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FUNCTIONAL ASYMMETRY IN FLY'S WING VEINS AS PIPE NETWORK

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Abstract: *The wing veins of insects are blood-transporting pipes that form a network. The wing vein network of a Drosophila fly has asymmetry created by one vein named V14. The advantage of the asymmetry in the fly's wing veins was discussed via pipe network calculation, the Hardy-Cross method. Our numerical simulation revealed V14 influences blood flow in the veins on the posterior region of the wing, and it contributes to a decrease in the pressure difference between the inlet and outlet of the network required to flow the blood. This result suggests that the asymmetric wing vein network is a strategy for less energy consumption in pumping blood into the wing veins of the fly.*

Keywords: Fluid Mechanics; Insect; Wing Veins; Pipe Network; Blood Flow

INTRODUCTION

The wing veins on an insect wing are pipes to transport blood, so their network should be optimum as fluid conduits. Broadly known, the wing veins function as the framework of the wing; it provides toughness (Dirks & Taylor, 2012) and proper deformation during flight (Ennos, 1989) to the wing. Less broadly known, however, they transport blood. They are pipes containing living structures such as cells that require blood called hemolymph (Salcedo & Socha, 2020). Maintaining blood flow should need much pressure and consume much energy due to their small diameters relative to their lengths. An insect should deal with this problem, tweaking its vein network.

Topologically looked at, a wing vein network of a fly has asymmetry along one axis. The upper figure in Figure 1 is a simple illustration of the wing veins, the black or red lines, of the fly, *Drosophila melanogaster*. The red and blue circles, respectively captioned "IN" and "OUT", are the inlet and outlet of the network. White circles are nodes placed at the branches of the veins. Hemolymph enters the vein network at the anterior veins from the thorax and is withdrawn from the posterior veins by a pump in the thorax (Salcedo & Socha, 2020). With preserved connections or the nodes of the actual veins, this network could be expressed as the bottom figure in Figure 1 which shows a ladder-like structure. It is treated as a symmetric structure along the horizontal axis connecting the inlet and outlet. However, it is asymmetric along the vertical axis because of the presence of the red-colored wing vein numbered 14, V14.

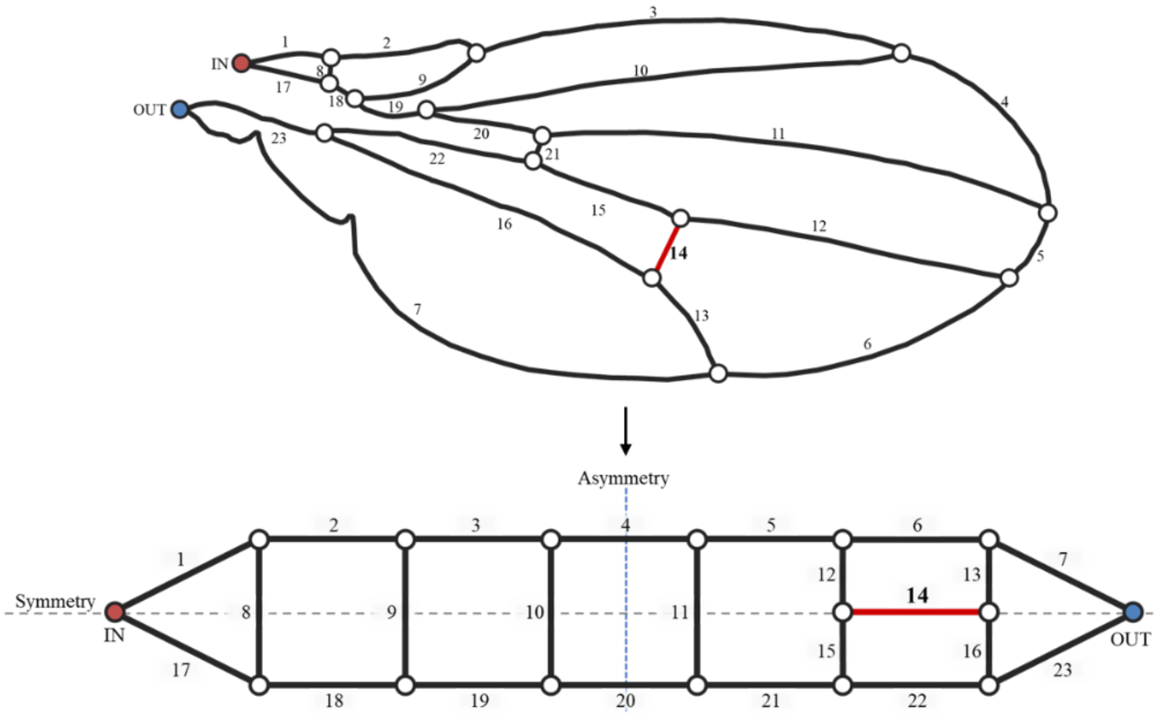

Figure 1 Topological simplification of the wing vein network of a fruit fly, Drosophila melanogaster. It is symmetric along an axis shown as the gray dashed line connecting the inlet and outlet but asymmetric along the other axis shown as the blue dashed line which is normal to the former one.

What does this asymmetry or V14 provide an insect wing? To discuss the advantage of the asymmetric network as blood conduits, the volume flow rates of blood and the required pressure difference between the inlet and outlet in both cases, the complete network, and the V14-lost network, were calculated by the Hardy-Cross method and compared.

RESEARCH

To know blood flow and the required pressure difference in the wing vein network and V14-lost network, a pipe network calculation was conducted. Based on the Darcy-Weisbach equation, the head difference, Δh, between a pipe in which fluid flows is expressed as follows: $\Delta h = 8\lambda LQ2/\pi 2gD5$ where λ is the friction coefficient, L is the length of the pipe, Q is the volume flow rate, g is the gravitational acceleration, and D is the diameter of the pipe; the head difference basically depends on the pipe's geometry and the flow rate of the fluid. The Hardy-Cross method is a technique to derive the volume flow rate in each pipe forming a network through the simultaneously established Darcy-Weisbach equations for all pipes in the network. Known volume flow rate introduces the head difference between both ends of a pipe which lets us know the total head difference between the inlet and outlet of the pipe network. The head difference can be converted to the pressure difference Δp: $\Delta p=\rho g\Delta h$ where ρ is the density of the fluid. This method was our strategy to calculate the volume flow rate of the blood and the pressure difference. It allows us to know them without observing blood flow in the complete network and the network with lost V14.

The parameters provided to this simulation were volume flow rates at the inlet and outlet, which were equal, the diameters of the wing veins, and the length of the wing veins. The inflow and outflow rate and the inlet and outlet refer to the observation of the inflow and outflow velocities of the wing of a mosquito, *Anopheles gambiae* (Chintapalli & Hillyer, 2016), a Dipteran insect as same as a fruit fly, and the geometries of the wing veins were measured via the image (Torquato, *et al*., 2014).

Figure 2 is the results of the pipe network calculation on the complete wing veins, the upper figure, and the wing veins without V14, the bottom figure. Each vein is colored based on the ratio of its blood flow rate Q to the inflow rate Q_{in}; the lightness and darkness of the vein color indicate the little blood flow rate and the much flow rate in that vein respectively. The white triangle on each vein means flow direction. In the complete wing veins, from a broad perspective, blood flows along veins near the base of the wing, the base veins (V17 to V23), and those along the wing edge, edge veins (V1toV7), and blood flowing in the edge veins joins that in the base veins through the veins connecting the base veins and the edge veins, the cross veins (V8 to V16). V14 in the complete wing veins seems to collect blood flow from V12 and V15 and distribute it to V13 and V16. It results in blood flow towards the edge vein in V13 and V15 which are different from the global trend among flow directions in other cross veins. The pressure difference to propel blood into the veins is 3.7×10^3 Pa.

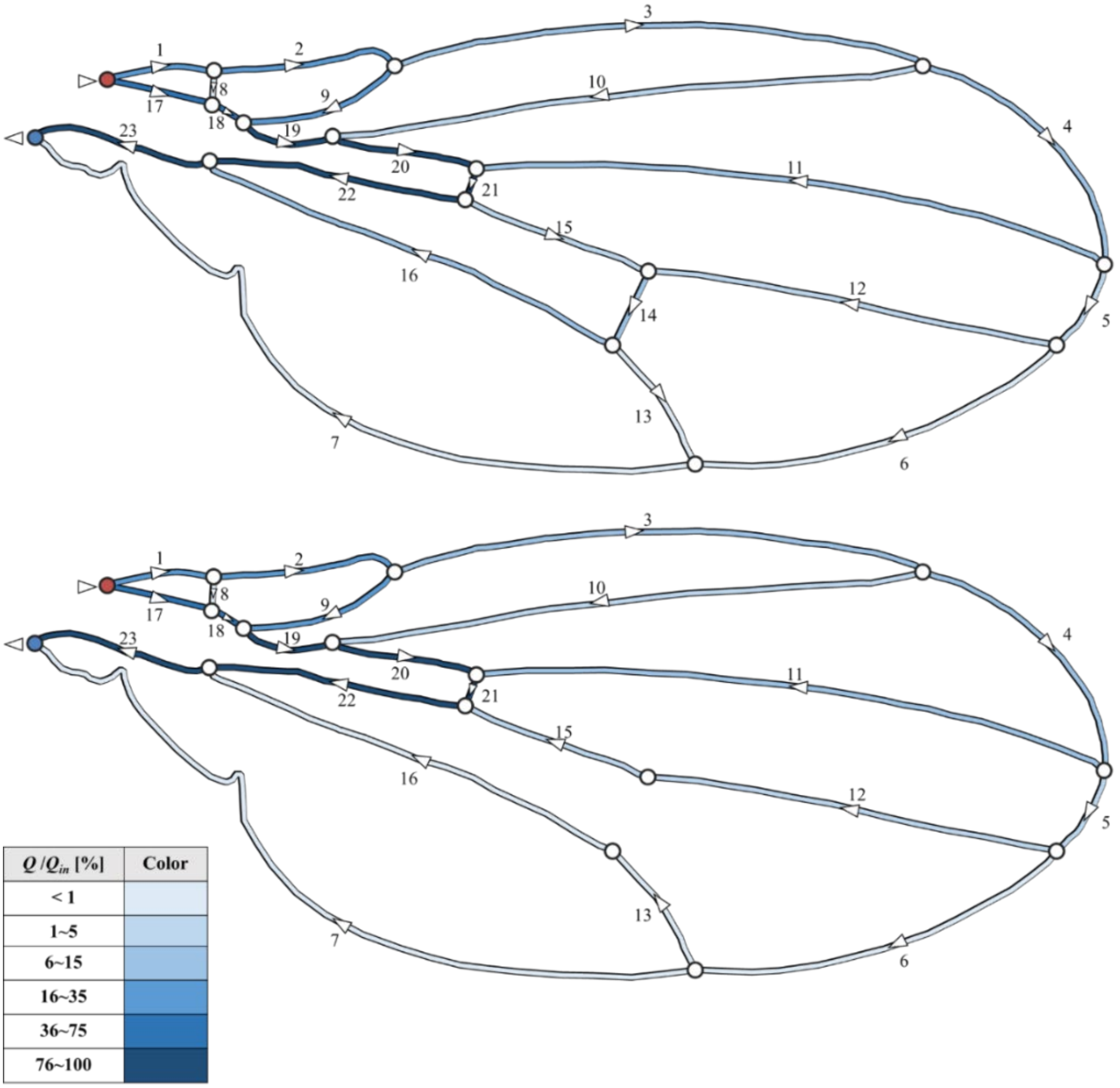

Figure 2 The result of pipe network calculation of the complete wing vein network (upper) and the wing vein network without V14. In a dark-coloured vein there is a large amount of blood flow, and a small amount is in a light-coloured vein.

The lack of V14 mainly influences blood flow in the posterior region and the required pressure. Flow directions in V13 and V15 towards the base veins as the same as the other cross veins; it is opposite to the complete vein network. Blood flow in the posterior region decreases. *Figure 3* shows the influence of the V14 absence on blood flow in the wing veins. The wing veins are colored based on the ratio of the amount of blood flow in the vein network without V14, Q_{-V14}, to that in the complete network, Q_o; dark ones have the larger blood flow rate and light ones have the smaller flow rate, compared to those in the complete network. It shows the decreased blood flow rate in the veins located on the posterior part (V7, V12, V15, and V16) although the flow rate in two veins in the same part (V6 and V13) increases. The total amount of blood flow in V6, V7, V12, V13, V15, and V16 decreases to 37% of the complete network. Since blood flow in the wing veins is thought to provide water to wing membranes not to be brittle (Salcedo & Socha, 2020), the presence of V14 may help distribute water to the membrane of the posterior part. The required pressure difference in the V14-lost vein network is calculated as 3.9 x 10^3 Pa; 5% higher than that of the complete network. V14 also contributes to decreasing the required energy to pump blood into the veins. Therefore, the asymmetry in the fly's wing due to the V14 existence would help water distribution to wing membranes in the posterior part and save energy consumption in sending blood into the wing vein network.

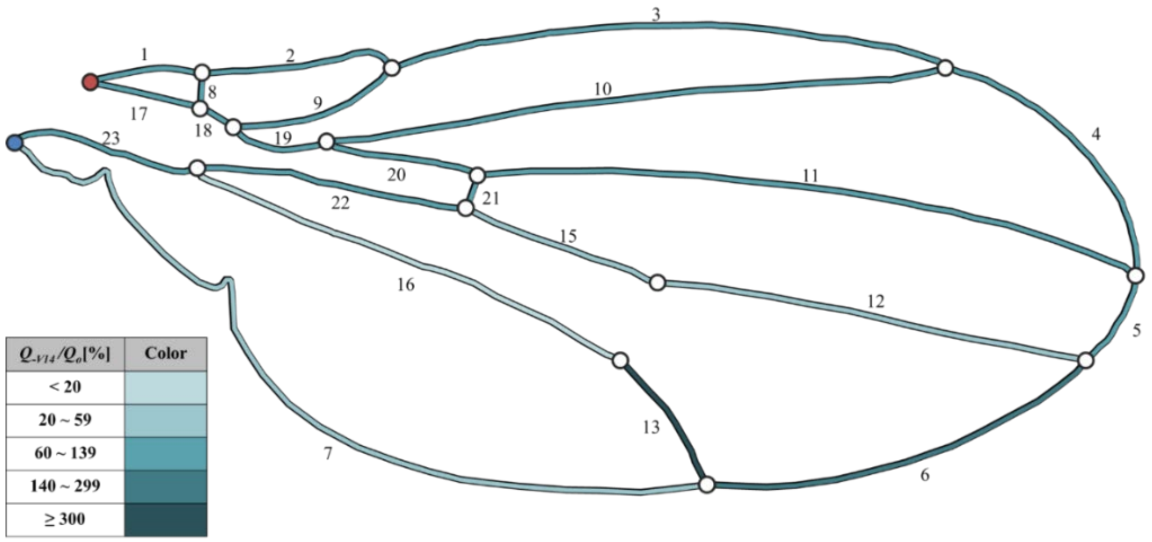

Figure 3 Influence of the V14 absence on blood flow in the wing veins.
It is shown whether V14 absence increases (dark) or decreases (light) blood flow in each wing vein.

CONCLUSION

The advantage of the asymmetry in the fly's wing veins was discussed based on the pipe network calculation. The existence of V14 alters the flow directions and blood flow rate in the veins on the posterior regions of the wing and decreases the pressure difference between the inlet and outlet of the network. The change in the flow rates might affect the water supply to the wing membrane. This result suggests that the asymmetric wing vein network contributes to less energy consumption in pumping blood and proper water supply to the wing membranes for their maintenance.

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Osamu MOCHIZUKI

Once upon a time, Osamu Mochizuki was a brave man. He rode a big motorcycle to explore different places and saved people from the devil. Since the day when the world became peaceful, he has been a professor in the fields of fluid engineering and biomimetics at Toyo University and is now an emeritus professor.