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Liquid-intake flow around the tip of butterfly proboscis

Sang Joon Lee [a,b,*], Seung Chul Lee [a,b], Bo Heum Kim [b]

[a] *Department of Mechanical Engineering, Pohang University of Science and Technology, Pohang Gyeongbuk 790-784, Republic of Korea*
[b] *Center for Biofluid and Biomimic Research, Pohang University of Science and Technology, Pohang Gyeongbuk 790-784, Republic of Korea*

HIGHLIGHTS

- Flow around the tip of butterfly proboscis was analyzed during liquid feeding.
- A micro-PIV velocity field measurement technique was used to quantify flow fields.
- A theoretical model for the intake flow field of a butterfly was established.
- This result helps understanding the liquid-feeding behavior of a butterfly.

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ABSTRACT

Butterflies drink liquid through a slender proboscis using a large pressure gradient induced by the systaltic operation of a muscular pump inside their head. Although the proboscis is a naturally well-designed coiled micro conduit for liquid uptake and deployment, it has been regarded as a simple straw connected to the muscular pump. There are few studies on the transport of liquid food in the proboscis of a liquid-feeding butterfly. To understand the liquid-feeding mechanism in the proboscis of butterflies, the intake flow around the tip of the proboscis was investigated in detail. In this study, the intake flow was quantitatively visualized using a micro-PIV (particle image velocimetry) velocity field measurement technique. As a result, the liquid-feeding process consists of an intake phase, an ejection phase and a rest phase. When butterflies drink pooled liquid, the liquid is not sucked into the apical tip of the proboscis, but into the dorsal linkage aligned longitudinally along the proboscis. To analyze main characteristics of the intake flow around a butterfly proboscis, a theoretical model was established by assuming that liquid is sucked into a line sink whose suction rate linearly decreases proximally. In addition, the intake flow around the tip of a female mosquito's proboscis which has a distinct terminal opening was also visualized and modeled for comparison. The present results would be helpful to understand the liquid-feeding mechanism of a butterfly.

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1. Introduction

Butterflies suck nectar through a long proboscis using a large pressure gradient induced by the cyclic expansion and contraction of a muscular pump inside their head (Eastham and Eassa, 1955; Borrell, 2006). The proboscis is a deployable micro-conduit. The proboscis of a resting butterfly is coiled under the head. The proboscis is straightened when a butterfly detect liquid food.

In most previous studies, the liquid feeding of butterflies has been mainly investigated for the relation between nectar concentration and intake flow rate. The effects of nectar concentration on the feeding flow rate of butterflies have been experimentally investigated to find the optimal concentration that maximizes the energy intake rate (May, 1985; Pivnick and McNeil, 1985; Boggs, 1988; Hainsworth et al., 1991). In addition, the nectar-feeding phenomena in butterflies were numerically simulated based on the Hagen–Poiseuille equation for a steady, laminar flow in a pipe to find the optimal concentration of nectar (Pivnick and McNeil, 1985; Kim et al., 2011). In these studies, the proboscis was regarded as a simple straight pipe, even though it has complicated morphological structures.

The morphological structure of the mouthparts including proboscis was studied in detail by Eastham and Eassa (1955). The proboscis consists of two maxillary galeae joined ventrally by toothed hooks and dorsally by overlapping plates. Food canal is formed between the two maxillary galeae. The proboscis has no distinct terminal opening, but numerous intake slits through

* Corresponding author at: Department of Mechanical Engineering, Pohang University of Science and Technology, San31, Hyojadong, Namgu, Pohang, Gyeongbuk 790-784, Republic of Korea. Tel.: +82 54 279 2169; fax: +82 54 279 3199.
E-mail address: sjlee@postech.ac.kr (S.J. Lee).

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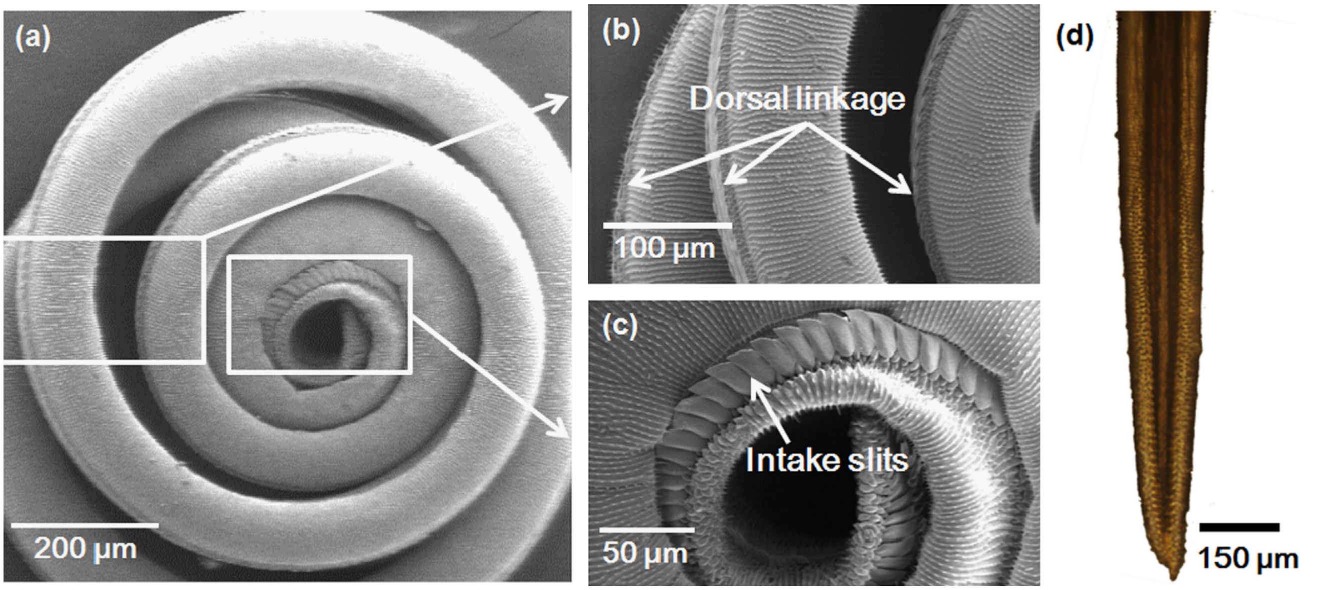

Fig. 1. (a)–(c) SEM images of a typical coiled proboscis of a butterfly, *Pieris rapae*. The dorsal linkage of the proboscis has a slit-like structure in the region near the tip. (d) Optical image of the tip region of a straightened proboscis of a butterfly.

which liquid enters into the food canal between the dorsal linkages in the tip region (Fig. 1). These intake slits take up about 5 to 20% of the total length of the proboscis. When the intake slit was observed using a scanning electron microscope (SEM), each intake slit was about a few micrometers in physical dimension (Krenn, 1998, 2010; Krenn and Kristensen, 2000; Monaenkova et al., 2012).

Recently, Monaenkova et al. (2012) observed the penetration of a small droplet into the food canal through the dorsal linkage of the proboscis using synchrotron X-ray imaging technique. The droplet was sucked by capillary force generated from the small intake slits of the dorsal linkage. This explains how butterflies drink nectar from porous substrates. However, when butterflies drink from a pool of liquid, the food canal is submerged in the liquid (Monaenkova et al., 2012). In this situation, the capillary force produced by the slit structure is only available at initial immersion, and liquid is mainly sucked by the systaltic operation of the cibarial pump. Therefore, the cyclic variation in the flow rate can occur during intake of pooled liquid, although the intake flow has been considered as a steady, laminar flow in previous studies (May, 1985; Pivnick and McNeil, 1985; Lee et al., 2009; Kim et al., 2011). However, the intake of pooled liquid through the slit structure has not been studied yet in detail.

Butterflies deploy their long coiled proboscis to intake pool of nectar in deep flowers. For stable and efficient flight, the long proboscis is tightly coiled and stowed under the head when it is not used for liquid feeding. However, the long and coiled shape of the proboscis can make it difficult to position the tip of the proboscis at a liquid target inherently (Borrell and Krenn, 2006). Butterflies may compensate for this disadvantage by developing the intake region instead of the apical opening. The dorsal linkage of a butterfly's proboscis forms elongated slits near the tip region for liquid intake (Fig. 1). This unique structure of dorsal linkage is also helpful for coiling and uncoiling mechanism of the proboscis (Eastham and Eassa, 1955). Therefore, the study on the intake process of pooled liquid through the dorsal linkage is essential to understand the liquid-feeding mechanism of butterflies.

The intake flow around the submerged proboscis of a butterfly was visualized using a micro particle image velocimetry (PIV) velocity field measurement technique. Flow images were consecutively recorded using a high-speed camera. The velocity vectors were extracted from two successive flow images using a cross-correlation PIV algorithm based on two-dimensional (2-D) fast Fourier transform (FFT). The velocity field distributions of the intake flow were divided into three distinct phases. The cyclic variations of the intake flow rate around the tip of the proboscis were analyzed to find out connections with the systaltic operation of the cibarial pump. The basic theory for a sink flow was adopted to establish the model expressing the intake flow around the proboscis tip of a butterfly. This modeling work was aimed at estimating the main features of the intake flow of a liquid feeding butterfly. In this study, a female mosquito was also tested as a comparative sample. A mosquito also drinks liquid using a proboscis and pump organs. The liquid-feeding mechanism of mosquitoes is similar to that of butterflies in terms of fluid mechanics (Lee et al., 2009; Kim and Bush, 2012). However, mosquitoes have a rigid food canal for liquid feeding. In addition, their proboscis has a distinct apical opening for liquid intake (Clements, 1992). Therefore, the comparison of the flow around the proboscis of a female mosquito with that of a butterfly would be important and interesting. For this comparison, the sink flow around the tip of a female mosquito's proboscis was analyzed under the same condition.

2. Materials and methods

2.1. Sample preparation

Butterflies (*Pieris rapae*) and mosquitoes (*Aedes togoi*) were reared and maintained in an air-conditioned room at 27 °C with 80% relative humidity under 16 h:8 h light:dark cycles. *P. rapae* pupae were purchased from a merchant in Goyang, South Korea and kept in a transparent plastic box. Most of the pupae became adult butterflies within 10 days. After emergence, the butterflies were transferred into a net cage and fed with artificial nectar using a 10% sucrose-soaked cotton rod. The adult butterflies at 4 to 7 days post-emergence were tested in this experiment.

The mosquito larvae were hatched in distilled water and fed with slurry of ground fish food and baker's yeast. After pupation, the mosquitoes were transferred into a cage made of a fine-mesh net. After emergence, they were also fed with artificial nectar.

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