Protective Effect of Dietary Potassium Against Vascular Injury in Salt-Sensitive Hypertension

Makiko Kido, Katsuyuki Ando, Maristela L. Onozato, Akihiro Tojo, Masahiro Yoshikawa, Teruhiko Ogita, Toshiro Fujita

Abstract—Hypertensive cardiovascular damage is accelerated by salt loading but counteracted by dietary potassium supplementation. We suggested recently that antioxidant actions of potassium contribute to protection against salt-induced cardiac dysfunction. Therefore, we examined whether potassium supplementation ameliorated cuff-induced vascular injury in salt-sensitive hypertension via suppression of oxidative stress. Four-week-old Dahl salt-sensitive rats were fed a normal-salt (0.3% NaCl), high-salt (8% NaCl), or high-salt plus high-potassium (8% KCl) diet for 5 weeks, and some of the rats fed a high-salt diet were also given antioxidants. One week after the start of the treatments, a silicone cuff was implanted around the femoral artery. Examination revealed increased cuff-induced neointimal proliferation with adventitial macrophage infiltration in arteries from salt-loaded Dahl salt-sensitive rats compared with that in arteries from non–salt-loaded animals (intima/media ratio: 0.471±0.070 versus 0.302±0.037; P<0.05), associated with regional superoxide overproduction and reduced nicotinamide-adenine dinucleotide phosphate oxidase activation and mRNA overexpression. On the other hand, simultaneous potassium supplementation attenuated salt-induced neointimal hyperplasia (intima/media ratio: 0.205±0.012; P<0.001), adventitial macrophage infiltration, superoxide overproduction, and reduced nicotinamide-adenine dinucleotide phosphate oxidase activation and overexpression. Antioxidants, which decrease vascular oxidative stress, also reduced neointima formation induced by salt excess. In conclusion, high-potassium diets seems to have a protective effect against the development of vascular damage induced by salt loading mediated, at least in part, through suppression of the production of reactive oxygen species probably generated by reduced nicotinamide-adenine dinucleotide phosphate oxidase. (Hypertension. 2008;51:225-231.)

Key Words: hypertension ■ sodium ■ potassium ■ antioxidants ■ arteries

Numerous studies have demonstrated that excessive salt intake causes cardiovascular damage and that this was counteracted by potassium supplementation.1 According to the earlier report,2 salt loading reduced the survival rate of Dahl salt-sensitive (DS) rats, a model of salt-sensitive hypertension, whereas potassium supplementation alleviated this salt-induced premature mortality, independent of its hypotensive action. It has been speculated that this may be a result of the vasoprotective effect of potassium, because potassium supplementation has been shown to ameliorate vascular endothelial dysfunction in salt-loaded DS rats.3 Also, Ma et al4 clearly demonstrated that high-potassium intake inhibited neointimal formation in several vascular injury models, such as a balloon injury of rat carotid and swine coronary arteries from animals without hypertension. Thus, dietary potassium may have vasoprotective mechanisms beyond the blood pressure (BP)–lowering effect. Although it has been shown in vitro experiments that potassium inhibited migration5 and proliferation6 of vascular smooth muscle cells, a factor(s) mediating vasoprotective effects of dietary potassium has not yet been clarified by in vivo studies.

Arterial damage could cause intimal thickening, which originates from accumulation of vascular smooth muscle cells and deposition of the extracellular matrix, followed by vascular reactive oxygen species (ROS) overproduction.8 Actually, in our previous report,9 we demonstrated enhanced cuff-induced neointimal proliferation associated with vascular ROS overproduction and adventitial upregulation of reduced nicotinamide-adenine dinucleotide phosphate (NADPH) oxidase in mice with an intrinsic deficiency of antioxidant adrenomedullin. Interestingly, salt loading increased plasma and urinary markers of oxidative stress10,11 and ROS production from the injured aorta12 and kidney11 in DS rats. Conversely, in our recent study,13 potassium supplementation ameliorated cardiac dysfunction associated with inhibition of NADPH oxidase in salt-loaded DS rats. Actually, in cultured endothelial cells and monocytes/macrophages, a physiological increase in potassium concentration suppressed ROS production.14 Also, a low-potassium diet increased ROS generation from the carotid arteries of rabbits,15 and potassium supplementation suppressed lipid peroxide content in aorta from salt-loaded, stroke-prone, spon-
taneously hypertensive rats. However, these earlier reports did not evaluate the role of ROS in vascular injury in detail and, to the best of our knowledge, the effect of dietary potassium on the ROS-generating system has never been demonstrated in in vivo studies, although the role of NADPH oxidase has been hypothetically proposed. In the present study, therefore, we investigated the effect of dietary salt and potassium on the progression of vascular damage and NADPH oxidase–related ROS generation using a cuff-injured model of the femoral artery in DS rats. We also examined the effects of a membrane-permeable superoxide dismutase mimetic, 4-hydroxy-2,6,6-tetramethyl-piperidine-N-oxyl (tempol), and an NADPH oxidase inhibitor, 4-hydroxy-3-methoxy-acetophenone (apocynin), on neointima formation in a cuff-ed artery prepared from salt-loaded DS rats to clarify the role of ROS on vascular damage.

Methods

Animals
Four-week-old male DS and Dahl salt-resistant (DR) rats were obtained from SLC. The DS rats were randomly assigned to rat chow containing a normal salt (0.3% NaCl), a high-salt (8% NaCl), or a high-salt plus high potassium (8% KCl; standard and high-salt rat chow containing 1.3% KCl; Oriental Yeast Co, Ltd) diet. DR rats were randomly divided into normal- and high-salt chow. Tempol (1 mmol/L) or apocynin (1.5 mmol/L) dissolved in tap water, was administered orally to some of the salt-loaded DS rats. The animals were maintained in a humidity- (60±5%), temperature- (23±1.5°C), and light cycle- (7 AM to 7 PM) regulated room and were allowed free access to the designated diets and water for 5 weeks. During the last week of the treatment, the rats were placed in individual metabolic cages, and 24-hour urine samples were collected. Systolic BP (SBP) was measured using a tail-cuff method (BP-98A, Softron) in unanesthetized animals every week. On the last day of the study, the femoral artery was cannulated under ether anesthesia. Mean arterial pressure was measured after waiting for recovery of the animals from anesthesia for ≥3 hours. All of the animals were handled in an accredited institute facility in accordance with the institutional animal care policies, and all of the research protocols conformed to the guiding principles for animal experimentation as laid down by the ethics committees on animal research of the University of Tokyo.

Cuff Placement
One week after the start of the treatments, a silicone cuff (ID: 0.64 mm; OD: 1.24 mm; length: 5 mm) was placed around femoral artery, as described previously. All of the procedures were performed under sterile conditions to prevent inconsistently enhanced vascular injury attributable to postoperative infection. The rats were anesthetized with an injection of sodium pentobarbital (50 mg/kg IP). The femoral artery was exposed and cleared of connective tissue, and a longitudinally cut silicone rubber tube was loosely placed around the artery. The contralateral femoral artery was only isolated without cuff placement (sham-operated artery).

Tissue Harvesting and Histological Examination
Four weeks after the cuff placement, the animals were anesthetized by sodium pentobarbital, and blood samples were obtained from the abdominal vein. Then, the rats were euthanized by an overdose of pentobarbital and perfused with PBS. The cuffs were removed, and arteries were cleaned of connective tissue, fixed with 4% paraformaldehyde, and embedded in paraffin. Sections of the middle portion of the cuffed artery were stained with elastic-Verhoeff-von Gieson method. The cross-sectional areas of the intima and media were measured in micrometers squared using Image-ProPlus 5.0 software (Media Cybernetics). The intima/media (I/M) ratio of each artery was determined by averaging the values to evaluate the intimal mass.

Immunohistochemistry
Arteries were processed for immunohistochemistry using the labeled streptavidin biotin method as described previously. Sections were incubated with 3% H2O2, blocking serum, and thereafter with an anti-ED1 antibody (mouse IgG; BMA Biomedicals AG) at a 1:100 dilution. The sections were rinsed with Tris-buffered saline Tween-20 and incubated with a biotinylated secondary antibody against mouse IgG (Dako) at a 1:300 dilution, followed by incubation with horseradish peroxidase–conjugated streptavidin solution (Dako). Horseradish peroxidase labeling was detected using a peroxide substrate solution with 0.8 mmol/L of diaminobenzidine and 0.01% H2O2. The sections were counterstained with hematoxylin.

Measurement of Vascular Superoxide Production
The superoxide (O2•−) production was measured by the bis-N-methylacridinium nitrate (lucigenin)–enhanced chemiluminescence assay. Our previous study showed that O2•− production from the cuff-injured femoral artery increased in a time-dependent fashion until 3 days after the operation and subsequently decreased. Therefore, in this study, the femoral artery was harvested on the third postoperative day for the measurement of O2•− production. For lucigenin chemiluminescence, DS rats were perfused with PBS, the cuff was gently removed, and the femoral artery was excised and freed of surrounding tissue. After 30-minute equilibration in modified Heps buffer at 37°C, the specimen was transferred into test tubes containing 5 μmol/L of lucigenin. The chemiluminescence was measured using a scintillation counter (Lumat LB9507, Berthold Technologies). To examine the direct effect of antioxidants, cuff-ed femoral arteries in salt-loaded DS rats were treated for 30 minutes with tempol (0.1 mmol/L or 1 mmol/L) or apocynin (1 mmol/L or 10 mmol/L). For assessment of NADPH oxidase activity, NADPH (100 μmol/L) was added as a substrate, and the measurement was conducted. Repeated measurements of the specimens were interpreted every 30 seconds, and the average value over a 5-minute period was reported. The fresh femoral arteries were weighed, and the lucigenin counts were normalized by the wet weights (milligrams).

Real-Time Quantitative RT-PCR Analysis of NADPH Oxidase Subunit Expression
Total RNA was prepared from the pooled samples of femoral arteries of DS rats on the third postoperative day, and mRNA expression levels of NADPH oxidase subunits, p22phox, gp91phox, and p47phox, were quantified. RNA was isolated using RNeasy Fibrous Tissue Mini Kit (Qiagen Inc) and reverse transcribed. For real-time PCR, primers of TaqMan probe from PE Biosystems were used. An Applied Biosystems Prism 7000 Sequence Detection System (Applied Biosystems) was used with the default thermal cycle program (95°C for 10 minutes, followed by 40 cycles of 95°C for 20 seconds and 60°C for 1 minute). The transcript levels of components of NADPH oxidase were normalized with those of the 18S RNA transcript.

Assay of Serum and Urine
Sodium and potassium concentrations in serum and urine were measured by flame photometry.

Statistical Analysis
Data are expressed as mean±SEM. In all of the cases, “n” refers to the numbers of animals. Statistical analysis was done by a 1-way and repeated-measurements (SBP; Figure 1A) ANOVA followed by Turkey’s posthoc multiple comparisons. P values <0.05 were considered to be statistically significant.
Results

Effects of Salt Loading on Cuff-Induced Neointima Formation in Femoral Arteries of DS and DR Rats

Urinary sodium excretion suggested successful salt loading (Table). Serum sodium and potassium did not change with salt loading. Salt loading increased SBP (209 ± 6.9 versus 135.7 ± 1.7 mm Hg; P < 0.001; Figure 1A) and mean arterial pressure (164 ± 2.3 versus 111 ± 4.5 mm Hg; P = 0.001; Figure 1B) in DS rats. Intimal hyperplasia developed in the femoral artery by 28 days after the cuff implantation (Figure 2). Because there was no apparent increase in medial thickness, a statistical comparison was conducted using the I/M ratio. Salt loading accelerated neointima formation in DS rats (I/M ratio: 0.471 ± 0.070 versus 0.302 ± 0.038; P < 0.001; Figures 2 and 3). On the other hand, a high-salt diet did not significantly increase the I/M ratio in DR rats (Figure 3), in which salt loading also did not affect SBP (131 ± 1.9 versus 134 ± 2.3 mm Hg; n = 4, respectively).

Effects of Potassium Supplementation on Salt-Induced Acceleration of Neointima Formation in Cuff-Injured Femoral Arteries of DS Rats

As suggested by urinary electrolytes excretion, potassium supplementation did not decrease salt intake (Table). With potassium supplementation, serum sodium was not altered, but serum potassium increased (P < 0.001). Dietary potassium supplementation slightly reduced BP in salt-loaded DS rats (SBP: 187 ± 4.1 mm Hg; mean BP: 147 ± 3.9 mm Hg; P < 0.05, respectively; Figure 1A and 1B). In spite of the small reduction in BP, potassium supplementation almost completely attenuated salt-induced acceleration of neointima proliferation in DS rats (I/M ratio: 0.205 ± 0.012; P < 0.001; Figures 2 and 3).

ROS Production in Cuff-Injured Femoral Arteries After Salt Loading and Potassium Supplementation

High-salt diet increased O$_2^-$ production in the cuffed arteries of DS rats (544.0 ± 67.1 versus 164.3 ± 17.7 cpm/mg; P < 0.001; Figure 4A). On the other hand, potassium supplementation reduced salt-induced O$_2^-$ overproduction (219.3 ± 24.4 cpm/mg; P < 0.001; Figure 4A). Also, ex vivo treatment with tempol and apocynin inhibited the O$_2^-$ generation in cuffed arteries of salt-loaded DS rats in a dose-dependent fashion (Figure 4B). The potent ROS-inhibitory action of apocynin suggests that the major source of ROS may be NADPH oxidase. Actually, NADPH-induced O$_2^-$ production was increased in the cuffed arteries of salt-loaded DS rats than in non–salt-loaded rats (P < 0.001), whereas potassium supplementation reversed the increase induced by salt loading (Figure 4C, right; P < 0.001). In addition, the O$_2^-$ production induced by NADPH from the cuffed femoral arteries was significantly increased compared with that produced in the absence of NADPH in DS rats fed high- and normal-salt diets (P < 0.05, respectively), but not in DS rats fed a high-salt plus high-potassium diet (Figure 4C); NADPH oxidase activity was lower in cuffed arteries of DS rats fed a high-salt plus high-potassium diet than in those fed a normal-salt diet (P < 0.05; Figure 4C, right).

### Table. Serum and Urinary Electrolytes in DS Rats

<table>
<thead>
<tr>
<th>Variable</th>
<th>Normal Salt</th>
<th>High Salt</th>
<th>High Salt + Potassium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serum Na, mean ± SEM, mEq/L</td>
<td>143.2 ± 1.2</td>
<td>144.8 ± 1.6</td>
<td>145.8 ± 0.71</td>
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<tr>
<td>Serum K, mean ± SEM, mEq/L</td>
<td>4.7 ± 0.21</td>
<td>4.4 ± 0.10</td>
<td>5.2 ± 0.18*</td>
</tr>
<tr>
<td>Urinary Na, mean ± SEM, mEq/d</td>
<td>1.18 ± 0.10</td>
<td>23.5 ± 1.71†</td>
<td>23.8 ± 0.83†</td>
</tr>
<tr>
<td>Urinary K, mean ± SEM, mEq/d</td>
<td>3.20 ± 0.09</td>
<td>4.24 ± 0.22</td>
<td>23.3 ± 0.79†</td>
</tr>
</tbody>
</table>

*P < 0.01 vs high-salt DS rats.
†P < 0.001 vs normal-salt DS rats.
mRNA Expressions of NADPH Oxidase Subunits in the Cuffed Femoral Artery
Expression of p22phox ($P<0.01$), gp91phox ($P<0.001$), and p47phox ($P<0.001$) was significantly higher in salt-loaded DS rats than in non–salt-loaded animals (Figure 5). Dietary potassium supplementation restored the expression levels of NADPH oxidase subunits in salt-loaded DS rats ($P<0.001$, respectively).

Effect of Tempol and Apocynin Administration on Salt-Induced Acceleration of the Cuff Injury
Tempol suppressed neointima formation in salt-loaded DS rats (I/M ratio: 0.276±0.042; $P<0.01$; Figure 3), associated with decreased vascular $O_2^-$ production ($P<0.001$; Figure 4A), although it did not decrease BP (SBP: 203±2.1 mm Hg; mean BP: 157±3.9 mm Hg; Figure 1A-B). Apocynin, which reduced BP (SBP: 186±4.9 mm Hg; $P<0.05$; mean BP: 141±3.1 mm Hg; $P<0.01$; Figure 1A and 1B) and $O_2^-$ production ($P<0.001$; Figure 4A), potently suppressed neointima formation (I/M ratio: 0.145±0.021; $P<0.001$; Figure 3) in salt-loaded DS rats.

Macrophage Infiltration in the Cuffed Femoral Arteries
In DS rats fed a normal-salt diet, immunohistochemical staining for ED1 was slightly increased in the adventitia of cuffed arteries compared with that in adventitia of a sham-operated artery (Figure 6). Salt loading further increased the adventitial macrophage infiltration, whereas simultaneous potassium supplementation and Tempol decreased it.

Discussion
In the present study, salt loading exacerbated cuff-induced intimal thickening in the femoral artery of DS rats, accompanied by regional ROS overproduction. Dietary potassium supplementation alleviated a salt-induced increase of neointima proliferation and ROS generation. The vascular redox status may contribute to both salt-induced acceleration of neointima forma-

Figure 2. Representative histological photomicrographs of cross-sections of femoral arteries (elastic-Verhoeff-von Gieson staining) at 28 days after the cuff placement. Compared with sham-operated arteries of DS rats (top left), cuffed arteries in DS rats on a normal-salt diet showed a mild increase of intimal thickness (top right). The neointima proliferation was markedly enhanced in DS rats fed a high-salt diet (bottom left). Potassium supplementation (bottom right) significantly reduced the neointimal area in cuffed arteries of salt-loaded DS rats. Original magnification, ×200. Bar=100 μm. Abbreviations are the same as those shown in the legend for Figure 1.

Figure 3. Effects of dietary salt, potassium, and antioxidants on the I/M ratio in cuffed femoral arteries of DS and DR rats. Salt loading increased the I/M ratio in DS rats (open and closed bars; n=5 and 7, respectively) but did not significantly affect the I/M ratio in DR rats (shaded bar; n=5 and 6, respectively). Potassium supplementation (n=10) reversed the salt-induced increase of the I/M ratio in DS rats. Similarly, tempol (n=5) and apocynin (n=4) decreased the I/M ratio in salt-loaded DS rats. The graph shows measurements of the I/M area ratio at 28 days. †$P<0.01$, ‡$P<0.001$. Abbreviations are the same as those shown in the legend for Figure 1.
NADPH oxidase may be the major source of ROS. Actually, the changes in ROS production caused by salt loading and potassium supplementation were parallel to changes in regional NADPH oxidase activity and expression.

A cuff implanted around arteries works as a foreign body, activating inflammation in the affected area. In the present study, macrophage infiltration was predominantly observed in the adventitia of cuffed arteries. Adventitial macrophage infiltration was enhanced in salt-loaded DS rats, which was attenuated by potassium supplementation. Similarly, in the previous study, a high-potassium diet ameliorated macrophage infiltration of the aorta in stroke-prone, spontaneously hypertensive rats. Vascular injuries by cuff placement and balloon angioplasty have been shown to be associated with adventitial inflammation characterized by accumulation of leukocytes, leading to subsequent intimal hyperplasia. Because there is in vivo evidence implicating that proliferating adventitial fibroblasts might migrate into the intima after arterial injury, adventitial inflammation may play a key role in neointimal hyperplasia. In the present study, tempol suppressed both salt-induced enhancement of adventitial infiltration by macrophages and neointimal proliferation in cuffed arteries. Conversely, intimal thickening with enhanced adventitial macrophage infiltration was observed in cuffed arteries of mice with intrinsic antioxidant deficiency. Moreover, adequate anti-ROS therapy directed at adventitial cells can potentially counteract neointima formation. Thus, numerous macrophages infiltrating adventitia could generate excessive ROS and play an important role in the inflammatory responses in the vasculature.

In the present study, dietary potassium supplementation counteracted salt-induced acceleration of vascular injury, possibly via its antioxidant effect mediated through inactivation of NADPH oxidase. Recently, it has been postulated that an increase in extracellular potassium can boost the membrane sodium pump activity, hyperpolarizing the cell membrane and “turning off” NADPH oxidase activation, because membrane depolarization upregulates the activity of this enzyme complex. However, whereas potassium supplementation slightly increased serum potassium in salt-loaded DS rats, a mere increase of serum potassium by 0.8 mEq/L (Table) cannot fully explain the ~60% decrease in ROS production observed in this study (Figure 4A); in another study, a 1-mEq/L increase of serum potassium caused only a 10% to 20% reduction in oxidative stress. On the other hand, negative sodium balance may contribute to potassium-induced suppression of ROS overproduction, because potassium supplementation causes natriuresis. Recently, in relation to salt-induced stimulation of oxidative stress, it has been suggested that endogenous cardiotonic steroids, which have been shown to be increased because of volume expansion, might play an important role in the antioxidant effect of dietary potassium, because the cardiovascular protective effect of dietary potassium was certainly apparent in salt-loaded hypertensive models. Actually, the antioxidant effect of potassium supplementation has been demonstrated in vivo only in salt-loaded, stroke-prone, spontaneously hypertensive rats, although dietary potassium depletion, which may be more critical in potassium homeostasis compared with potassium supplemen-
tation, has been shown to induce ROS overproduction in the non–salt-loaded state.\textsuperscript{15}

Although arterial NADPH oxidase activity was suppressed in potassium-supplemented and salt-loaded DS rats compared with normal-salt diet–fed animals in this study, ROS generation from cuffed arteries was similar in these animals. Thus, NADPH oxidase–independent ROS-producing or -scavenging systems, eg, mitochondrial ROS generation\textsuperscript{30} and microvascular superoxide dismutase,\textsuperscript{31} which have been reported to be stimulated by salt loading but might not be inhibited by dietary potassium, may also contribute to ROS production in cuffed arteries of salt-loaded DS rats.

In this study, potassium supplementation slightly inhibited the salt-induced rise of BP. Because hypertension is one of the major determinants of vascular injury, changes in BP induced by dietary salt and potassium may have contributed to the observed vascular effects. However, tempol ameliorated intimal hyperplasia in cuffed arteries of salt-loaded DS rats without significant BP reduction, suggesting that ROS may, nonetheless, be the key mediator of influences of hypertension, has been shown to induce ROS overproduction in the non–salt-loaded state.\textsuperscript{15}

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![Figure 5](image-url)\textsuperscript{†}\textsuperscript{P}<0.01, ‡\textsuperscript{P}<0.001. Abbreviations are the same as those shown in the legend for Figure 1.

![Figure 6](image-url)
sodium and potassium balance on vascular damage. Actually, in spite of higher BP, the I/M ratio was slightly, but nonsignificantly, reduced in DS rats fed a high-salt plus high-potassium diet compared with animals fed a normal-salt diet.

In conclusion, we demonstrated that excessive salt intake enhanced neointimal hyperplasia in the cuffed femoral artery in DS rats, accompanied by ROS overproduction mediated via upregulation of NADPH oxidase, and that potassium supplementation protected against salt-induced intimal thickening by suppressing NADPH oxidase activity. Thus, suppressive action of potassium on NADPH oxidase may be important in the attenuation of vascular injury in salt-sensitive hypertension.

**Perspectives**

Our results showed that potassium supplementation could blunt the progression of vascular injury, possibly through suppression of salt-induced oxidative stress, in DS rats. However, antioxidant therapies in humans have often failed to ameliorate cardiovascular risks and have even been harmful in some cases.32 Also, antioxidant vitamin supplementation impaired myocardial perfusion and coronary endothelial function in pigs.33 Dietary potassium may differ from these so-called “antioxidants”; the antioxidant mechanism of dietary potassium may involve mainly its counteracting action against salt-induced NADPH oxidase activation, a harmful effect of salt excess, but potassium supplementation might not inhibit some other vascular ROS-generating systems. Thus, potassium supplementation might be physiological and superior to an antioxidant that completely inhibits all of the ROS. Thus, dietary potassium is expected to be more effective for cardiovascular protection than a simple antioxidant.

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**Disclosures**

None.

**References**

3. Zhou MS, Kosaka H, Yoneyama H. Potassium augments vascular responsiveness to ameliorate cardiovascular risks and have even been harmful in some cases.32 Also, antioxidant vitamin supplementation protected against salt-induced intimal thickening by suppressing NADPH oxidase activity. Thus, suppressive action of potassium on NADPH oxidase may be important in the attenuation of vascular injury in salt-sensitive hypertension.

**Effect of Dietary Potassium on Vascular Injury**

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