Abdominal Aortic Aneurysm
Pathogenesis and Implications for Management

Jonathan Golledge, Juanita Muller, Alan Daugherty, Paul Norman

Abstract—Abdominal aortic aneurysm (AAA) affects approximately 5% of elderly men and is responsible for a significant number of deaths in Western Countries. At present surgery by open or endovascular means is the only widely used therapy for this condition. In this review we examine the risk factors, serum, and genetic associations of AAA. Epidemiology studies suggest that smoking cessation and control of cholesterol and blood pressure should reduce the number of patients developing AAA. Natural history studies suggest that smoking cessation should reduce the rate of progression of AAA. Clear level 1 evidence for drug treatments of AAA are presently lacking; however, animal and human in vitro studies suggest that medication targeted at reducing inflammation and proteolysis are most likely to be beneficial, with limited data to support the use of statins, Angiotensin II inhibitors, and macrolides. Work has commenced in understanding which patients, identified by clinical, serum, and genotype, are more at risk of AAA progression and thus should be selected out for aggressive treatment. Well designed large multicenter randomized controlled trials are required to examine the medical treatment of AAA.

Key Words: abdominal aortic aneurysm ■ pathogenesis ■ medication

Abdominal aortic aneurysms (AAAs) usually occur in the infrarenal part of the aorta. An AAA is generally defined as a maximal aortic diameter of ≥3 cm, although definitions such as ≥4 cm and an infrarenal to suprarenal diameter ratio of 1.2 to 1.5 have also been used.1,2 Irrespective of the definition, the underlying problem in aneurysmal disease is weakening of the aortic wall, resulting in progressive dilatation and, left untreated, eventual aortic rupture. Less common complications include distal embolization, aortoenteric or aortocaval fistulae, and iliac vein compression resultant in deep vein thrombosis. As a result, AAA is estimated to be the tenth commonest cause of mortality and is responsible for ≈2% of all deaths. Estimates of mortality are hampered by low rates of postmortems and it is likely that some sudden deaths attributable to ruptured AAA are certified as cardiac deaths unless a preexisting AAA was documented. Unlike coronary heart disease, the incidence of AAA is reported to be increasing in Western Countries.3,4 In Scotland, for example, the mortality rates from AAA increased 2.6-fold...
between 1981 and 2000. Larger increases in admissions and operations have been reported. Although improved detection and reduction in mortality from other types of cardiovascular disease may have contributed to these increases, the rising age-standardized mortality appears to indicate a genuine increase in the incidence of AAA.

Two large randomized controlled trials have indicated that survival is not improved by elective surgery for AAAs \(<5.5\) cm in diameter. & Small abdominal aortic aneurysms are followed by periodic ultrasound surveillance until the aortic diameter approaches 5.5 cm when repair by open or endoluminal surgery is indicated for those patients deemed suitable. Trials comparing conservative treatment, open or endoluminal repair have identified shortcomings in both forms of intervention: a case fatality of 2.7 to 5.5% for open repair and a cumulative reintervention rate at 5 years of 20% for endoluminal repair. & Trials comparing surveillance with endoluminal treatment of small (4 to 5.4 cm) AAAs have now commenced.

The increased incidence of AAA suggests that the public health measures that have helped reduce the burden of occlusive cardiovascular disease are not effective for this condition. Surgery is currently the only therapy for individuals with AAA, but intervention is costly and associated with morbidity and mortality. This highlights the need for further research into the cause of AAAs to facilitate the development of medical therapies. With the possible introduction of screening for AAAs, large numbers of small aneurysms will be diagnosed over the next decade.

The growing interest in treating small AAAs by endovascular repair may eliminate the opportunity to scientifically investigate drug therapies for the condition. This review outlines recent developments in the understanding of AAA pathogenesis and its relevance to the medical treatment of the condition.

**Risk Factors for Abdominal Aortic Aneurysm**

Our best understanding of the risk factors for AAAs comes from epidemiological screening studies (Table 1). Male gender and increasing age are consistently identified as non-modifiable risk factors for AAA. A positive family history of AAA is reported in 1% to 5% of patients (see below). Ethnicity may also be important with some evidence that AAAs are more common in Northern Europeans than Asians or Africans.

All case control studies report that smoking is a significant risk factor for AAA (Table 1). The relative risk for current smokers is at least 2 and the association of ever smoking with AAA is 2.5 times greater than the association of ever smoking with CHD. Continued smoking also results in increased AAA expansion, a greater risk of rupture and a worse prognosis. There is some evidence of a slow decline of risk after cessation of smoking. These studies indicate that smoking cessation is a priority in any patient with an AAA.

A history of, or being treated for, high plasma cholesterol concentrations has been associated with an increased risk of identifying an AAA in large screening studies. Most, but not all, case-control studies in which fasting lipids have been measured indicate modest elevations of total cholesterol and LDL-cholesterol concentrations in individuals with AAAs. Reducing cholesterol concentrations in patients is therefore desirable, although there is no evidence that this either prevents or slows the expansion of AAAs.

**Hypertension**

Hypertension has only a weak association with AAA (Table 1). Assessment of the correlation between blood pressure and AAA is complicated because the definition of hypertension is often based on whether the patient is receiving treatment for this condition. Interestingly, in subgroup analysis of data from the Chichester and Huntington population screening study, Wilmink and colleagues reported an association between aortic aneurysm and treatment of hypertension only in patients receiving calcium channel blockers (adjusted odds ratio 2.6, 1.5 to 4.3). The authors related the worse prognosis in these patients to increased aortic stiffness and reduced collagen turn-over. Because medications prescribed for hypercholesterolemia or hypertension may themselves affect the development of AAA, the relationship between these risk factors and aneurysm presence is difficult to assess. Interestingly diabetes mellitus has a negative association with AAA, although the reasons for this are not known (Table 1).

**Studies on Human Tissue and Serum**

To identify critical mechanisms underlying aortic weakening and subsequent aneurysm formation, a large number of studies
have assessed aortic histology, protein abundance and gene expression, and circulating markers in patients and controls.\cite{25-37}

The findings of these studies have been recently reviewed in detail.\cite{25} Gene array studies have highlighted loss of extracellular matrix, accumulation of proteolytic enzymes, and cytokines as reproducible findings in human AAA biopsies (Table 2).

The assessment of circulating markers has identified a number of lipids, cytokines, extracellular matrix, and thrombogenic proteins altered in the presence of AAAs, including high-density lipoprotein, lipoprotein (a), antibodies to Chlamydia, the proteolytic enzyme metalloproteinase 9, plasminogen activator inhibitor (PAI)-1, Tenascin-X, and homocysteine (Table 2).\cite{38-43} The findings from different studies are not always in agreement. Sangiorgi et al reported higher serum levels of matrix metalloproteinase (MMP)-9 in patients with aortic aneurysm; however, the reproducibility of these findings from different studies are not always in agreement.\cite{46}

**Genetics and AAA**

Screening studies suggest that having a first-degree relative with an AAA is associated with an odds ratio of 1.9 to 2.4 of developing a similar problem (Table 1). AAAs develop in at least 2 affected members.\cite{47,48} Genome-wide scans of these studies have concentrated on multiplex AAA families (with at least 2 affected members).\cite{49-61} The study of the expansion of AAAs presents a number of methodological challenges. Firstly, the change in aortic diameter over time is small and characterized by periods of rapid growth and quiescence. Simple estimates of growth usually overestimate the rate of progression, and, given that losses to follow-up are inevitable, estimation techniques such

**Natural History of AAA**

Our understanding of the rates of expansion of AAA and risk factors for expansion comes from longitudinal studies of cohorts with small (3 to 5.5 cm) AAAs.\cite{22,62-66} Data about larger AAAs and risk factors for rupture come from studies of patients deemed unsuitable for surgery.\cite{67}

The study of the expansion of AAAs presents a number of methodological challenges. Firstly, the change in aortic diameter over time is small and characterized by periods of rapid growth and quiescence. Simple estimates of growth usually overestimate the rate of progression, and, given that losses to follow-up are inevitable, estimation techniques such
as a Bayesian multilevel random effect model have been recommended.22 Secondly, the measurement of aortic diameter using ultrasound (and to a lesser extent CT) has an error margin of 2 to 3 mm,22,65,68 which is larger than the annual expansion of many small AAAs. Finally, larger AAAs are regularly lost to surveillance when clinicians recommend surgical intervention on the basis of risk of rupture. This is a particular problem in studies of 4 to 5 cm AAA (the group most likely to require medical treatment) where the intervention rate is around 10, 25, and 40% at 1, 2, and 3 years, respectively, even in centers with conservative surgical protocols.1,6

Determinants of AAA Expansion
Understanding the cause of AAA progression can help identify secondary prevention strategies aimed at slowing expansion. The importance of diameter in predicting subsequent aneurysm growth has been clearly identified in studies of small AAAs.5,6,22,65,66 Maximum aortic diameter is also the best determinant of the risk of rupture. In a study of 198 patients unsuitable for surgery, in which postmortems were carried out in 46%, rupture rate was estimated as ~8%, 10%, and 20% per year for aneurysms measuring 5.5 to 5.9, 6.0 to 6.9, and ≥7.0 cm, respectively.67

Current cigarette smoking is associated with AAA growth resulting in an estimated increase in expansion rate of 15% to 20%.22,69 Other atherosclerotic risk factors such as hypertension and dyslipidemia are of uncertain importance with many studies finding no association.22,65 Conversely, diabetes and peripheral vascular disease have been negatively associated with expansion.22,70 Of the risk factors known to be associated with AAA presence, only smoking and diabetes mellitus have been consistently shown to predict AAA progression. Thus different factors may promote progression as opposed to initiation of AAA.

**TABLE 3. Genetic Polymorphisms Associated With AAA**

<table>
<thead>
<tr>
<th>SNP</th>
<th>Population</th>
<th>AAA</th>
<th>Control</th>
<th>OR</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE ID</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Florence66</td>
<td>II</td>
<td>38</td>
<td>104</td>
<td>104</td>
</tr>
<tr>
<td>Italy66</td>
<td>ID</td>
<td>17</td>
<td>46</td>
<td>61</td>
</tr>
<tr>
<td>Japan64</td>
<td>DD</td>
<td>51</td>
<td>48</td>
<td>26</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>106</td>
<td>202</td>
<td>191</td>
</tr>
<tr>
<td>MTHFR C677T</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dunedin64†</td>
<td>CC</td>
<td>210</td>
<td>169</td>
<td>49</td>
</tr>
<tr>
<td>Florence64</td>
<td>CT</td>
<td>141</td>
<td>217</td>
<td>80</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>351</td>
<td>386</td>
<td>129</td>
</tr>
<tr>
<td>MMP-9 C1562T</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dunedin64†</td>
<td>TT</td>
<td>257</td>
<td>145</td>
<td>12</td>
</tr>
<tr>
<td>PAI-1 4G5G</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dunedin65§</td>
<td>CC</td>
<td>4646</td>
<td>4G5G</td>
<td>5G5G</td>
</tr>
<tr>
<td>IL-10 1082</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Florence66</td>
<td>TT</td>
<td>69</td>
<td>109</td>
<td>72</td>
</tr>
<tr>
<td>Oestrogen receptor β</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Riso66</td>
<td>AA</td>
<td>14</td>
<td>217</td>
<td>109</td>
</tr>
<tr>
<td>Chemokine receptor CCR5Δ32 deletion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milano65§</td>
<td>WT/WT</td>
<td>51</td>
<td>18</td>
<td>152</td>
</tr>
<tr>
<td>IL-10 1082</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leipzig66</td>
<td>GG</td>
<td>17</td>
<td>49</td>
<td>34</td>
</tr>
<tr>
<td>TIMP1 nt = 434</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vienna66</td>
<td>SS</td>
<td>2</td>
<td>27</td>
<td>41</td>
</tr>
<tr>
<td>HLA-DR B1 *02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detroit66§</td>
<td>T allele</td>
<td>176</td>
<td>135</td>
<td>103</td>
</tr>
<tr>
<td>HLA-DR B1 *04</td>
<td>Rochester66¶</td>
<td></td>
<td>40</td>
<td>62</td>
</tr>
</tbody>
</table>

*Age and sex matched healthy controls.
†Matched for age, sex, and coronary artery disease, but controls have greater frequency of hypercholesterolemia and diabetes with less history of smoking.
‡Age and sex matched patients with peripheral vascular disease.
§Controls not matched for age or sex.
¶Age and sex matched vascular patients, some controls without aortic imaging.
Role of Medication for AAA: Human Studies

Three types of human studies have been carried out to investigate the efficacies of putative medical therapies for AAA, namely explant studies, medication association studies, and randomized controlled trials. In explant studies biopsies retrieved from AAA at the time of open surgery are incubated with drugs to assess their ability to modulate biological factors associated with AAA progression. In this type of study allowance needs to be made for patient heterogeneity and the concurrent use of drugs by subjects from which the biopsies are removed. The viability of cultured samples is also limited (usually around one week). These studies have highlighted the potential of statins, Angiotensin II inhibitors (Angiotensin Converting Enzyme inhibitors and Angiotensin II blockers), macrolides, and cyclooxygenase inhibitors in reducing the production of proteinases and cytokines from human AAA biopsies.106

Indomethacin for example has been demonstrated to reduce IL-1β, IL-6, and PGE2 secretion from explants but had no effect on MMP production.109 Similarly, Angiotensin II blockers have been shown to reduce the production of the cytokine osteoprotegerin from aortic aneurysm explants.31 Tetracyclines have been shown to reduce MMP production,108 while the MMP-3 and MMP-9 concentrations are reduced in the AAA biopsies of patients receiving statins.107 The findings of human in vitro and animal studies (Table 4) suggest potential benefit from statins, Angiotensin II inhibitors, beta adrenoceptor blockers, nonsteroidal antiinflammatory medications, and macrolides in the treatment of AAA.

Unfortunately, clinical studies to examine the role of these medications in slowing AAA progression have been limited to date.110–112 In a cohort of patients in the UK small aneurysm trial the concurrent use of nonsteroidal antiinflammatory medication was noted to be associated with reduced aortic expansion.113 Concerns regarding the cardiac effect of cyclooxygenase inhibitors might limit the use of this medication.114 The largest and best conducted study to date examined the effect of propranolol in a randomized controlled trial of 548 patients with small (3 to 5 cm) AAAs followed for a mean of 2.5 years.110 No effect on AAA growth, intervention rate, or mortality could be demonstrated for the treatment group. Furthermore, 42% of patients receiving propranolol had to discontinue the medication and the patients randomized to this group reported a worse health-related quality of life.110 The effect of antibiotics targeting Chlamydia pneumoniae in patients with AAAs have been studied in two small randomized trials.111,112 In addition, the antibiotics used, doxycycline and roxithromycin, have also been shown to reduce MMP production in animal models and/or human explants, and inhibit aneurysm development experimentally (Table 4). Mosorin and colleagues randomized 32 patients with small aneurysms to doxycycline or placebo and followed them for 18 months, reporting a nonsignificant reduction in expansion overall.111 Vannem et al randomized 92 patients with small aneurysms between roxithromycin and placebo over a mean of 1.5 years and reported a significant reduction in aortic expansion from 2.75 to 1.56 mm/year, although growth rate appears to have been calculated by linear regression.112 Neither of the medications were associated with significant side-effects and drop-outs were minimal.111,112
TABLE 4. Medication Demonstrated To Inhibit AAA in Animal Models

<table>
<thead>
<tr>
<th>Medication</th>
<th>Model</th>
<th>Diameter control</th>
<th>Diameter treated</th>
<th>Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propranolol</td>
<td>WKHT elastase</td>
<td>6.9±0.3 (n=18)</td>
<td>2.9±0.2 (n=14)*</td>
<td>Blood pressure reduction.§</td>
</tr>
<tr>
<td>Propranolol</td>
<td>Male BLO</td>
<td>1.70±0.10 (n=14)</td>
<td>1.13±0.09 (n=11)</td>
<td>Not investigated.</td>
</tr>
<tr>
<td>Simvastatin</td>
<td>Rat elastase</td>
<td>4.3±0.19 (n=19)</td>
<td>3.4±0.08 (n=19)*</td>
<td>Antiinflammatory, proteolytic &amp; oxidative stress.</td>
</tr>
<tr>
<td>Simvastatin</td>
<td>Mice Apo E−/− elastase**</td>
<td>1.37±0.08 (n=25)</td>
<td>1.14±0.07 (n=28)*</td>
<td>MMP-9 suppression, elastin and VSMC preservation.</td>
</tr>
<tr>
<td>Doxycycline</td>
<td>Mice Apo E−/− / All**</td>
<td>18/21 (86%)</td>
<td>7/20 (35%)†#</td>
<td>Not clarified.</td>
</tr>
<tr>
<td>BB-94</td>
<td>Rat elastase</td>
<td>4.2±0.2 (n=11)</td>
<td>3.6±0.1 (n=12)*</td>
<td>Elastin preservation, decreased inflammation.</td>
</tr>
<tr>
<td>Rs132908</td>
<td>Rat elastase</td>
<td>5.98±1.02 (n=6)</td>
<td>3.59±0.34 (n=8)*</td>
<td>Preservation of elastin.</td>
</tr>
<tr>
<td>Captopril94</td>
<td>Rat elastase</td>
<td>5.17±0.44 (n=6)</td>
<td>2.96±0.21 (n=6)*</td>
<td>Elastin preservation.</td>
</tr>
<tr>
<td>Losartan29</td>
<td>Rat elastase</td>
<td>5.17±0.44 (n=6)</td>
<td>4.58±0.57 (n=6)</td>
<td>No effect.</td>
</tr>
<tr>
<td>1400W15</td>
<td>Rat elastase</td>
<td>5.6±0.9 (n=10)</td>
<td>3.8±1.1 (n=10)*</td>
<td>Aortic elastin preservation.</td>
</tr>
<tr>
<td>Aminoguanidine26</td>
<td>Rat elastase</td>
<td>8.7±1.2 (n=8)</td>
<td>4.8±0.6 (n=8)*</td>
<td>Suppression of iNOS.</td>
</tr>
<tr>
<td>Fasudil72</td>
<td>Mice Apo E−/− / All**</td>
<td>2.1±0.2 (n=24)</td>
<td>1.5±0.1 (n=29)*</td>
<td>Suppressed VSMC apoptosis and proteolysis.</td>
</tr>
<tr>
<td>Vitamin E102</td>
<td>Mice Apo E−/− / All**</td>
<td>2.25±0.2 (n=10)</td>
<td>1.7±0.25 (n=10)*</td>
<td>Antioxidant, decreased macrophage infiltration and OPN concentration.</td>
</tr>
<tr>
<td>PDTC10</td>
<td>Mice elastase</td>
<td>1.44±0.03 (n=34)</td>
<td>1.16±0.02 (n=49)†</td>
<td>NF-κB, MMP-9 and IL-1β &amp; IL-6 suppression.</td>
</tr>
<tr>
<td>Rapamycin100</td>
<td>Rat elastase</td>
<td>4.5±0.5 (n=10)</td>
<td>3.3±0.8 (n=20)*</td>
<td>Suppression of NF-κB and MMP-9.</td>
</tr>
<tr>
<td>Indomethacin25</td>
<td>Rat elastase</td>
<td>5.27±2.37 (n=82)</td>
<td>3.45±1.11 (n=73)*</td>
<td>Elastin preservation, suppression of PGE2 and MMP-9.</td>
</tr>
<tr>
<td>Celecoxib122</td>
<td>Mice Apo E−/− / All**</td>
<td>22/30 (73%)</td>
<td>2/19 (11%)†#</td>
<td>Selective inhibition of COX-2, reducing inflammatory prostanoid production.</td>
</tr>
<tr>
<td>176-estradiol125</td>
<td>Rat elastase</td>
<td>538±106% (n=13®)</td>
<td>241±57% (n=13)*</td>
<td>Suppression of macrophages, MMP-9 and elastin preservation.</td>
</tr>
<tr>
<td>176-estradiol154</td>
<td>Mice Apo E−/− / All**</td>
<td>1.9±0.1 (n=20)</td>
<td>1.45±0.1 (n=19)*</td>
<td>Suppression of atherosclerosis, NF-κB and adhesion molecules. Increased PPAR α and γ.</td>
</tr>
<tr>
<td>Tamoxifen105</td>
<td>Rat elastase</td>
<td>434±30% (n=6)</td>
<td>218±37% (n=6)*</td>
<td>Increased antioxidant capacity, decreased inflammation and MMP-9.</td>
</tr>
<tr>
<td>SP600125106</td>
<td>Mice CaCl2</td>
<td>1.2±0.05 (n=8)</td>
<td>0.95±0.05 (n=9)*</td>
<td>Inhibition of c-Jun N-terminal kinase led to regression of AAA.</td>
</tr>
</tbody>
</table>

**Models in which atherosclerosis as well as aneurysm is promoted.
#Percentage of aneurysm formation only reported.
| Percentage of atheromus formation only reported. |
| Using gene chips. |
| *Percentage increase of diameter after elastase infusion only reported. |
| ‡Inhibition of c-Jun N-terminal kinase led to regression of AAA. |

BB-94 indicates Batimastat, an MMP inhibitor; Rs132908, MMP antagonist; 1400W, selective iNOS inhibitor; PDTC, Pyrrolidine dithiocarbamate, an antioxidant that specifically suppresses NF-κB; SP600125, specific inhibitor of c-Jun N-terminal kinase; WKHT, genetically hypertensive Wistar-Kyoto rats; BLO, the spontaneously hypertensive rat; AII, Angiotensin II; MMP, Matrix Metalloproteinase; VSMC, Vascular Smooth Muscle Cell, iNOS, Inducible Nitric Oxide Synthase; OPN, Osteopontin; IL, interleukin; PGE2, Prostaglandin E2; COX-2, cyclooxygenase-2; PPAR, peroxisome proliferator-activated receptor.

Larger studies with longer follow-up incorporating these and other medications are needed to clarify the role of these treatments on a range of end points, including expansion and intervention rates. In addition to considering the effect of variable growth rate, losses to follow-up, measurement error, and calculation of expansion, investigators should also pay attention to concurrent medication. A recent follow-up study of 150 patients with small AAAs reported an association between concurrent statin therapy and reduced AAA expansion.115 However, without a randomized controlled trial it is impossible to be clear that the medication rather than another associated factor, such as other risk factors in these patients or other concurrent medications, were responsible for this finding. Previous studies have highlighted that >40% of patients with AAA are routinely prescribed statins, beta adrenoceptor blockers, and angiotensin II inhibitors. Use of these drugs will probably increase as evidence for their benefit accumulates. Although it is plausible that concurrent use of these drugs would inhibit AAA expansion, it may now be impossible to assess this in a large randomized controlled trial.

Future Directions

Data from epidemiological studies highlight the potential benefit of smoking cessation and control of blood pressure and lipids in reducing the development of AAA. In patients who already have an AAA, treatments which reduce aortic inflammation and proteolysis and support vascular smooth muscle cell (VSMC) recovery are required. In vitro and animal studies highlight the potential of statins, Angiotensin II inhibitors, macrolides, and medication blocking inflamma-
tory pathways. Work has commenced on understanding how traditional risk factors, circulating markers, and genotype can be used to define risk of AAA progression and therefore select out patients for aggressive treatment.

The further development of specific medical therapies for AAAs requires a number of carefully planned large randomized trials using such promising medications in at risk patients. When effective medications have been identified it may be possible to incorporate these with surgical treatments. Thus oral medications or drugs coated onto an endoluminal graft may improve the results of endovascular AAA repair.

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None.

References


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