

Hemodynamic Effects of the Unique Network Topology of Hawaiian Flies' Wing Veins

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Abstract

Specific Hawaiian fruit flies exhibit a unique wing vein network featuring an extra crossvein (ECV), forming a cruciform network topology. Vein diameters were small for the wing size in these flies, feasibly reducing wing's mass but increasing hydraulic resistance and pressure loss during blood transportation. This study demonstrated our hypothesis that the ECV's presence mitigates these hemodynamic drawbacks. Leveraging circuit analogy of the vein networks, the flow rates and pressure losses in the wing veins were numerically derived based on Kirchhoff's and Poiseuille's laws. Our results showed a 3.1% decrease in total pressure loss due to the ECV's presence. This vein and its contiguous crossvein diverted blood from their topologically parallel veins, reducing pressure loss in those veins. The cruciform topology formed by these crossveins minimized bypassing blood path and total pressure loss. Our findings suggest that the ECV's presence may compensate for increased hydraulic resistance owing to constricted veins.

Keyword: *Wing veins, Circuit analogy, Pipe Networks, Blood circulation, Extra crossvein*

1. Introduction

The wing vein networks in insect wings transports hemolymph (insect blood) and supplies nutrients to the wings. Hemolymph flow is driven by a pulsatile organ located in the thorax [1]. Considering the Reynolds number of hemolymph flow on the order of 10^{-3} [1], as Hagen-Poiseuille flow, pressure loss in the veins is inversely proportional to the fourth power of the vein diameter and directly proportional to its length. Reducing pressure loss in the entire vein network can decrease the pressure requirement for the pulsatile organ. A previous study has shown that the topological structure of the wing vein networks, common to almost all fruit fly species, reduces frictional pressure loss within the network [2]. This suggests that the vein network morphology may be associated with the reduction in pressure loss and further energy consumption during hemolymph circulation.

A specific group of Hawaiian fruit flies, such as *Drosophila cyrtoloma* shown in Fig. 1, has an extra crossvein (ECV) in their wing vein network, differing its network topology from others found in most other typical species [3]. This group is also known for its large wing size [3]; for instance, the forewing of *D. cyrtoloma* is 2.9 times larger than that of the typical species in length dimension. However, the ratio of the vein diameters does not increase proportionally. This allometrically small vein diameter can reduce the hemolymph mass in the wing and the overall moment of inertia of the wing but increase hydraulic resistance and pressure loss across the vein network. In this study, a hypothesis that the network topology featuring the ECV mitigates the increased pressure loss was demonstrated, using numerical analysis to investigate hemodynamic effects of this unique vein's presence.

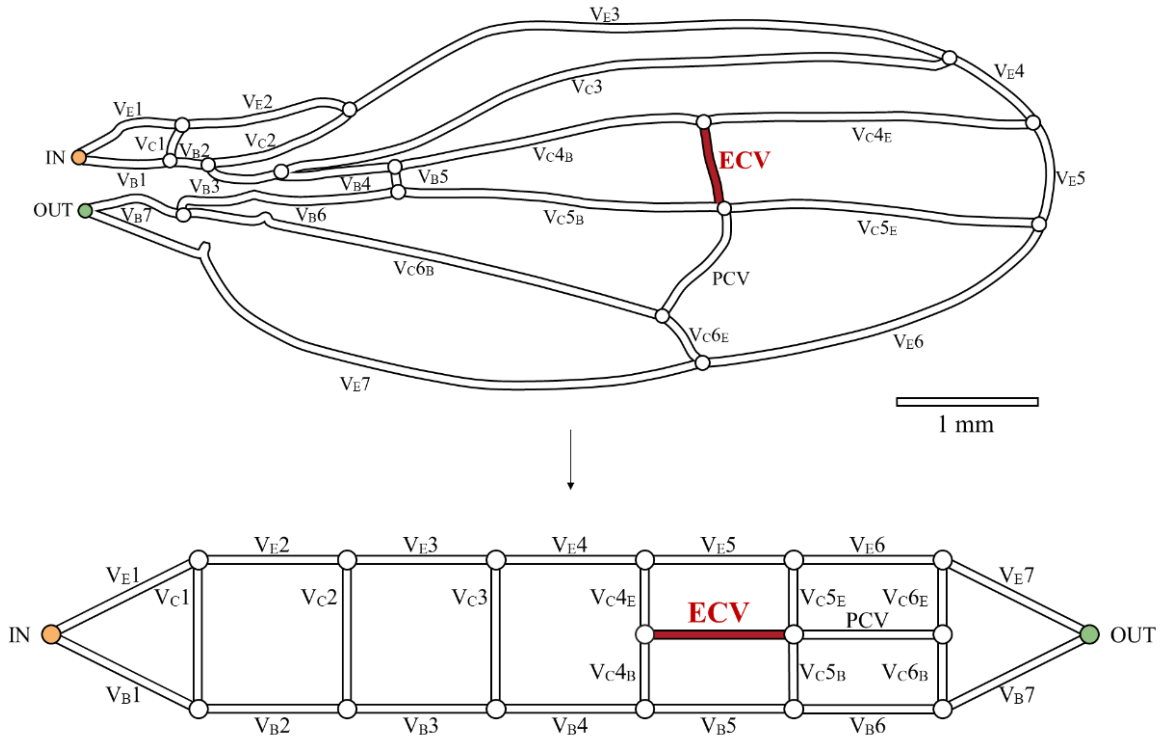


Fig. 1 Topological characterization of the Hawaiian fruit fly's wing

2. Analysis Method

The volumetric flow rate and pressure loss of hemolymph in each wing vein were analytically determined in the forewing of *D. cyrtoloma*. The veins along the wing's outer edge and base were respectively referred to as the edge veins (V_E) and base veins (V_B) shown in Fig. 1. The veins connecting these veins were termed connecting veins (V_C). The ECV and the posterior crossvein (PCV) bridge a respective pair of connecting veins and were adjacent to each other. The length (l_n) and diameter (d_n) of each vein were measured in an image from the literature [3] using ImageJ software. Hemolymph flow within the veins was modeled as Poiseuille flow because of low Reynolds number and hemolymph behaving as a Newtonian fluid [4]. The viscosity, μ , was set to 1.3×10^{-3} Pa·s [5], and the hemolymph inflow rate (Q_{in}) into the wing was set constant at 12 pl/s based on an allometric assumption from a previous report on typical fruit flies [2]. For each vein, a linear equation referring to Poiseuille law was established relating the unknown pressure loss (p_n) and flow rate (q_n) in steady state as follows:

$$\Delta p_n = \frac{128\mu l_n}{\pi d_n^4} q_n. \quad (1)$$

This equation corresponds to Ohm's law in electric circuits. Applying Kirchhoff's laws for electrical circuits to our vein network model, a linear matrix was generated from the simultaneously established equations and solved to determine hemolymph flow rates and pressure losses in all wing veins.

The effects of the ECV's presence on hemolymph flow were assessed by comparing results from the intact network model and a no ECV model. The positional effects of the ECV were also examined by parametrically shifting its connection points in a vein network model. To lessen the calculation complexity, the network model for connection shifting was geometrically simplified. These computational methods obviate the impractical physical manipulations of the wing veins in living insects, whereas observation-based experiments in traditional studies could not.

3. Results & Discussion

3.1 Changes in hemolymph flow rate and pressure loss owing to ECV's presence

Fig.2 shows the changes in hemolymph flow rate due to the ECV's presence from the absence of the ECV. In orange veins, flow rates increased, while they decreased in blue ones. Color intensity indicates the level of changes in flow rates in logarithmic scale. Triangles on the veins indicate flow direction, with red indicating a direction opposite to that in the ECV-absent model. A portion of the hemolymph flows into the ECV through the fourth connecting vein segments, bypassing the fifth base and edge veins in Fig.2. The flow rate within the ECV was $0.14Q_{in}$, which equaled the total decrease in flow rates in the bypassed veins. The PCV, supplied by the ECV and fifth connecting vein, showed a 30% increase in flow rate, while the flow rates in the sixth base and edge veins decreased. The total pressure loss between the inlet and outlet decreased by 3.1% in the network model with the ECV compared to that without ECV.

The ECV and PCV are topologically parallel to the fifth and sixth pairs of the edge and base veins, respectively as depicted in topological model in Fig.1. The total pressure loss equals the sum of pressure losses in the base or edge veins, with each local pressure loss proportional to the hemolymph flow rate (Equation 1). An increase in hemolymph flow rate through the crossveins corresponds to a decrease in flow rates through their parallel veins along base or edge which reduces their local pressure losses. This contributed to the reduction in total pressure loss within the entire vein network.

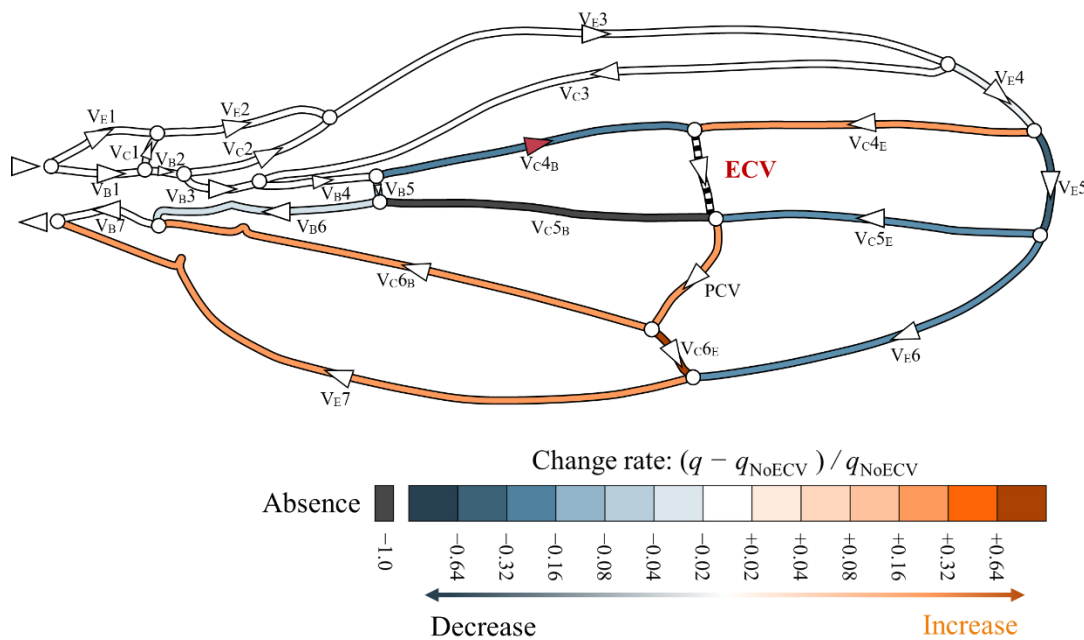


Fig. 2 Changes in blood flow rate due to the ECV's presence in comparison with the absence

3.2 Pressure loss variation with ECV's connecting positions

Fig.3 shows the total pressure loss corresponding to the varied ECV connection positions in the simplified vein network model. The vertical axis of the colormap represents the anterior connection point of the ECV, while the horizontal axis represents the posterior connection point. The red circle indicates the actual positions of the connections. The color intensity indicates the level of the total pressure loss corresponding to the connecting positions. The pressure loss tended to decrease as the anterior connection point was closer to the wingtip. Regardless of the anterior connection position, the minimum pressure loss occurred with the posterior connection at the actual position. This scenario is equivalent to the ECV being directly connected to the PCV. Hemolymph bypassing the base and edge veins flows from the ECV to PCV. When these crossveins are distant, an extra pressure loss, proportional to their distance, occurs between them. Directly connected, no extra pressure loss occurs because their distance is zero. Therefore, the ECV directly connected to the PCV minimizes the total pressure loss, forming cruciform network topology.

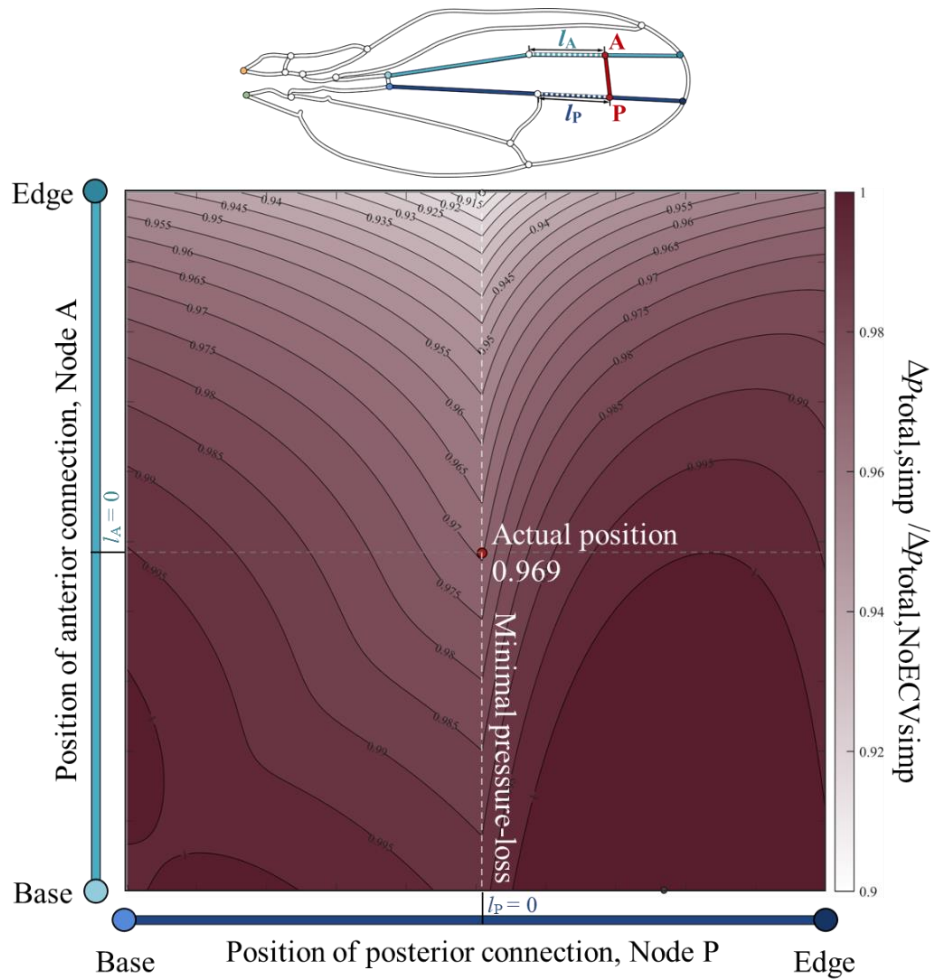


Fig. 3 Variation of the total pressure loss with the positions of the ECV's connections

4. Conclusion

The presence of the ECV in the forewings of specific Hawaiian fruit flies reduces the total pressure loss within the wing vein network by 3.1%. This reduction is due to an increase in hemolymph flow bypassing the base and edge veins and flowing through the ECV and PCV instead. The position of the ECV minimizes the distance and pressure loss between these crossveins directly connected with the PCV. The unique structure of the wing vein network found in the Hawaiian fruit flies may help hemolymph transportation within allometrically constricted wing veins.

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