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Study of the mechanism of embolism removal in xylem vessels by using microfluidic devices

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Supplementary Note 1. In spherical coordinate system, the water flowing around the bubble can be described by the Navier—Stokes equation in the form of flow function (Fig. 1e):

$$\left[\frac{\partial^2}{\partial r^2}+\frac{\sin\theta}{r^2}\times\frac{\partial}{\partial\theta}\left(\frac{1}{\sin\theta}\times\frac{\partial}{\partial\theta}\right)\right]^2\psi=0, \tag{1}$$

where r is the radial distance from the bubble centre, θ is the azimuth angle in spherical coordinate system, and ψ is the flow function.

The velocity of water around the bubble can be described as:

$$v_\theta=\frac{1}{2}U\sin\theta, \tag{2}$$

where U is the initial flow velocity.

The continuity equation for water flow in spherical coordinate system is:

$$\frac{1}{r\sin\theta}\times\left(\frac{\partial\ v_\theta\sin\theta}{\partial\theta}\right)=0. \tag{3}$$

At constant temperature and pressure, the concentration of air dissolved in water is $c(r,t)$, and the solubility of air in water is S_a. The equilibrium concentration of gas dissolved in water is c_0. Due to the small diffusion coefficient of air in flowing water, the concentration boundary layer is relatively thin comparing to the bubble volume. So, it is reasonable to consider that the velocity field is not affected by mass transfer from gas to liquid. The mass transfer process can be described by the advection-diffusion equation:

$$v_\theta\frac{\partial c}{\partial r}=D_{\mathrm{AB}}\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial c}{\partial r}\right), \tag{4}$$

where D_{AB} is the diffusion coefficient.

Combining the equation (2), (3), (4) and Fick's first law, t the average molar flux of gas across the bubble surface is given by:

$$N_{\mathrm{avg}}=\left(S_a-c_0\right)\sqrt{\frac{2D_{AB}U}{3\pi R}}, \tag{5}$$

where R is the equivalent radius of the air bubble.

For a stationary bubble boundary, the mass transferred from the bubble to the fluid per unit time is conserved:

$$\frac{dn_a}{dt} = c_a \frac{dV}{dt} = -N_{avg} S, \tag{6}$$

where n_a is the amount of substance of the bubble, c_a is the molar concentration of the gas in the bubble, V is the bubble volume and S is the gas-liquid interface area.

The concentration boundary condition on the bubble surface is described by Henry's law:

$$S_a = K_H P_a, \tag{8}$$

where K_H is the Henry's coefficient, P_a is the pressure of gas inside the bubble.

For an isothermal liquid at temperature T, the relationship between the pressure of gas in the bubble and its amount of substance can be described by the equation of state for ideal gas:

$$P_a V = \left(P_3 + \Delta P_w + \frac{2\sigma}{R} \right) V = n_a \Re T, \tag{9}$$

where P_3 is the pressure at the head of the bubble, $\Re$ denotes the universal gas constant and ΔP_w is the pressure difference between the head and tail of the bubble.

The pressure difference ΔP_w is affected by the structure parameters of pits and vessels, bubble radius and the pressure difference ΔP caused by the perforation plate:

$$\Delta P_w = 0.71 \rho_w \left(1 - \frac{d_2^2}{d_1^2} \right) \left(\frac{4Q}{\pi d_2^2} \right) + \rho_w K \frac{v_\theta^2}{2} + \Delta P, \tag{10}$$

where ρ_w is the density of water, d_1 and d_2 are diameters of vessel and pit, separately, Q is the water flow rate in the vessel and K is the local loss coefficient depend on the bubble radius and the geometric parameters of adjacent vessels.

Finally, we can achieve the change rate of bubble volume by solving equations from (7) to (10):

$$\frac{dV}{dt} = -\Re T S (K_H - \frac{c_0}{P_3 + \Delta P_w + \frac{2\sigma}{R}}) \sqrt{\frac{2 D_{AB} U}{3\pi R}}. \tag{11}$$

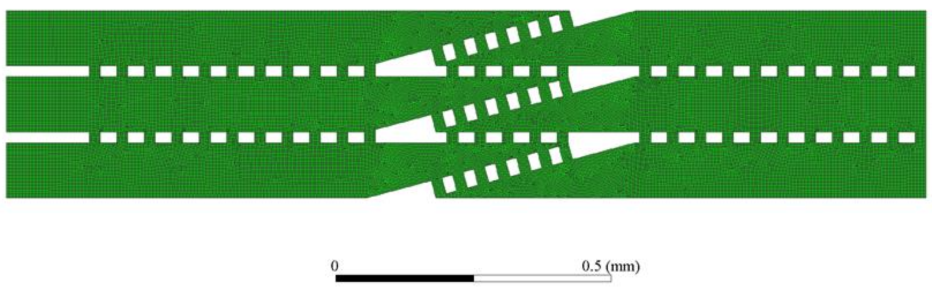

Fig. S1 The CFD model used to analyze the role that perforation plates play in the embolism repair process of xylem vessel.

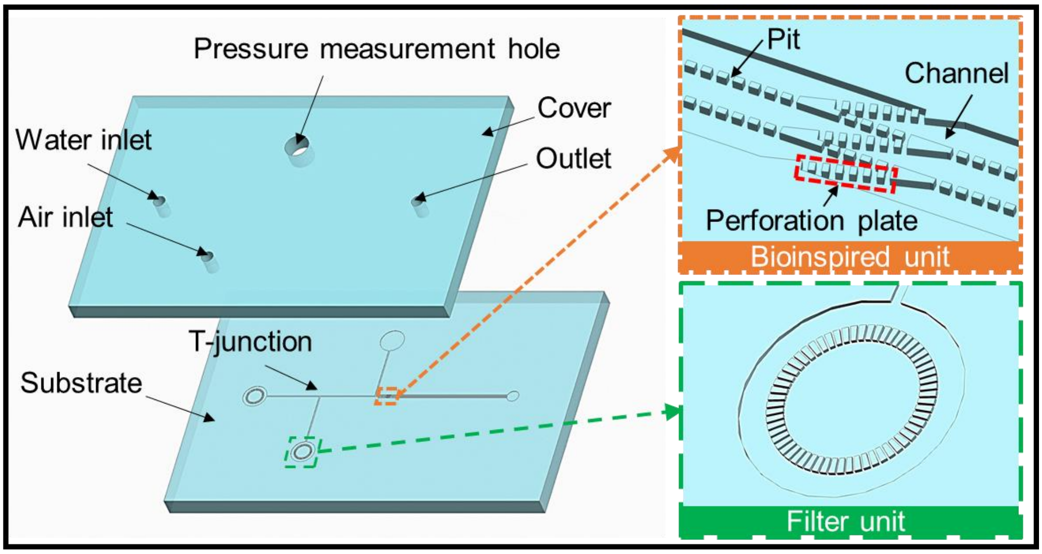

Fig. S2 Biomimetic devices used to carry out analysis to further verify the role that the perforation plates play in embolism removal of plants.

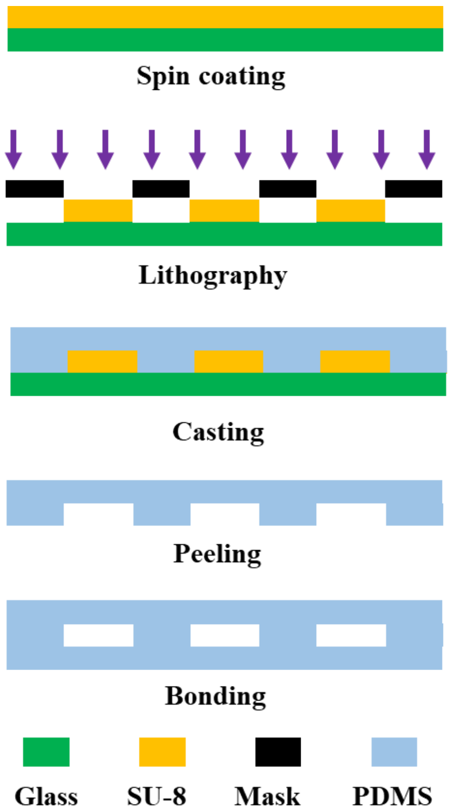

Fig. S3 The soft etching process of fabricating bionic devices.

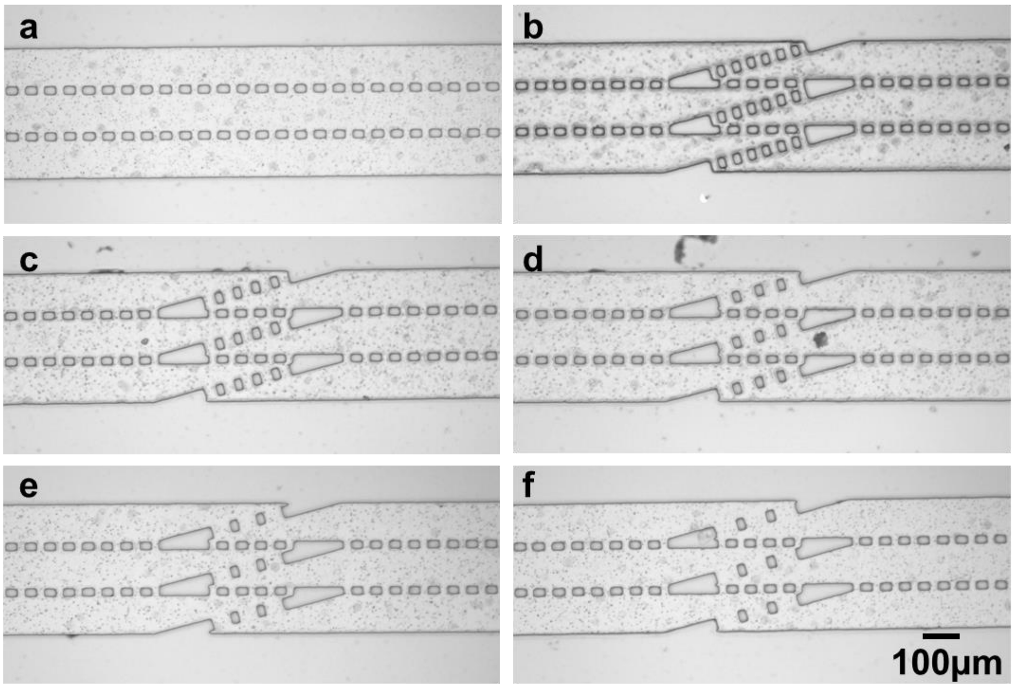

Fig. S4 The bionic device used for evaluating the role that the perforation plates play in embolism repair. a-f. Perforation plates with perforation widths from 20 μm to 60 μm.

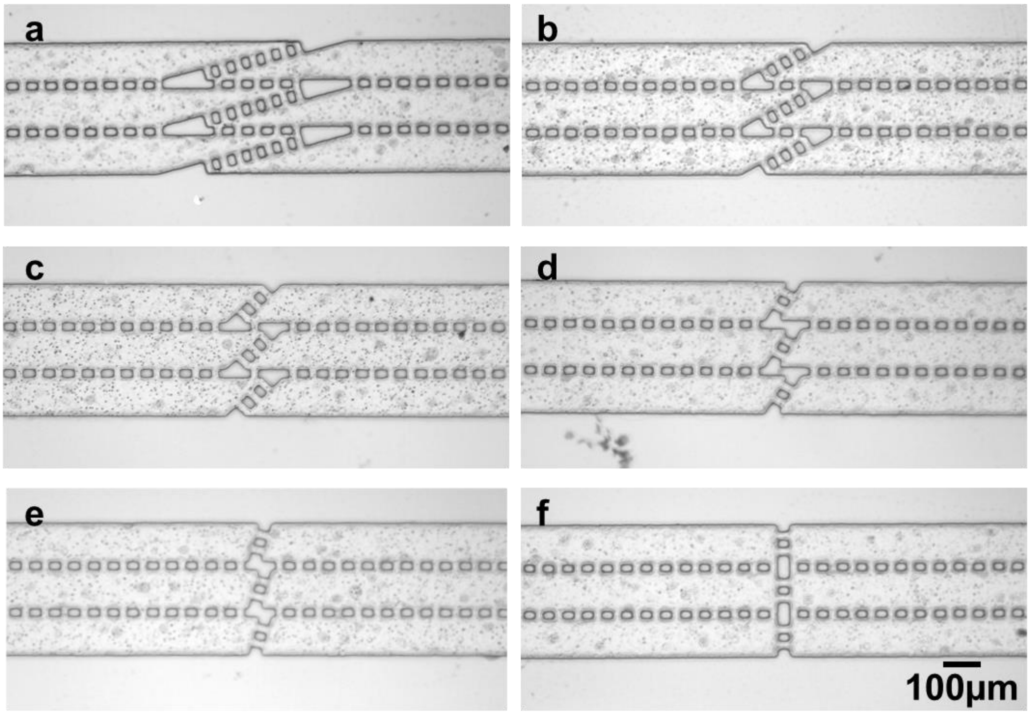

Fig. S5 The bionic device used for evaluating the role that the perforation plates play in embolism repair. a-f. Perforation plate angle from 15° to 90°.

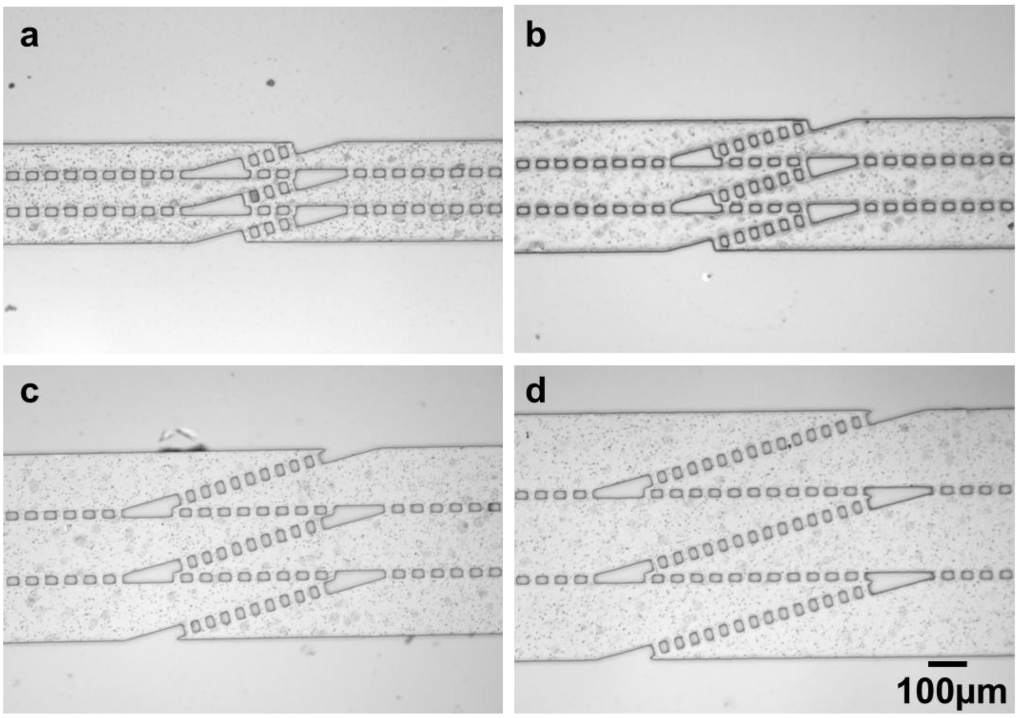

Fig. S6 The bionic device used for evaluating the role that the perforation plates play in embolism repair. a-f. Bionic devices with channel widths of 75 μm, 100 μm, 150 μm and 200 μm.