reviewed. These changes may be of significance for the development of various cardiovascular diseases beyond pulmonary arterial hypertension which is the currently approved indication for ET receptor antagonists.
1.2. The family of ET peptides

Since the discovery of an endothelium-derived constricting factor in 1985 [2] and the complex description of ET performed by Yanagisawa et al. in 1988 [3], three structurally different ET isoforms [4] have been described (i.e. ET-1, ET-2, ET-3 as well as vasoactive intestinal constrictor) [4]. In addition, 31-residue ETs have been identified [5]. Amongst the three ET isopeptides, the 21-amino acid peptide ET-1 is regarded as the most prominent isoform in the cardiovascular system, accounting for the majority of pathobiological effects exerted by ETs [6].

Mature ET-1 is formed from pre-pro-ET-1 via a 39-amino acid intermediate, big ET-1 [7]. Big ET-1 is processed to ET-1 by a family of ET converting enzymes (ECEs) and other enzymes such as chymases, non-ECE metalloproteinases and endopeptidases [7,8]. Under physiological conditions, ET-1 is produced in small amounts mainly in endothelial cells, primarily acting as an autocrine/paracrine mediator. Under pathophysiological conditions however, the production is stimulated in a large number of different cell types, including endothelial cells, vascular smooth muscle cells, cardiac myocytes [9], and inflammatory cells such as macrophages [10] and leukocytes [11] (Fig. 1).

1.3. The receptors of ET peptides

The biological effects of ET-1 are transduced by two pharmacologically distinguishable receptor subtypes, ETA and ETB receptors, respectively [12]. In the vasculature, the ETA receptor is mainly located on vascular smooth muscle cells and mediates potent vasoconstriction (Fig. 1). ET-1 may also induce indirect vasoconstrictor effects due to the generation of endothelium-derived thromboxane A2 [13]. The ETB receptor is primarily located on endothelial cells, but may also be present on vascular smooth muscle cells. Stimulation of the endothelial ETB receptor results in release of NO and prostacyclin [14] which cause vasodilatation, whereas stimulation of the vascular smooth muscle cell ETB receptor results in vasoconstriction (Fig. 1). Thus, the net effect produced by ET-1 is determined on the receptor localisation and the balance between ETA and ETB receptors. Under physiological conditions, the net effect is vasoconstriction mediated by the ETA receptor, which is partly counteracted by ETB receptor-mediated release of NO. However, under certain pathophysiological conditions the response to ET receptor antagonists may be changed, which will be discussed below.

2. The endogenous ET system and vascular dysfunction

2.1. Changes in vascular reactivity to ET-1

In healthy humans ET-1 increases mean arterial blood pressure, reduces heart rate, cardiac output and stroke volume and causes potent and long lasting vasoconstriction in the pulmonary [15], renal, splanchnic, myocardial [16], and skeletal muscle [17] vasculature. Haynes and Webb demonstrated that the selective ETA receptor antagonist BQ123 evokes increases in forearm blood flow in healthy men [18]. ETB receptor antagonism may either alone or on a background of ETA receptor antagonism cause local vasoconstriction in young healthy subjects [19]. These findings suggest that endogenous ET-1 has a physiological role in the maintenance of vascular tone in healthy humans.

Several studies have demonstrated marked changes in the vascular reactivity to ET-1 in disease (Table 1).
vascular sensitivity to ET receptor stimulation is shown in patients with hypertension and atherosclerosis. Cardillo et al. found that the vasoconstrictor response to intra-arterial infusion of ET-1 in the forearm was enhanced in hypertensive as compared to normotensive individuals [20]. This response was mediated via activation of both ETA and the ETB receptors. In patients with atherosclerosis, the vasoconstrictor response to ET-1 was not different from that observed in age-matched controls [21]. On the other hand, the ETB receptor agonist sarafotoxin S6c produced more pronounced reduction in forearm blood flow in patients with atherosclerosis than in the control group, indicating an upregulation of vasoconstrictor ETB receptors. Results from studies using receptor agonists may be difficult to interpret, however. Therefore, studies in which ET receptor antagonists were administered have been performed. Administration of the selective ETA receptor antagonist BQ123 increased forearm blood flow only in hypertensive patients but not in normotensive controls [20]. Obese hypertensives dilate more following ETA receptor blockade than non-obese hypertensive patients [22]. In addition, BQ123 induced a greater vasodilatation in hypertensives than in subjects with hypercholesterolemia or in smokers [23]. Cardillo et al. showed that BQ123 induced a significant increase in forearm blood flow in patients with hypercholesterolemia compared to normal subjects [24] supporting the notion that risk factors for cardiovascular disease stimulate the ET system in vivo.

The increase in forearm vasodilatation in response to BQ123 was attenuated by inhibition of NO generation [19] indicating that the effect to a major part is dependent on increased NO availability. A combination of ETA and the ETB receptor antagonists (BQ123 and BQ788) also evokes a more pronounced increase in forearm blood flow in patients with hypertension than in controls [20]. In accordance, Taddei et al. found that the dual ETA/ETB receptor antagonist TAK-044 produced a greater degree of vasodilatation in

Table 1
Hemodynamic effects of ET receptor antagonists in various clinical conditions

<table>
<thead>
<tr>
<th>Clinical condition</th>
<th>Study parameter</th>
<th>ETA</th>
<th>ETB</th>
<th>Comments</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypertension</td>
<td>Forearm blood flow increase</td>
<td>33%</td>
<td>63%</td>
<td>No effect in age-matched controls [20]</td>
<td>[20]</td>
</tr>
<tr>
<td>Hypertensives (n=10) and controls (n=10)</td>
<td>Forearm blood flow increase</td>
<td>30%</td>
<td>-</td>
<td>No effect in controls [25]</td>
<td>[25]</td>
</tr>
<tr>
<td>Obese and lean hypertensives (n=27)</td>
<td>Forearm blood flow increase</td>
<td>-</td>
<td>60%</td>
<td>No effect in lean hypertensives or obese controls [22]</td>
<td>[22]</td>
</tr>
<tr>
<td>Hypercholesterolemia (n=12)</td>
<td>Forearm blood flow increase</td>
<td>60%</td>
<td>-</td>
<td>No effect of BQ123 in healthy controls [24]</td>
<td>[24]</td>
</tr>
<tr>
<td>Atherogenic risk factors (n=10–12)</td>
<td>Forearm blood flow increase</td>
<td>HT: 46%</td>
<td>-</td>
<td>Healthy; 20%. No difference between smokers, healthy and hypercholesterolemic</td>
<td>[23]</td>
</tr>
<tr>
<td>Atherosclerosis (n=44)</td>
<td>Epicardial artery diameter change</td>
<td>+5.6±1.0%</td>
<td>-</td>
<td>Vascular resistance fell by 12±3% [39]</td>
<td>[39]</td>
</tr>
<tr>
<td>Coronary artery disease (n=8)</td>
<td>Coronary blood flow increase</td>
<td>16.3%</td>
<td>-</td>
<td>Normal arteries 7.3% [28]</td>
<td>[28]</td>
</tr>
<tr>
<td>Coronary and peripheral artery disease (n=10)</td>
<td>Forearm blood flow increase</td>
<td>39%</td>
<td>102%</td>
<td>Controls; ET A/ET B: 0%, no difference to patients by ETA, and ET B reduced flow</td>
<td>[27]</td>
</tr>
<tr>
<td>Insulin resistance (n=11)</td>
<td>Forearm blood flow increase</td>
<td>18%</td>
<td>0%</td>
<td>Neither treatment affected blood flow in controls [43]</td>
<td>[43]</td>
</tr>
<tr>
<td>Coronary artery disease and diabetes (n=44)</td>
<td>Forearm blood flow increase</td>
<td>33%</td>
<td>10%</td>
<td>Similar vasodilatation following 3 months ACE inhibition [40]</td>
<td>[40]</td>
</tr>
<tr>
<td>Diabetes mellitus type 2 (n=15)</td>
<td>Forearm blood flow increase</td>
<td>33%</td>
<td>33%</td>
<td>No response by ETA blockade in healthy controls [29]</td>
<td>[29]</td>
</tr>
<tr>
<td>Diabetes and microalbumin-urea (n=10)</td>
<td>Nailbed nutritive capillary blood flow</td>
<td>100% + increased temperature</td>
<td>-</td>
<td>No effect in age-matched controls [99]</td>
<td>[99]</td>
</tr>
<tr>
<td>Renal failure (n=8)</td>
<td>Renal blood flow</td>
<td>38%</td>
<td>No change</td>
<td>15% decrease</td>
<td>ET A or dual blockade had minimal effects in controls [96]</td>
</tr>
<tr>
<td>Renal failure (n=7)</td>
<td>Renal blood flow</td>
<td>24%</td>
<td>No change</td>
<td>ET A/ET B: increased insulin sensitivity [30]</td>
<td>[30]</td>
</tr>
</tbody>
</table>
hypertension than in normotensive patients [25]. Collectively these observations indicate that the increased vascular tone induced by ET-1 seems to be more pronounced in hypertension than in association with other risk factors for cardiovascular disease.

The formation and activity of endogenous ET-1 has also been evaluated in patients with atherosclerosis (Table 1). Administration of big ET-1 by intra-brachial artery infusion resulted in more pronounced forearm vasoconstriction in patients with atherosclerosis than in age-matched controls [26]. This effect was accompanied by increased formation of ET-1 as well as presence of ECE immunoreactivity in atherosclerotic plaques in the radial artery, indicating increased ECE activity in patients with atherosclerosis. In another study, dual ET<sub>A</sub>/ET<sub>B</sub> receptor blockade evoked greater increase in forearm blood flow in patients with atherosclerosis than in controls indicating enhanced vasoconstrictor tone mediated by ET-1 [27]. Furthermore, the vasodilator response to dual ET<sub>A</sub>/ET<sub>B</sub> receptor blockade was greater than that induced by selective ET<sub>A</sub> receptor blockade in patients with atherosclerosis, whereas the opposite was observed in control subjects. This suggests that antagonizing both receptors may be of greater value in achieving vasodilatation in patients with atherosclerosis. Kinlay et al. investigated the response to ET<sub>A</sub> receptor blockade in coronary arteries of patients with coronary artery disease and that this switch may be of importance for the progression of atherosclerosis [31]. A recent study found both ET<sub>A</sub> and ET<sub>B</sub> receptor expression were increased in internal mammary arteries from patients with coronary artery disease [32]. Increased expression of ET<sub>B</sub> receptors in relation to ET<sub>A</sub> receptors has also been demonstrated in experimental models and patients with pulmonary arterial hypertension [33,34].

2.2. Mechanisms behind changed vascular activity

One explanation behind the altered response to ET receptor blockade in cardiovascular disease states may be the upregulation of ET-1 expression as described above. Another possible mechanism is related to changes in the expression and activity of the different receptor subtypes. An increased number of ET<sub>B</sub> receptors has been demonstrated in human atherosclerotic arteries [31]. The receptors were present on inflammatory cells (i.e. macrophages, T-lymphocytes) and vascular smooth muscle cells. Moreover, intimal smooth muscle cells close to foam cells showed increased expression of ET-1 and ET<sub>B</sub> receptors. The authors suggested that foamy macrophages and T-lymphocytes may modulate the switch from ET<sub>A</sub> to ET<sub>B</sub> receptors on vascular smooth muscle cells and that this switch may be of importance for the progression of atherosclerosis [31].

2.3. Effects of ET receptor antagonists on endothelial function

There exist important interactions between ET-1 and other endothelium-derived substances such as NO. Apart from the stimulating effect of ET-1 on NO release via the ET<sub>B</sub> receptor as discussed above, NO is known to inhibit the production of ET-1, possibly via inhibiting superoxide [35]. Administration of ET-1 in healthy humans impairs endothelium-dependent dilatation (Fig. 2) [36,37]. Conversely, administration of ET receptor antagonists improves endothelial function in pathological situations of impaired endothelial function like atherosclerosis and hypertension. Barton et al. demonstrated in apolipoprotein E-deficient mice that ET<sub>A</sub> antagonism improves endothelium-dependent, NO-mediated relaxation and reduces atherosclerosis, which occurred concomitantly with a reduction in tissue ET-1 concentrations [38]. This finding in experimental models has led to clinical studies in which it was demonstrated that selective ET<sub>A</sub> receptor blockade improves forearm [36] and coronary [39] endothelium-dependent vasodilatation in patients with atherosclerosis. Interestingly, also dual ET<sub>A</sub>/ET<sub>B</sub> receptor antagonism improves endothelial function in the forearm of patients with atherosclerosis (Fig. 3) [40]. In internal mammary arteries, obtained from patients undergoing coronary artery bypass graft surgery, both selective ET<sub>A</sub> and selective ET<sub>B</sub> receptor blockade, as well as dual ET<sub>A</sub>/ET<sub>B</sub> receptor blockade with bosentan improved
endothelium-dependent vasodilatation [41]. Dual ETA/ETB receptor blockade improves forearm endothelium-dependent vasodilatation also in hypertensive patients, whereas this manoeuvre had no effect in controls [42]. These observations suggest that both selective ETA and dual ETA/ETB receptor blockade improves endothelium-dependent vasodilatation in clinical studies of patients with cardiovascular disease. In a direct comparison, it was recently demonstrated that dual ETA/ETB but not selective ETA receptor blockade enhanced endothelium-dependent vasodilatation in individuals with insulin resistance but without clinical signs of cardiovascular disease, however [43]. These observations imply that blockade of the ETB receptor-mediated release of NO is not detrimental regarding endothelium-dependent vasodilatation. On the contrary, dual ETA/ETB blockade may have additional beneficial effects in comparison to selective ETA receptor blockade due to the upregulation of ETB receptors on vascular smooth muscle cells and inflammatory cells as discussed above.

As ACE inhibitors improve endothelial function in patients with coronary artery disease [44] and decrease the production of ET-1 [45], one of the mechanisms of action may be attenuation of ET-mediated vasoconstriction and endothelial dysfunction. We recently observed that ET-mediated vasoconstriction did not differ between patients with atherosclerosis treated with the ACE inhibitor ramipril or placebo [40]. However, the improvement in endothelium-dependent vasodilatation induced by dual ET receptor blockade was still evident after 3 months on ramipril [40]. This extends findings in isolated saphenous veins in which both selective ETA receptor blockade with BQ123 and dual ETA/ETB receptor blockade with bosentan augmented the acetylcholine-induced vasorelaxation following ACE inhibition [46]. These observations suggest that ET receptor blockade may exert beneficial effects regarding endothelial function also when given on top of treatment with ACE inhibitors in patients with atherosclerosis.

Endothelial dysfunction is an early feature during reperfusion following an episode of ischaemia [47]. Ischaemia–reperfusion injury is at least partially related to impaired availability of endothelium-derived NO [47]. Previous studies on experimental animal models have demonstrated that ET receptor antagonists ameliorate myocardial ischaemia–reperfusion injury by reducing infarct size and improving post-ischaemic endothelium-dependent vasodilatation [48]. Selective ETA receptor blockade (BQ123) restored endothelium-dependent vasodilatation to pre-reperfusion values in atrial microvessels harvested during coronary artery bypass surgery, with a more marked vasodilatation in vessels from patients with diabetes [49]. In a recent study, the effect of the dual ETA/ETB receptor antagonist bosentan was tested in a human model of ischaemia–reperfusion injury in the forearm. It was demonstrated that administration of bosentan inhibited the development of endothelial dysfunction following 20 min of forearm ischaemia (Fig. 4) [50]. Furthermore, ET-1 plasma levels were found to predict angiographic no-reflow after successful primary or rescue PCI in patients with acute myocardial infarction [51]. This indicates that ET-1 is involved in microvascular dysfunction during ischaemia–reperfusion injury, and ET receptor antagonists might be beneficial in the management of no-reflow and to prevent endothelial dysfunction following ischaemia–reperfusion in humans.

3. The molecular mechanisms linking the endogenous ET system and vascular dysfunction

3.1. Interference with NO and increased oxidative stress

Several possible molecular mechanisms may underlie the effect of ET-1 and ET receptor antagonists on endothelial
function and NO bioavailability (Fig. 5). The vasodilatation induced by ET\textsubscript{A} receptor antagonism in healthy humans was reduced by 95% following inhibition of NO generation\cite{19}, whereas inhibition of prostanoid generation did not affect the response. This finding suggests that improvement of NO bioavailability plays an important role in the vasodilatation induced by ET receptor blockade. Both dual ET\textsubscript{A}/ET\textsubscript{B} and selective ET\textsubscript{A} receptor blockade increase endothelial NO synthase activity in hypercholesterolemic pigs\cite{52}. Total and calcium-dependent NO synthase activity was significantly higher in aortic endothelial cells after dual ET\textsubscript{A}/ET\textsubscript{B} antagonism than in those after selective ET\textsubscript{A} blockade\cite{52}. ET-1 impairs NO production and downregulates the expression of endothelial NO synthase in endothelial cells\cite{53}. In addition, bosentan increased the expression of endothelial NO synthase in hearts subjected to ischaemia and reperfusion\cite{54}. Thus, ET-1 may reduce NO bioavailability via interference with the expression and activity of endothelial NO synthase.

Another mechanism linking ET-1 to NO may be via formation of reactive oxygen species, which will result in decreased bioactivity of NO by virtue of formation of peroxynitrite (Fig. 1). The reactive oxygen species can, apart from interfering with NO, also inhibit other endothelium-dependent vasodilator pathways mediated through prostacyclin and endothelium-derived hyperpolarizing factor\cite{55,56}. ET-1 increases superoxide production in the rat aorta in vitro, an effect that could be inhibited by the selective ET\textsubscript{A} receptor antagonist BQ123\cite{57}. ET-1 also stimulates NADPH oxidase-derived superoxide formation in hypertensive rats, an effect that could be inhibited by ET\textsubscript{A} receptor blockade\cite{58}. ET-1 increased the expression of gp91\textsubscript{phox}, the rate-limiting subunit of NADPH oxidase\cite{59}, and augmented superoxide production in endothelial cells via the ET\textsubscript{B} receptor in human endothelial cells\cite{60}. The stimulating effect of ET-1 on superoxide production may also be coupled to the NADPH oxidase subunit p22\textsubscript{phox}\cite{61,62}. The stimulation of superoxide is linked to functional effects since ET-1 was demonstrated to impair endothelium-

![Fig. 4. Change in forearm blood flow (FBF) induced by acetylcholine before ischemia and at 15 and 30 min of reperfusion following 20 min ischaemia. Each subject was investigated after administration of (A) placebo and (B) the dual ET receptor antagonist bosentan. Significant differences from the pre-ischemic response are indicated. Means±SEM; n=13. Modified and reproduced with permission from\cite{50}. © The Biochemical Society.](https://academic.oup.com/cardiovascres/article-abstract/76/1/8/349882)

![Fig. 5. Molecular mechanisms of vascular dysfunction induced by ET-1 including pro-inflammatory and pro-atherosclerotic effects. Potential benefit in cardiovascular disease states may be mediated by altering these mechanisms through dual ET\textsubscript{A}/ET\textsubscript{B} receptor blockade and/or selective ET\textsubscript{A} receptor blockade. [\textendash]=Reference; \textarrowright=stimulation; \textarrowleft=inhibition.](https://academic.oup.com/cardiovascres/article-abstract/76/1/8/349882)
dependent relaxations of aorta from control and diabetic rats via a mechanism involving superoxide production, PI3-kinase activity and p22phox expression. Furthermore, chronic treatment with the dual ET₁/ET₂ receptor antagonist J-104132 improved acetylcholine-mediated endothelium-dependent vasodilatation, reduced superoxide formation and prevented p22phox formation in diabetic rats [61]. These data are in agreement with in vivo observations in transgenic mice overexpressing ET-1 [63]. These mice exhibit endothelial dysfunction, increased NADPH oxidase activity, and increased expression of gp91phox. The endothelial dysfunction could be restored by vitamin C, supporting the role of increased oxidative stress [63]. Furthermore, vitamin C has been shown to inhibit the formation of reactive oxygen species induced by ET-1 in isolated smooth muscle cells [64]. In addition, the effects of ET-1 on coronary vasoconstriction may be more pronounced in states of reduced bioavailability of the eNOS-co-factor tetrahydrobiopterin (BH₄) [65]. Recent data demonstrate that ET-1 mediates superoxide production and vasoconstriction through activation of NADPH oxidase and uncoupled NOS in the rat aorta [66]. The uncoupling of NOS means that NOS generates superoxide instead of NO in states of BH₄ deficiency. Interestingly, these effects could be inhibited by BH₄ and by dual ET receptor blockade, but not by selective ET₁ receptor blockade [66]. ET-1 may also promote BH₄ deficiency in a rat model of hypertension via an ET₁-mediated NADPH oxidase pathway which contributes to impaired endothelium-dependent relaxation [67]. These data suggest that increased oxidative stress induced by ET-1 in the vessel wall is an important factor leading to endothelial dysfunction and enhanced susceptibility to atherosclerosis.

ET-1 has also been demonstrated to be associated with increased oxidative stress and endothelial dysfunction in humans. ET-1 stimulates superoxide formation and impairs endothelium-dependent vasodilatation in human venous bypass conduits from patients with diabetes [68]. Importantly, recent data suggest that the impairment in endothelium-dependent vasodilatation in vivo induced by ET-1 in healthy humans can be prevented by administration of the anti-oxidant vitamin C (Fig. 2) [37]. Taken together, these findings suggest that ET-1 may increase oxidative stress through induction of reactive oxygen species. Furthermore, ET receptor antagonists may be a therapeutic option that results in increased NO bioavailability and decreased levels of reactive oxygen species, thereby improving endothelial function in various cardiovascular disease states.

3.2. Pro-inflammatory and pro-atherosclerotic effects

Apart from its direct vasomotor activity, ET-1 has been implicated in inflammatory processes within the vascular wall (Fig. 5). Specifically, ET-1 in subnanomolar concentrations has been demonstrated to activate macrophages, resulting in the release of pro-inflammatory and chemotactic mediators, including tumor necrosis factor (TNF)-α, interleukin (IL)-1, IL-6 and IL-8 [69–71] which are of importance in the atherosclerotic process [72]. Cardiac overexpression of ET-1 in mice is associated with an inflammatory response involving increased activation of the pro-inflammatory transcription factor NF-κB and expression of several pro-inflammatory cytokines including TNF-α, IL-1 and IL-6 [73]. Interestingly, significant prolongation of survival was observed only with a dual ET₁/ET₂ antagonist, but not with a selective ET₁ antagonist [73]. In turn, transcription factors and pro-inflammatory cytokines such as NF-κB, TNF-α, and IL-6 stimulate ET-1 production [74]. ET-1 enhances the expression of adhesion molecules on TNF-α stimulated vascular endothelial cells [75] and stimulates aggregation of polymorphonuclear neutrophils [76]. Conversely, ET receptor blockade attenuates the accumulation of neutrophils and myeloperoxidase activity in the ischemic myocardium [77].

IL-6 has been implicated in the development of atherosclerosis [72] and endothelial dysfunction in humans [78]. As noted above, ET-1 stimulates IL-6 release in vitro [71] and in vivo [37]. The release of IL-6 induced by ET-1 from human vascular smooth muscle involves activation of NF-κB [71]. Possibly, release of IL-6 may further increase oxidative stress as suggested by the in vitro observation that IL-6 induces production of reactive oxygen species [79].

C-reactive protein (CRP) has emerged as a predictor and possible mediator of atherosclerotic cardiovascular disease. Verma et al. demonstrated that CRP stimulated the expression of adhesion molecules and monocyte chemoattractant protein-1 in endothelial cells [80]. Interestingly, this effect was inhibited by bosentan as well as an antibody against IL-6 suggesting involvement of ET-1 and IL-6 in the pro-inflammatory effect of CRP.

Hypercholesterolemia is associated with impaired endothelium-dependent vasodilation and elevated plasma and tissue ET-1 concentrations, which may account for the vasomotor dysfunction under this condition [81]. In support of this notion, inhibition of either ET₁ or both ET₁ and ET₂ receptors restores endothelium-dependent vasodilation and NO production in hypercholesterolemic pigs [82]. The normalized NO production results from increased activity of NO synthase. The effect of dual ET₁/ET₂ blockade was significantly higher than that of selective ET₁ antagonism [52]. Statin therapy may further improve the beneficial effects of ET antagonism on NO-mediated vasodilation in hypercholesterolemia [83,84].

There also seems to exist important interactions between oxidized low-density lipoprotein (LDL) and ET-1 which may be of importance in atherogenesis. ET-1 augments the uptake of oxidized LDL [85], whereas oxidized and native LDL in turn stimulate the production of ET-1 [86]. Interestingly, statins have been demonstrated to decrease the expression of pre-pro ET-1 mRNA in endothelial cells [87] and the vasoconstrictor response to ET-1 in vivo [88]. In addition, ET-1 stimulates uptake of oxidized LDL in endothelial cells via an ET₂ receptor-mediated effect [89]. ET-1 is known to be elevated in both type 2 diabetes and by high LDL cholesterol.
Selective ETA vs. dual ETA/ETB receptor blockade

ET receptor blockade exerts anti-atherogenic effects. Taken together, these data clearly suggest that ET receptor blockade in comparison with selective ETA receptor antagonism in various cardiovascular disorders (Table 1). Additional biological effects beyond direct vascular effects of potential importance during pathophysiological conditions such as superoxide production, stimulation of pro-inflammatory cytokines and LDL uptake as well as insulin resistance seem to be mediated by the ETB receptor in addition to the ETA receptor (Fig. 5). Even though most studies have not compared the two different ET receptor blocking strategies, available literature suggests that it may be preferable to block both receptors to fully antagonize the pathophysiological actions of ET-1 in cardiovascular disease. On the other hand, blockade of ETB receptors will reduce clearance of ET-1 [94] and thereby increase circulating levels of ET-1. Furthermore, the ETB receptor may exert beneficial effects by releasing NO from endothelial cells. An additional beneficial effect mediated by the ETB receptor is the stimulation of renal sodium and water excretion [95]. Accordingly, it has been demonstrated that only selective ETA receptor blockade increases renal blood flow and improves renal function in patients with renal failure [96]. On the other hand, dual ETA/ETB receptor blockade, but not selective dual ETA receptor blockade, increased renal blood flow in patients with coronary artery disease and type 2 diabetes but with normal renal function [30]. These apparently conflicting results illustrate the need for carefully designed larger randomised clinical studies to clarify the potentially beneficial clinical effects of dual ETα/ETβ receptor blockade over selective ETα receptor blockade in different patient groups. Moreover, since the expression of ET receptors differs between healthy subjects and patients with cardiovascular disease as well as between various types and states of cardiovascular disease, it is of importance to characterize the response to receptor blockade in each population.

5. Conclusion and future perspectives

At present ET receptor antagonists are approved for the treatment of pulmonary arterial hypertension. A large body of evidence has accumulated, indicating that the ET system is causally involved in vascular dysfunction during a large number of additional cardiovascular diseases. ET-1, the ET receptors and the biological effects mediated by ET-1 are markedly altered and become substantially more pronounced during development of cardiovascular disease. ET receptor antagonists have been shown to be effective in several animal models, and initial clinical studies indicate that they also improve vascular function in patients with cardiovascular disease. The ETB receptor becomes of functional greater importance in several disorders like hypertension [20], atherosclerosis [27] and insulin resistance [30,43]. This suggests that dual ETA/ETB receptor blockade may be superior to selective ETA receptor blockade in certain conditions by inducing vasodilatation, improving endothelial function and insulin sensitivity in humans, however further studies with head to head comparisons in various cardiovascular disorders are warranted. Larger clinical studies have so far mainly been performed in pulmonary hypertension with favourable clinical results. Liver toxicity, as a main side effect of ET receptor antagonists has to some extent limited their use but was not considered a major problem in clinical trials [97]. However, transaminase levels should be monitored in future clinical studies, since this may be a limitation if ET receptor antagonists are to be considered in larger cohorts of patients with cardiovascular disease. Considering the potentially important role of ET-1 in the development of vascular dysfunction reviewed in the present article, conditions with increased inflammatory activity, oxidative stress and vascular tone such as atherosclerosis, hypertension and vascular complications in diabetes may be of interest to explore in larger clinical trials using ET receptor antagonists.
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