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Towards electroactive gel artificial muscle structures

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ABSTRACT

Polyvinyl chloride (PVC) gel is a promising, soft-smart material with electroactive properties, which can be used to make soft robotic actuators with impressive characteristics. However, until now, PVC gel actuators have always been made with rigid metal electrodes, preventing the fabrication of fully soft devices. Here, we present a novel conceptual design for PVC gel actuators. By moving the microstructure from the electrode to the gel itself, we enable PVC gels which exhibit linear contraction when sandwiched between planar electrodes made from any conductive material. We investigate four different microstructures, three of which exhibit higher displacements compared with a traditional (mesh-based) PVC gel actuator. The best performing gel achieved a displacement of 26% of the microstructure height. Finally, we demonstrate an entirely soft PVC gel actuator with thin conductive rubber electrodes. This article is a first step towards totally compliant artificial muscles made from soft electrodes and PVC gels.

Keywords: Soft robotics, electroactive polymer, PVC gel, soft actuator, anodophilic behaviour

1. INTRODUCTION

Polyvinyl chloride (PVC) gel actuators are a recently discovered class of electroactive polymer[1], which exhibit impressive characteristics: 12% contraction, 78 kPa stress, 3 W kg^{-1} specific power, 4.3 kW m^{-3} power density, and 9 Hz^2 bandwidth. When a PVC gel is placed between oppositely charged electrodes, the gel creeps towards the anode, increasing its anode-contacting surface area[1,3,4] (Fig. 1).
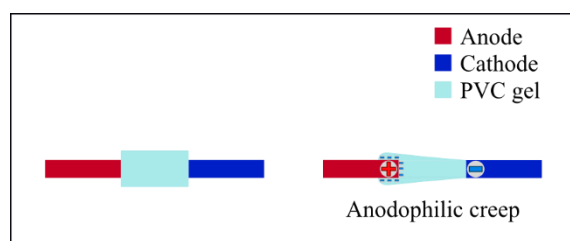
Figure 1. Anodophilic creep in PVC gels. When the electrodes are charged, the gel creeps towards the anode.

This "anodophilic" (anode-loving) behaviour can be captured as an actuation mechanism. To achieve a bending actuator, a long sample of gel may be sandwiched between two short electrodes[1]; upon activation the gel creeps towards the anodes resulting in a bulk bending motion (Fig. 2a). To achieve a contracting actuator, a sample of gel may be sandwiched between a standard, planar cathode and a porous, mesh-like anode[5]. When voltage is applied, the gel creeps around the individual strands of the mesh, squeezing between the mesh pores, resulting in a bulk reduction in height of the overall structure (Fig. 2b)

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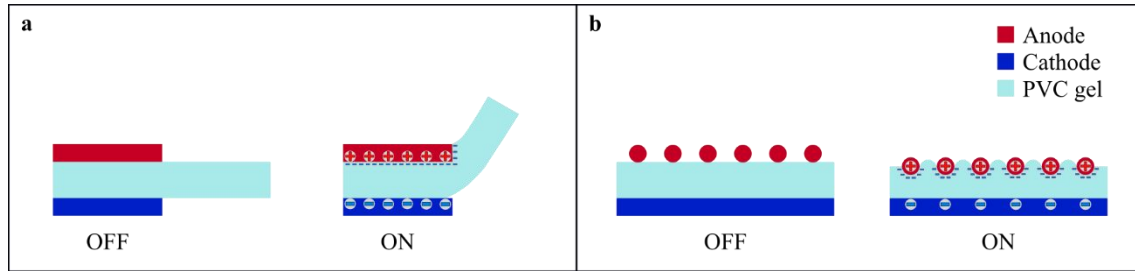
Figure 2. Traditional embodiments of PVC gel actuators. (**a**) shows a bending actuator, while (**b**) shows a contracting actuator, whose anode is a steel mesh.

The PVC gel phenomena has been investigated in detail[6–10], and has allowed for various complete multilayer actuators[2], wearable variable-stiffness spats[11] and a wearable robotic walking assist device for locomotion assistance[12]. The study of soft robotic devices which are entirely made of soft materials has been an area of considerable interest recently[13]. However, so far, PVC gel actuators have always used rigid metal electrodes, preventing the development of a completely soft PVC gel actuator.

In this article, we present a new conceptual design for PVC gel actuators. In our design, the microstructure previously provided by the mesh is instead embodied on the PVC gel itself (Fig. 3). This allows the anode to be made from any planar conductive material and presents the possibility of both electrodes and electroactive gel having extremely low compliance allowing for totally soft PVC gel devices.
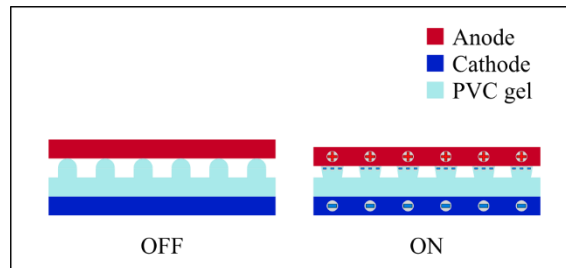

Figure 3. Proposed design for microstructured PVC gels. In contrast to the traditional embodiment whereby the microstructure is provided by the anode, we pattern the surface of the PVC gel itself. As such, the anode can be made from any planar conducting material.

2. METHODOLOGY

Our method of manufacturing PVC gels is similar to the typical method[5], however we additionally use an aluminium mould which acts as a negative for the microstructure of the PVC gel surface (Fig. 4). First a known quantity of plasticiser (dibutyl adipate (DBA), 309494, Sigma-Aldrich, USA) is mixed with powdered PVC (81388, Sigma-Aldrich, USA) resulting in a plasticiser–PVC mixture. In the experiments described in this article, the ratio of PVC to DBA was 1:4. This mixture is dissolved in a solvent (Tetrahydrofuran (THF), 186562, Sigma-Aldrich, USA) while stirring for 1 minute. The resultant solution is poured into a Teflon evaporating dish containing a mould patterned with the inverse of the desired microstructure. The solution is then left to evaporate under a fume cupboard for several days. Once the THF has evaporated, a solid gel remains, which may be removed from the evaporating dish and trimmed.
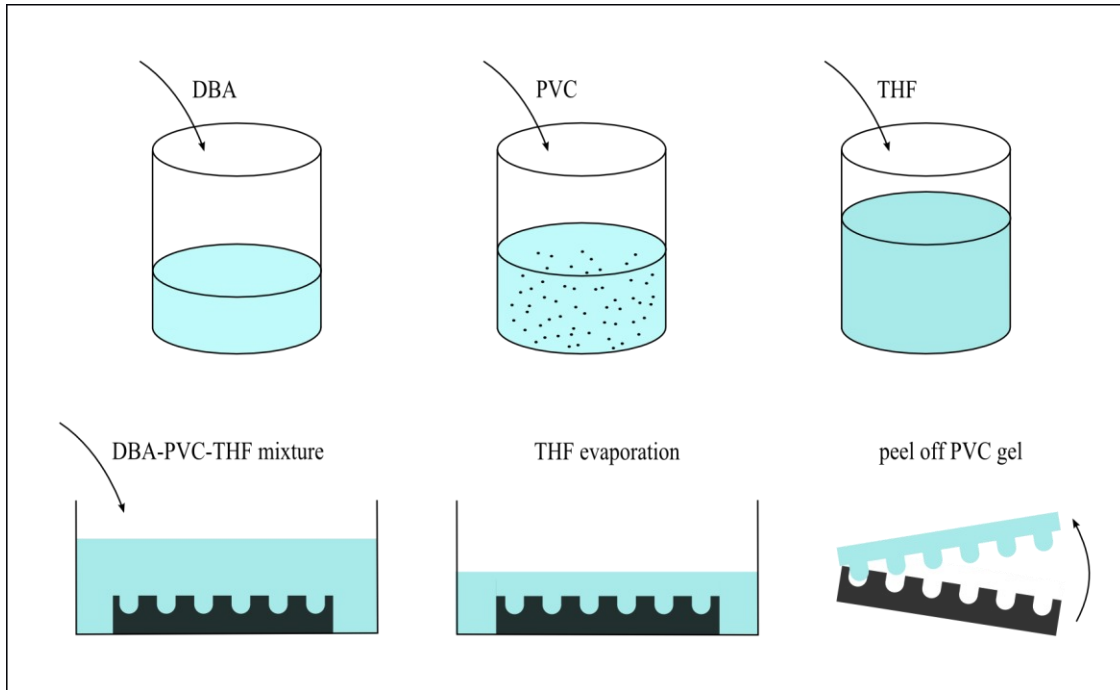
Figure 4. Fabrication method of microstructured PVC gels. PVC and DBA are mixed, before being dissolved in THF. After stirring for one minute to ensure the mixture is fully dissolved, it is poured into an evaporating dish containing a mould patterned with the negative of the desired microstructure. Once the THF has evaporated after several days, the microstructured PVC gel may be removed from the mould.
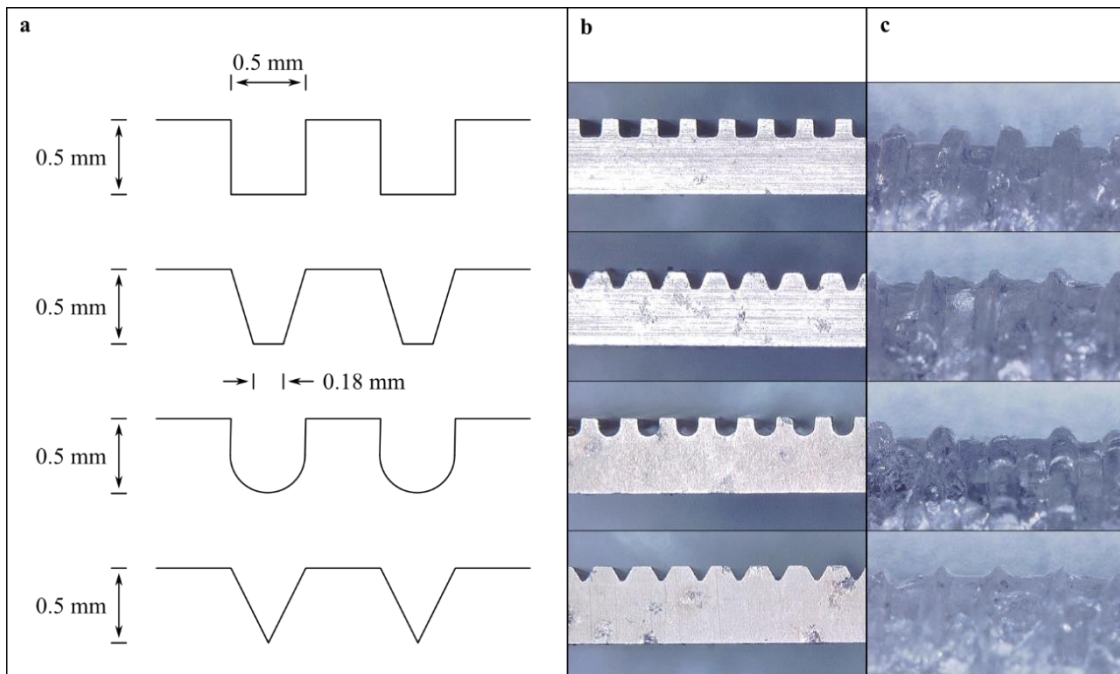
Figure 5. Moulds designs, moulds, and resultant microstructures of PVC gels. (**a**) shows mould designs; a characteristic length of 0.5 mm was used throughout, for the microstructure height, width and spacing. (**b**) shows the moulds themselves, which were made out of aluminium using electrical discharge machining. (**c**) shows the resultant microstructures of the PVC gels.

Four moulds were manufactured using electrical discharge machining (EDM) from aluminium (Fig. 5). To investigate the effect of microstructure upon performance, we varied the nature of the microstructure between moulds. The four microstructures studied were square (S), isosceles trapezium (T), U-shaped (U) and V-shaped (V). In all cases the microstructure characteristic length was 500 μm. Photographs of the resultant PVC gel microstructures are shown in Fig. 5c. The resultant gels had a total height (including microstructure) of 1.2 mm.

During testing (Fig. 6), a PVC gel sample was placed on a planar copper tape cathode, with the microstructure surface facing upwards. A disc-shaped, 20 mm diameter, 1 mm thick copper anode (mass 2.5 g) was placed on top of the sample. The displacement of the anode was measured using a laser displacement meter (LK-G152, Keyence, Japan). A high voltage was applied between the two electrodes using a high voltage amplifier (UltraVolt 5HVA24-BP1, Advanced Energy Industries, Inc., USA) which had a maximum output voltage of 5 kV and current 200 μA. The high voltage amplifier also had output monitor voltages to enable recording of applied voltage and delivered current.
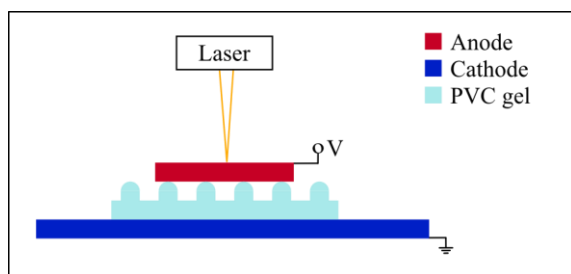
Figure 6**. Test protocol for testing PVC gels.** The gels were laid upon a copper tape cathode, and a disc-shaped copper anode were placed on top. A laser displacement meter recorded the displacement of the anode when a voltage was applied between the electrodes.

To confirm that resultant displacement was caused by the anodophilic behaviour rather than simply Maxwell pressure, we also tested each sample with the polarity of the electrodes was reversed. During these tests, the gel microstructure was adjacent to a cathode rather an anode, implying no anodophilic creep at the microstructure surface.

In an additional round of testing, we tested a flat (not microstructured) 1.2 mm thick sample of PVC gel with a steel mesh anode like those used in traditional PVC gel actuator assemblies. A mesh with a pore size of 500 μm was chosen to match the characteristic length of the microstructures. The mesh thickness was also 500 μm.

Finally, we placed a microstructured sample of PVC gel on a flat cathode made from 0.2 mm thick conductive rubber (000 397 043, J-Flex, UK). On the gel, we placed a disc shaped, 20 mm diameter anode made from the same conductive rubber, resulting in a compete PVC gel actuator that was totally soft. The displacement of the anode was recorded as voltage was applied to the electrodes.

3. RESULTS

Figure 7 shows typical applied voltage, delivered current and resultant displacement during a test. Current is initially high but decays as the PVC gel exhibits anodophilic creep before reaching a constant leakage current. Displacement is initially rapid before settling at a constant value.

In the latter half of the test shown in Figure 1, a negative voltage (-1 kV) was applied implying the electrode adjacent to the microstructure was negatively charged. This resulted in a small displacement of around 6 μm. In this case the anode was adjacent to the non-microstructure side of the PVC gel, and anodophilic creep did not contribute to contraction. In contrast, when a positive voltage (1 kV) was applied, the electrode adjacent to the microstructure was positively charged. Anodophilic creep at the microstructure resulted in a considerably higher displacement of around 45 μm.
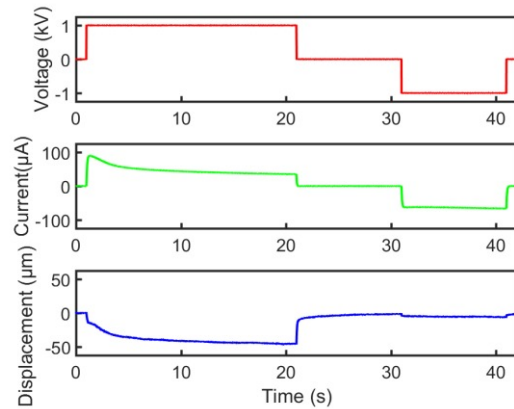
Figure 7. Voltage, current and displacement when 1 kV was applied to a square-microstructure PVC gel. When the electrode adjacent to the microstructure is positively charged, a large displacement occurs, driven by anodophillic creep at the microstructure surface. When the electrode adjacent to the microstructure is negatively charged, displacement is low, driven only by Maxwell pressure in the absence of anodophilic creep.

Figure 8 shows displacement variation with voltage for a flat (not microstructured) sample of PVC gel, with a 500 μm pore-sized steel mesh anode, as in traditional PVC gel actuator assemblies. Displacement increased with applied voltage, reaching a maximum average displacement of around 50 μm when 1 kV was applied.
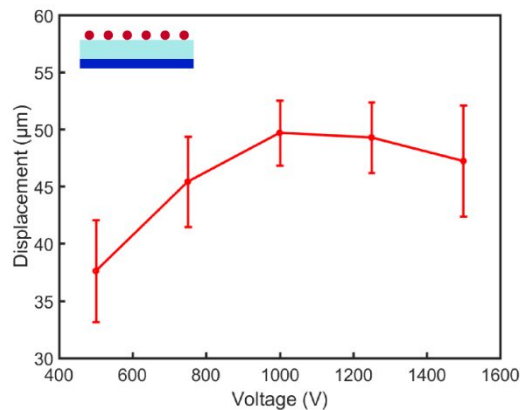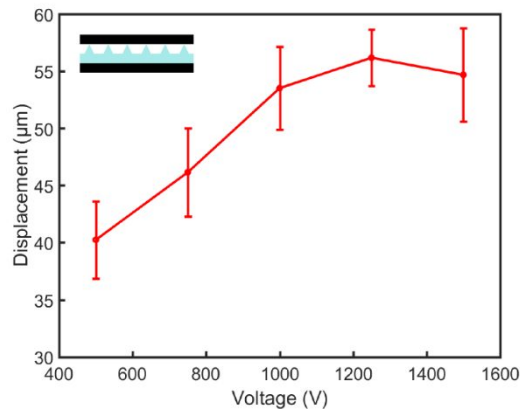

Figure 8. Displacement variation with voltage for a traditional PVC gel actuator. A flat (not microstructured) sample of PVC gel is sandwiched between a planar cathode and a steel mesh anode. Points are averages of four samples, and error bars show ± 1 standard deviation between samples.

Figure 9 shows displacement variation with voltage for microstructured PVC gels. Square-microstructure gels exhibited comparatively low displacements, reaching a maximum average displacement of around 44 μm when 1.25 kV was applied, lower than the traditional PVC gel actuator. Trapezium- and U-shaped-microstructure gels performed better than the traditional (mesh-based) actuator assembly, exhibiting maximum average displacements of around 109 μm at 1 kV and 92 μm at 0.75 kV respectively. V-shaped-microstructure gels performed considerably better than the traditional (mesh-based) actuator assembly, exhibiting a maximum average displacement of around 130 μm when 1 kV was applied. Given the microstructure is almost entirely responsible for the PVC gel's displacement (recall that displacement was negligible when the microstructure was adjacent to the cathode in Fig. 7), and the microstructure height was 500 μm, this represents a 26% controllable microstructure contraction.

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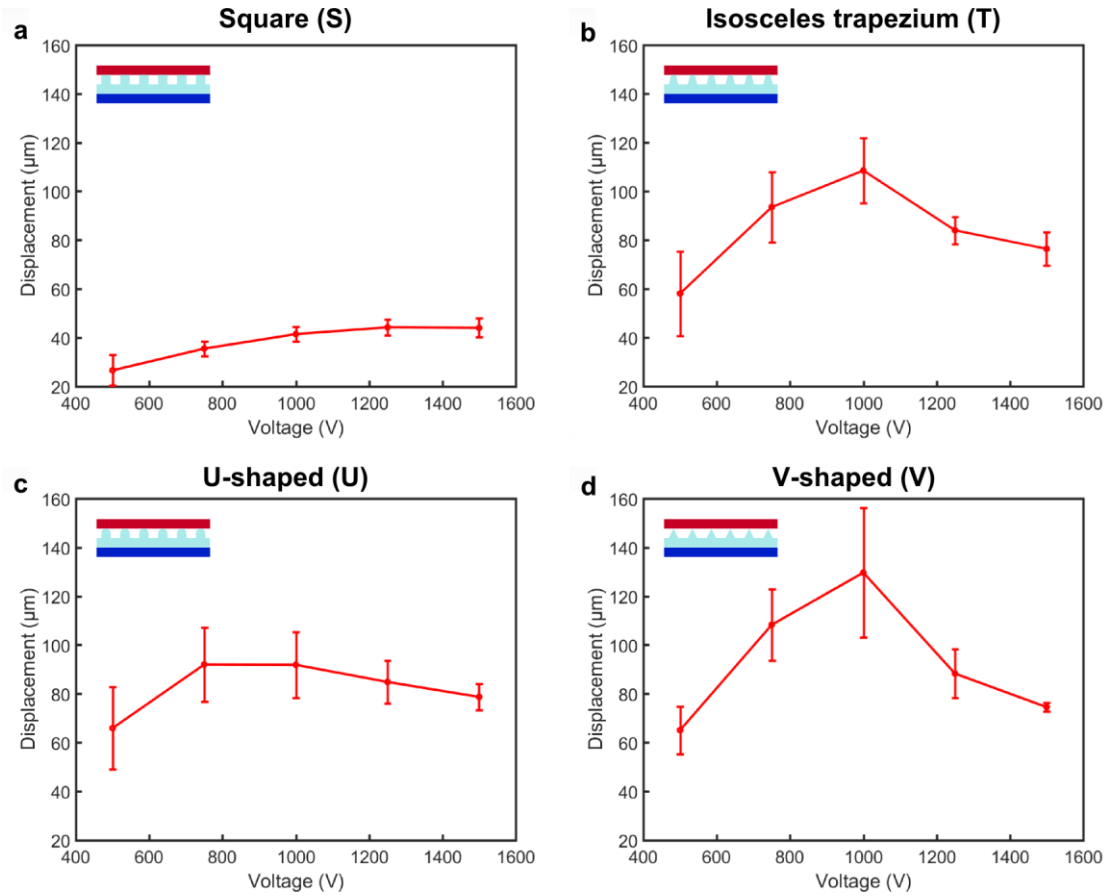
Figure 9. Displacement variation with voltage for a microstructured PVC gels. Points are averages of four samples, and error bars show ± 1 standard deviation between samples.

Figure 10. Displacement variation with voltage for the fully soft PVC gel actuator. Points are averages of four samples, and error bars show ± 1 standard deviation between samples.

Figure 10 shows results from the fully soft PVC gel actuator. We used the V-shaped-microstructure gel because it exhibited the highest displacement during characterisation experiments (Figure 9). Maximum average displacement was around 56

µm when 1.25 kV was applied, higher than that of the traditional mesh-based actuator but lower than during characterisation.

4. DISCUSSION AND CONCLUSION

We have presented a novel conceptual design for PVC gel actuators. By embodying the required microstructure on the PVC gel itself rather than on the electrode, we eliminated the requirement for the stiff steel mesh electrodes used in traditional PVC gel actuators. Square, isosceles trapezium, U-shaped and V-shaped cross-section parallel-channel microstructures were created on surface of the PVC gels. Isosceles trapezium, U-shaped and V-shaped microstructures exhibit higher displacements compared with a traditional mesh-based non-microstructured PVC gel actuator with a comparable mesh dimension, although it should be made clear that the gel patterns differed from the crossover patterns of a traditional mesh electrode.

For microstructure PVC gel actuators, when the polarity is reversed such that the microstructures were cathode- rather than anode-adjacent, displacement was negligible. This suggests that the microstructures were almost entirely responsible for the functionality and shortening of these contractile PVC gel actuators. Therefore, the thickness of entire gel can be optimized: the proportion of the gel that is not microstructure should be minimised, such that the degree of contraction as a percentage of total gel thickness is maximised. This should allow smaller, lighter, higher contraction and lower voltage (if applied field can be reduced) PVC gels, which will be the subject of future work.

We were also able to make a fully soft PVC gel actuator using a combination of microstructured PVC gel and conductive rubber. This delivers a considerable improvement for this actuation technology, providing a new subset of soft polymeric actuators in Soft Robotics, which can enable compliant features such as morphology adaptation, high stretchability and inherent safety for human-robot interaction. Removing rigid metals from polymeric structures can also reduce the likelihood of component failure associated with the long-term interaction between rigid components.

In the future, we plan to use this conceptual design to make entirely soft multilayer monolithic PVC gel actuators. These multilayer actuators will form a first-step towards complete artificial muscles powered by the microstructured-PVC-gel concept. We also plan to demonstrate how this novel soft actuator presents an opportunity for use in orthotics and wearables technologies.

ACKNOWLEDGEMENTS

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