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Modulation of $11\beta$-Hydroxysteroid Dehydrogenase as a Strategy to Reduce Vascular Inflammation

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Abstract Atherosclerosis is a chronic inflammatory disease in which initial vascular damage leads to extensive macrophage and lymphocyte infiltration. Although acutely glucocorticoids suppress inflammation, chronic glucocorticoid excess worsens atherosclerosis, possibly by exacerbating systemic cardiovascular risk factors. However, glucocorticoid action within the lesion may reduce neointimal proliferation and inflammation. Glucocorticoid levels within cells do not necessarily reflect circulating levels due to pre-receptor metabolism by $11\beta$-hydroxysteroid dehydrogenases ($11\beta$-HSDs). $11\beta$-HSD2 converts active glucocorticoids into inert 11-keto forms. $11\beta$-HSD1 catalyses the reverse reaction, regenerating active glucocorticoids. $11\beta$-HSD2-deficiency/ inhibition causes hypertension, whereas deficiency/ inhibition of $11\beta$-HSD1 generates a cardioprotective lipid profile and improves glycemic control. Importantly, $11\beta$-HSD1-deficiency/ inhibition is athoprotective, whereas $11\beta$-HSD2-deficiency accelerates atherosclerosis. These effects are largely independent of systemic risk factors, reflecting modulation of glucocorticoid action and inflammation within the vasculature. Here, we consider whether evidence linking the $11\beta$-HSDs to vascular inflammation suggests these isozymes are potential therapeutic targets in vascular injury and atherosclerosis.

Keywords Atherosclerosis · Neointima · Inflammation · Glucocorticoid · $11\beta$-Hydroxysteroid dehydrogenase

Abbreviations

| Abbreviation | Description               |
|--------------|---------------------------|
| $11\beta$-HSD | 11β-Hydroxysteroid dehydrogenase |
| GR           | glucocorticoid receptor |
| MR           | mineralocorticoid receptor |

Introduction

Atherosclerosis is widely acknowledged to be an inflammatory disease, with lesions resulting from an unchecked wound healing response to chronic arterial injury. Extensive inflammatory cell (macrophage and lymphocyte) invasion of the sub-endothelial space is key to lesion development [1–5]. Consequently, glucocorticoids, which are potent anti-inflammatory agents, might be expected to inhibit atherogenesis. In fact, glucocorticoid excess, whether endogenous (Cushing’s disease) or through pharmacotherapy, is associated with increased atherosclerosis and cardiovascular events [6–9], probably due, at least in part, to glucocorticoid-mediated exacerbation of systemic cardiovascular risk factors (including insulin resistance/type 2 diabetes, hypertension and dyslipidaemia). However, most atherosclerosis occurs independently of exogenous glucocorticoid administration, and plasma levels of glucocorticoids are not normally elevated in atherosclerosis. Nevertheless, recent evidence implicates cell-specific modulation of glucocorticoid action within the vasculature in this condition.

Glucocorticoid delivery and action within tissues can be modulated at a number of levels beyond the hypothalamic-pituitary-adrenal axis. Normally, the majority of plasma glucocorticoid (cortisol or corticosterone) is bound to the high affinity, but finite capacity, corticosterone binding globulin (CBG), leaving ~5% being "free" and accessible to tissues. The mineralocorticoid aldosterone, and the
intrinsically inactive 11-keto glucocorticoids cortisone and 11-dehydrocorticosterone, bind poorly to CBG, so that free concentrations are similar to free cortisol/corticosterone levels. However, CBG may not simply be an inert carrier; it can be cleaved by neutrophil elastase, releasing cortisol/corticosterone at sites of inflammation, thus potentially acting as a targeted glucocorticoid delivery mechanism [10]. Once inside cells, glucocorticoids can be actively removed by membrane pumps such as MDR1 [11], metabolised by 11β-hydroxysteroid dehydrogenase (11β-HSD; see below), or can bind to and activate cognate receptors, glucocorticoid receptor (GR) and, in cells which lack 11β-HSD2 (see below), the higher affinity mineralocorticoid receptor (MR). Activated receptors translocate to the nucleus to transcriptionally regulate specific gene networks.

Although all these mechanisms represent potential druggable targets in atherosclerosis, recent evidence points to the type 1 11β-HSD enzyme, which in vivo predominantly converts intrinsically inert glucocorticoids (cortisone, 11-dehydrocorticosterone) into corresponding active forms (cortisol, corticosterone), as a particularly attractive target [12]. Inhibition of 11β-HSD1 is atheroprotective, at least in animal models. Conversely, inactivation of renal 11β-HSD type 2 (11β-HSD2), which catalyses the opposite reaction, inactivating glucocorticoids in vivo, is well established as a cause of hypertension in humans. Recent data have shown that 11β-HSD2-deficiency worsens atherosclerosis independently of effects on hypertension [13]. Here, we assess the potential of 11β-HSD1 as a therapeutic target in atherosclerosis by reviewing the actions of 11β-HSDs on vascular inflammation, considering local effects on the vasculature as well as effects on systemic cardiovascular risk factors.

### Glucocorticoids and Cardiovascular Risk

To understand the potential benefits of 11β-HSD modulation in vascular inflammation, it is essential first to consider the actions of glucocorticoids. The complex relationship between glucocorticoids and cardiovascular disease is incompletely understood and may differ between humans and animal models (recently reviewed in [14–16]). Some of this complexity undoubtedly arises from the diverse actions of glucocorticoids: direct effects of glucocorticoids with the heart and vasculature may be largely beneficial, at least within certain cell types, whereas adverse effects may be mediated indirectly by changes in systemic risk factors (such as hypertension, lipids and insulin resistance/ diabetes).

The effect of glucocorticoids on dyslipidaemia and other systemic risk factors has been established for over 60 years [17–19]. Consistent with exacerbation of systemic risk factors, endogenous glucocorticoid excess or glucocorticoid pharmacotherapy in humans are associated with increased extent and severity of atherosclerosis, and predict cardiovascular morbidity and mortality [5, 20–28]. Discontinuation of glucocorticoid pharmacotherapy reduces cardiovascular risk [6, 29]. Similarly, normalisation of circulating glucocorticoids in Cushing’s disease largely reverses pathophysiological changes in vascular function and structure [9]. However, hyperglycaemia and dyslipidaemia are only modestly improved within the same time frame, suggesting distinct beneficial effects of reducing glucocorticoid action separate from effects on the classical systemic risk factors [9].

In contrast, animal studies suggest that glucocorticoids reduce atherosclerosis, despite causing hyperlipidaemia [30–40]. Furthermore, a recent report elegantly demonstrated that ‘painting’ dexamethasone onto atherosclerotic lesions improved markers of plaque stability (reducing macrophage content and increasing fibrous cap thickness) [41]. This discrepancy between the atherosclerosis-promoting effects of glucocorticoids in humans but not in animals remains unexplained, but may be related to the predominant use of dexamethasone as the glucocorticoid of choice in animals. Whereas endogenous glucocorticoids are agonists at both GR and MR, synthetic glucocorticoids, including dexamethasone, poorly activate MR. Chronically increased mineralocorticoid action, even at relatively modest levels, appears pro-inflammatory within the cardiovascular system, distinct from effects of MR activation upon blood pressure [42].

### Glucocorticoids and the Acute Vascular Response to Injury

The introduction of percutaneous angioplasty for treatment of occluded arteries highlighted the fibroproliferative vascular response to acute mechanical injury. Indeed, re-occlusion (restenosis) of atherosclerotic arteries following angioplasty is a clinically significant complication of the technique. Acute arterial injury (eg by insertion of a wire or stent, by ligation, or with a laser) in animals provides a tool to elucidate the mechanisms underlying restenosis in atherosclerosis as well as exploring novel treatments. Mechanical arterial injury provokes an influx of inflammatory cells, recruited by factors such as monocyte-chemoattractant protein (MCP)-1 released from the injured vascular/endothelial cells [43], which stimulates proliferation and migration of vascular smooth muscle cells, forming the neo-intima [44]. Inhibition of this inflammatory response has been central to the use of glucocorticoids as potential inhibitors of neointimal lesion formation/restenosis [45–50].

Despite the largely positive data obtained in animals, clinical use of glucocorticoids (methylprednisolone, dexamethasone) for prevention of restenosis was initially disappointing [51–55]. However, recent trials are promising
neither nephron, and limited other sites such as the skin, lung and adrenal cortex [65]. Both isozymes are modestly expressed in the vasculature; 11β-HSD1 is probably restricted to vascular smooth muscle cells, with 11β-HSD2 expressed in the endothelium (reviewed in [15, 16]). Some studies have reported 11β-HSD2 expression in the vascular smooth muscle cells [66] and 11β-HSD1 in the endothelium [67+], though these studies depend on antibody specificity and others have not confirmed these findings [68]. Whilst co-expression cannot be excluded, normally 11β-HSD isozyme expression is mutually exclusive within individual cells.

The 11β-HSDs Modulate Cardiovascular Disease Risk Factors

Both 11β-HSD isozymes modulate systemic cardiovascular risk factors, with a well-established role for 11β-HSD2 in regulating mineralocorticoid effects, including blood pressure, and with 11β-HSD1 implicated in the pathogenesis of metabolic syndrome.

By inactivating glucocorticoids, 11β-HSD2 activity confers mineralocorticoid-specificity upon MR in cells in which they are co-expressed. Deficiency in, or inhibition of, 11β-HSD2 allows inappropriate activation of MR by glucocorticoids, causing the syndrome of Apparent Mineralocorticoid Excess, characterised by hypertension, hypokalaemia and suppression of the renin-angiotensin-aldosterone system [69].

A physiological role for 11β-HSD1 has been slower to emerge. However, over the last decade it has become apparent that amplification of intracellular glucocorticoid levels by 11β-HSD1, especially in adipose tissue and/or brain, contributes to obesity-associated metabolic disease and age-related cognitive decline (reviewed in [70]). 11β-HSD1 expression in adipose tissue is selectively elevated in obese humans and in rodents with monogenic obesity. Inhibition of 11β-HSD1 reduces levels of plasma glucose, glycated haemoglobin A1c (HbA1c) and cholesterol in patients with type 2 diabetes [71] and 11β-HSD1-deficiency or inhibition improves insulin sensitivity in animal models of diabetes and/or obesity [63]. Conversely, in mice, transgenic over-expression of 11β-HSD1 selectively in adipose tissue produces local, but not systemic, glucocorticoid excess and causes visceral obesity, hypertension, diabetes and dyslipidaemia [72, 73], whereas over-expression in liver causes hypertension and mild insulin resistance [74].

In a similar manner, age-related cognitive decline (itself associated with impaired glycaemic control [75]) is associated with higher 11β-HSD1 activity in humans [76] and in rodents [77], and 11β-HSD1-deficient mice are protected from age-related cognitive decline (reviewed in [78]). A causative role is supported by the phenotype of transgenic mice with selective over-expression of 11β-HSD1 in forebrain, which develops cognitive deficits at an earlier age.
than wild-type controls [77]. In humans, age-related cognitive decline, diabetes and metabolic syndrome, like atherosclerosis, are all associated with increased markers of inflammation, including in macrophages (or microglia in the brain). It is conceivable that altered inflammatory responses underlie at least part of the effects of 11β-HSD1 manipulation.

**11β-HSDs and Inflammation**

11β-HSD1 and 11β-HSD2 show opposite regulation at sites of inflammation, likely because of opposite regulation by the pro-inflammatory cytokines IL-1 and TNF-α, with up-regulation of 11β-HSD1 and down-regulation of 11β-HSD2 (reviewed in [12]), suggesting they modulate local glucocorticoid action during inflammation (Fig. 1a). 11β-HSD1 is expressed in immune cells, including macrophages and lymphocytes. Its expression, by-and-large, is increased following immune cell activation. In contrast, 11β-HSD2 is not normally expressed in immune cells, though it may become expressed in human macrophages and possibly other mononuclear cells in certain pathological situations [79], suggesting resistance to endogenous glucocorticoids under these circumstances.

Unsurprisingly, given the well-known effects of glucocorticoids in limiting acute inflammation, 11β-HSD1-deficiency in mice increases the severity of acute inflammation. Inflammation is increased in an experimental model of arthritis, and more neutrophils and monocytes/macrophages are elicited in sterile peritonitis and pleurisy, consistent with a pro-inflammatory response under these circumstances. In contrast, 11β-HSD2 is not normally expressed in immune cells, though it may become expressed in human macrophages and possibly other mononuclear cells in certain pathological situations [79], suggesting resistance to endogenous glucocorticoids under these circumstances.

**11β-HSDs as a Therapeutic Target in Atherosclerosis**

Levels of 11β-HSD1 mRNA are increased in human atherosclerotic vessels compared either with nearby intact (atheroma-free) vasculature or with vessels from control patients without coronary artery disease [87, 88]. This may reflect a pro-inflammatory peri-vascular environment in disease rather than systemic inflammation; mRNA levels of both 11β-HSD1 and CD68 (a macrophage marker) are increased in epicardial adipose tissue of patients with coronary artery disease compared with controls [87], consistent with inflammation within the peri-vascular adipose tissue associated with vascular inflammation. Pro-inflammatory cytokines increase 11β-HSD1 expression (Fig. 1a) in human and murine vascular smooth muscle cells in vitro [89, 90], but acute systemic inflammation has little or no effect on vascular 11β-HSD1 expression in mice [90]. This situation, with locally increased 11β-HSD1, is similar to that associated with inflammation in adipose tissue of metabolic syndrome patients. It suggests that dysregulated vascular 11β-HSD1, possibly initially induced to control local inflammation within the vasculature, might then drive local inflammation both within the vasculature and in the surrounding adipose tissue by restricting angiogenesis, thus promoting a hypoxic environment. This, of course, points to 11β-HSD1 inhibition as an attractive target in atherosclerosis. Dysregulation of 11β-HSD2 in human arterial disease has not been described (Fig. 1a), but the opposite regulation of 11β-HSD2 by pro-inflammatory cytokines is predicted to decrease levels within endothelial cells, allowing cortisol activation of MR and its pro-inflammatory consequences, given a setting of high levels of systemic risk factors (see below).

The potential for 11β-HSD1 inhibition as an effective pharmacotherapy for atherosclerosis was demonstrated by Hermanowski-Vosatka and colleagues from Merck [91]. Compound 544, a selective 11β-HSD1 inhibitor, modestly reduced circulating cholesterol levels and markedly reduced intra-aortic cholesterol in atherosclerosis-prone ApoE−/− mice fed a cholesterol-enriched 'western diet' [91]. More
recently, this group has shown a similar reduction in intra-aortic cholesterol with a distinct inhibitor (Compound L-750), without effects on plasma lipids in Apoe$^{-/-}$ mice [67]. However, another study in triple knock-out mice (lacking the LDL receptor, apolipoprotein-b and leptin) with a different selective inhibitor (Compound 2922), reported no effect on atherosclerosis and only slightly reduced plasma LDL levels, despite improved glucose homeostasis [92]. A previous study in Ldlr$^{-/-}$ mice with the non-selective inhibitor, carbenoxolone, only showed an effect on plasma lipids and atherosclerosis in severely obese mice (due to an additional mutation in the Agouti gene), though the drug treatment is likely to have made the mice hypertensive through inhibition of 11β-HSD2 (blood pressure was not reported) [93]. More recently, we have shown that generating either homozygous or heterozygous Hsd11b1 deletion and, thus, 11β-HSD1-deficiency (avoiding possible off-target drug effects) attenuates atherosclerosis in Apoe$^{-/-}$ mice without affecting plasma glucose or lipid levels. This suggests that atheroprotection in this background is not simply due to improvements in systemic risk factors, although it should be noted that the contribution of hemostatic factors has not been addressed. Reconstitution of lethally irradiated Apoe$^{-/-}$ mice with bone marrow from Hsd11b1$^{-/-}$ Apoe$^{-/-}$ mice similarly reduced atherosclerosis compared to controls reconstituted with Apoe$^{-/-}$ donor bone marrow, implicating 11β-HSD1-deficiency in haematopoietic cells in the mechanism, and suggesting that any differences in plasma glucocorticoid turnover in 11β-HSD1-deficient mice [74, 94] are unlikely to be critical. The converse situation occurs with 11β-HSD2-deficiency, which accelerates atherosclerosis and worsens vascular inflammation in Apoe$^{-/-}$ mice.
independent of effects on blood pressure, even without the stimulus of western diet [13•]. Importantly, this suggests that it is intravascular glucocorticoid action that is the main culprit in 11β-HSD2-deficient Apoε<sup>−/*</sup> mice, rather than deficiency in the surrounding adipose tissue or circulating immune cells; 11β-HSD2 is not normally expressed either in immune cells or in adipose tissue, though inflammation within peri-vascular adipose tissue could, of course, contribute to pathology once initiated. A summary of experimental studies describing the effects of 11β-HSD inhibition or deficiency on atherosclerosis/vascular inflammation is shown in Table 1. Interestingly, neither 11β-HSD1- nor 11β-HSD2-deficiency affected neointimal proliferation following femoral artery wire injury in lean healthy mice, though it was reduced by 11β-HSD1-deficiency in Apoε<sup>−/*</sup> mice (Hsd11b2<sup>−/*</sup>Apoε<sup>−/*</sup> double knock-out mice were not tested) [95]. Thus, 11β-HSD1-inhibition is only likely to be effective in reducing neointimal proliferation when concurrent with exaggerated systemic risk factors.

### Mechanism of Action of 11β-HSD Manipulation

The mouse studies suggest at most a modest contribution of systemic risk factors to the effects of 11β-HSD deficiency or inhibition upon atherosclerosis, pointing instead to effects within both immune cells (11β-HSD1) and the vasculature (11β-HSD2). As stated above, immune cells are implicated as a target. Although macrophage density appears unaltered with 11β-HSD1-deficiency, T cell infiltration is reduced [96•] and 11β-HSD1 inhibition, either prophylactically or therapeutically in established atherosclerosis, reduces expression of pro-inflammatory and cell adhesion molecules in the vasculature of Apoε<sup>−/*</sup> mice [70, 96•]. Interestingly, the microarray studies on vasculature also highlight suppression of mRNAs encoding coagulation factors by 11β-HSD1-deficiency, something that warrants further investigation. Experimental studies have implicated the coagulation system in the pathogenesis of atherosclerosis and atherothrombosis (reviewed in [97]) and megakaryocytes, the precursors to platelets, would be transferred in the bone

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**Table 1** Experimental studies describing the effects of 11β-HSD inhibition or deficiency on vascular inflammation

| 11β-HSD1 inhibition/deficiency | Species | Outcome | Ref |
|-------------------------------|---------|---------|-----|
| 11β-HSD1 inhibitor (Compound 544) | Apoε<sup>−/*</sup> mice | ↓ atherosclerosis, ↓ circulating cholesterol, ↓ circulating MCP-1 | [91] |
| 11β-HSD1 inhibitor (Compound L-750) | Apoε<sup>−/*</sup> mice | ↓ atherosclerosis, ≠ circulating lipids | [67•] |
| 11β-HSD inhibitor (Compound 2922) | LDLr<sup>−/*</sup>/ Apob<sup>100/100</sup>Lep<sup>ob/ob</sup> mice | ≠ atherosclerosis, ↓ circulating LDL | [92] |
| 11β-HSD inhibitor Carbenoxolone (inhibits both isozymes) | LDLr<sup>−/*</sup>/ Agouti<sup>−/*</sup> mice | ↓ atherosclerosis in severely obese mice (additional agouti mutation), ↓ circulating lipids | [93] |
| 11β-HSD1 inhibitor (Compound 544) | Apoε<sup>−/*</sup> mice | ≠ fasting plasma cholesterol, triglycerides or NEFA, ↑ plaque stability | [96•] |
| 11β-HSD1 deficiency | Hsd11b1<sup>−/*</sup>/Apoε<sup>−/*</sup> mice | ≠ atherosclerosis, ↓ circulating lipids, ↓ circulating MCP-1, ↓ circulating Ly6C<sup>hi</sup> monocytes, ≠ macrophage density into lesions, ↓ T cell infiltration into lesions, ↓ aortic VCAM-1 mRNA expression, ↓ atherosclerosis in irradiated Apoε<sup>−/*</sup> mice receiving bone marrow cells from Hsd11b1<sup>−/*</sup>Apoε<sup>−/*</sup> donor mice | [96•] |
| 11β-HSD2 deficiency | Hsd11b2<sup>−/*</sup>/Apoε<sup>−/*</sup> mice | ↑ atherosclerosis, ≠ blood pressure | [13•] |

≠ no significant effect, ↓ reduced, ↑ increased, NEFA: non-esterified fatty acids
marrow reconstitution experiments that implicate immune cells [96•].
Western diet-induced monocytosis is attenuated with 11β-HSD1-deficiency in Apoe−/− mice, attributable to the pro-inflammatory Ly6C<sup>hi</sup> monocyte subset. Instead, monocytes are retained in the bone marrow and spleen of Hsd11b1<sup>−/−</sup>Apoe<sup>−/−</sup> mice [96•]. Lower circulating levels of MCP-1, the main macrophage chemoattractant in atherosclerosis [98], in Hsd11b1<sup>−/−</sup>Apoe<sup>−/−</sup> mice are implicated in this difference [67•, 91, 96•], though whether the MCP-1 originates from the vasculature or adipose tissue is currently unclear [67•, 96•]. Either way, circulating MCP-1 is unlikely to be the sole or even the main target of 11β-HSD1-deficiency/inhibition.

Plausibly, the opposite effects of deficiency in 11β-HSD1 or 11β-HSD2 activity upon atherosclerosis reflect different but complementary mechanisms. 11β-HSD2 is not expressed in mouse immune cells, but it is expressed in vascular endothelial cells, where it restricts activation of MR by glucocorticoids. In mouse aortic endothelial cells in vitro, vascular cell adhesion molecule-1 was induced by corticosterone in an MR-dependent manner, but only following inhibition of 11β-HSD2. In vivo, antagonism of MR with eplerenone, at doses which had no effect on blood pressure, attenuated lesion development and inflammation, whilst also increasing collagen and smooth muscle content, markers of plaque stability [13•]. Together, these data clearly suggest that preservation of vascular endothelial cell 11β-HSD2 activity is important in controlling vascular injury and subsequent inflammation.

The target of 11β-HSD1-generated ligand is less obvious. Although GR has long been known to shape macrophage phenotype, recent evidence has also shown a crucial role for MR in governing macrophage polarisation, with MR-deficient macrophages skewing towards a "pro-resolution" alternatively activated (or M2) phenotype [99]. In vivo, MR deficiency in macrophages alone is sufficient to protect against the vascular damage and cardiac hypertrophy and fibrosis induced by L-NAME and angiotensin II [99], consistent with pro-inflammatory MR activation by glucocorticoids (11β-HSD2 is absent from macrophages). However, the high affinity MR is predicted to be activated even at basal plasma glucocorticoid levels, and these are normal in 11β-HSD1-deficient mice [94]. 11β-HSD1 may therefore amplify ligand availability to GR. But GR activation in macrophages would be expected to promote a pro-resolution phenotype. Exactly how intracellular glucocorticoid activation of MR versus GR is achieved in cells that express both without 11β-HSD2 is currently unclear [99], but could conceivably involve GR:MR heterodimers [100] and might be critical in pro- and anti-inflammatory actions of endogenous glucocorticoids. An alternative target is GR in megakaryocytes, but whether 11β-HSD1 is even expressed in these cells is unknown. Future dissection of the cellular and molecular targets will require selective receptor antagonism, as well as tissue-specific disruption of the 11β-HSD1 gene in mice, to elucidate specific roles in key processes during inflammation and angiogenesis.

Conclusions

There is clearly a counterbalance between the pro-atherogenic effects of 11β-HSD1 activity and the atheroprotective effects of 11β-HSD2 activity during vascular inflammation (Fig. 1b). Any therapy based on manipulation of glucocorticoid metabolism should inhibit 11β-HSD1 activity whilst preserving 11β-HSD2 activity. Future work should concentrate on elucidating whether the cellular and molecular targets are indeed complementary or may be overlapping. New drug delivery methods [41], targeting macrophages or indeed other cell types, open up exciting new therapeutic possibilities in vascular inflammation and atherosclerosis.

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Conflicts of Interest Patrick WF Hadoke declares no conflicts of interest. Tiina Kipari declares no conflicts of interest. Jonathan R. Seekl has been a consultant for several commercial drug development programmes for 11beta-HSD1 inhibitors. Karen E. Chapman declares no conflicts of interest.

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