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Towards microprocessor-based control of droplet parameters for endoscopic laryngeal adductor reflex triggering

Abstract: The so-called Laryngeal Adductor Reflex (LAR) protects the respiratory tract from particle intrusion by quickly approximating the vocal folds to close the free glottal space. An impaired LAR may be associated with an increased risk of aspiration and other adverse conditions. To evaluate the integrity of the LAR, we recently developed an endoscopic prototype for LAR triggering by shooting accelerated droplets onto a predefined laryngeal target region. We now modified the existing droplet-dispensing system to adapt the fluid system pressure as well as the valve opening time to user-chosen values autonomously. This has been accomplished using a microcontroller board connected to a pressure sensor and a mechatronic syringe pump. For performance validation, we designed a measurement setup capable of tracking the droplet along a vertical trajectory. In addition to the experimental setup, the influence of parameters such as system pressure and valve opening time on the micro-droplet formation is presented. Further development will enable the physician to adjust the droplet momentum by setting a single input value on the microcontroller-based setup, thus further increasing usability of the diagnostic device.

Keywords: dysphagia, aspiration pneumonia, larynx, vocal folds, Laryngeal Adductor Reflex (LAR), droplet-dispensing system, solenoid valve.

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1 Introduction

Dysphagia is a frequent complication, e.g. after a stroke, and may result in serious consequences such as life-threatening aspiration pneumonia. This dangerous condition is caused by aspiration of foreign particles due to a dysfunctional swallowing process. Correspondingly, pneumonia is among the top ten causes of death in the elderly in the United States (age > 65) [1]. In healthy individuals, several mechanisms prevent irruption of particles into the subglottic space, the trachea and deeper airways [2]. One key mechanism is the fast, reflexive closing of the vocal folds following appropriate stimulation of the glottal mucosa, known as the Laryngeal Adductor Reflex (LAR). The LAR is usually triggered by bolus particles, but can also be provoked artificially.

Table 1 summarizes known methods to trigger the closing motion of the vocal folds.

Since aberrations in the LAR may predict an increased risk for dysphagia or portend clinical phenotypes of chronic cough, vocal cord dysfunction or pediatric apnea, it appears to be mandatory to test the LAR reliably. In previous research at the Hannover Medical School (MHH), it has been shown that impacts of accelerated micro-droplets in various regions of the larynx can successfully trigger the LAR. A prototype of an endoscopic system containing a micro-droplet dispenser was designed and tested *in vivo* [3,4]. By opening a solenoid valve in the endoscopic prototype, the actual droplet shooting process was initiated. In terms of constructing a droplet-dispensing system, it is very important to prevent damage to the target region by limiting the kinetic energy of the drop to an atraumatic level. Thus, the muzzle energy of the droplets needs to be controllable. To investigate the LAR more in-depth and especially to evaluate reflex activation thresholds in different mucosal areas of the larynx, we present a new design for the droplet-dispensing system based on a mechatronic actor-sensor unit and describe first experimental performance evaluation results.

Table 1: LAR triggering procedures

Triggering method	Description
Stimulation by air blast (FEESST)	No optical control of target region, undefined stimulation force and duration [5]
Electrical stimulation of laryngeal mucosa	Mix of tactile and electrical stimulation [6]
Tactile stimulation with endoscope tip	Performed during fiberoptic endoscopic evaluation of swallowing [7]
Tactile stimulation by accelerated droplet	High spatial resolution, low risk for trauma [3]

2 Material and methods

In a first section, theoretical considerations concerning the balance of forces acting on a droplet in mid-air and implications for a possible velocity measurement method are presented. The second section deals with the selection and assembly of components necessary to obtain a semi-autonomous, microcontroller-based device capable of triggering the LAR by impact of a droplet on the laryngeal target region. Development and testing of a velocity measurement setup for performance validation of the reflex-triggering device is subject of the third section of this chapter.

2.1 Theoretical considerations

The movement of a droplet during flight in the direction of the Earth's gravitational force can be examined systematically based on a balance of external forces (see **Figure 1**).

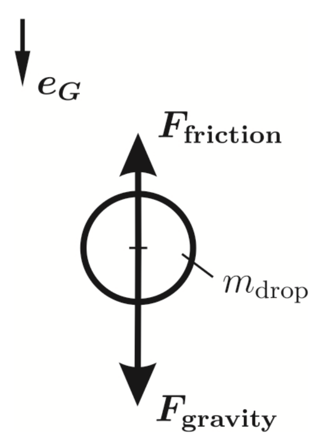

Figure 1: External forces acting on droplet in mid-air

According to Newton's second law, the acceleration vector $\ddot{\boldsymbol{y}}$ of a droplet moving in the direction of the vectorial acceleration of gravity can be obtained according to eq. **(1)**:

$$\ddot{\boldsymbol{y}} = \frac{1}{m_{drop}} \sum \boldsymbol{F}_{ext} = \frac{1}{m_{drop}} \left[\boldsymbol{F}_{gravity} - \boldsymbol{F}_{friction}\right] \quad (1)$$

with m_{drop} the drop mass, $\boldsymbol{F}_{gravity}$ the force of gravity acting on the drop and $\boldsymbol{F}_{friction}$ the force of friction due to the surrounding air resulting in a restricted final drop velocity. By numerical integration of eq. **(1)**, the initial droplet velocity $\boldsymbol{v_0} = \dot{\boldsymbol{y}}(t = 0)$ could be determined with high precision.

2.2 System design

Based on the experience gained beforehand using the manually adjusted droplet-shooting assembly [3,4], we identified the following core opportunities for system performance optimization:

- increase of user-friendliness through automatic and continuous adjustment of actual fluid pressure to pre-set level;
- overall diameter reduction of the endoscopic system by shifting the solenoid valve of the reflex-inducing part to a proximal position;
- display integration to provide system status information to the physician.

A miniature solenoid valve (INKX0514300AA, The Lee Company, Westbrook, USA) is the centerpiece of this newly developed droplet-shooting device. To allow for automatic pressure monitoring and adjustment, we combined a programmable syringe pump (NE-501, New Era Pump Systems Inc., Farmingdale, USA) and a relative pressure sensor (International Ind., Karachi, Pakistan) into an actor-sensor unit controlled by a microcontroller board (Arduino® Mega 2560, Arduino S.r.l., Scarmagno, Italy). The board continuously compares the pressure level given by the sensor to the user-chosen value and commands the syringe pump via its serial communication port to infuse or retract working fluid into or from the system as needed.

Due to the crystal oscillator integrated into the microcontroller, the valve opening time can also be adjusted in steps of 1 ms. The valve is connected to a Polytetrafluoroethylene tube (total length 30 cm, inner diameter 0.81 mm). Droplets are shot from the end of the tube by opening the valve restraining the pressurized fluid. Distilled water and a mixture of distilled water and Ammonia caramel coloring agent (INS no. 150c, Appel GmbH & Co.

KG, Cuxhaven, Germany) at a concentration of 1:10 v/v were used as working fluids. **Figure 2** gives an overview of the system layout including fluid and signal pathways.

The user input interface of the droplet-dispensing device is shown in **Figure 3**. The display in the upper left is regularly updated with the pressure value read by the relative pressure sensor connected to the microcontroller board.

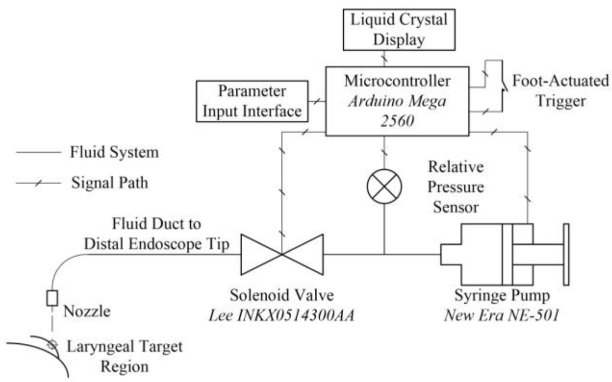

Figure 2: Schematic sketch of droplet-dispensing system

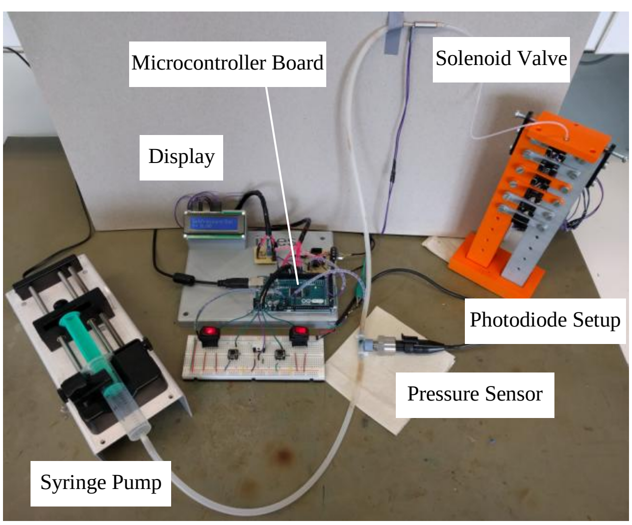

Figure 3: Droplet-dispensing system and measurement setup

2.3 Measurement setup

For experimental system performance validation, we designed an optoelectronic droplet velocity measurement device based on six photoelectric barriers (EE-SX1070, OMRON K. K., Kyoto, Japan) equidistantly aligned at distances of 20 mm using a 3D-printed mount. The first barrier is located near the tube outlet plane.

As a drop travels through the gap of each barrier, it occludes an infrared light beam. This leads to a voltage drop of the photodiode located at the other side of the U-shaped barrier. The temporal evolution of the diode voltages of all photo sensors is recorded simultaneously with an oscilloscope (MSO7034B, Agilent Technologies, Santa Clara, USA). This approach allows calculating average droplet velocities v_{av} between several positions along the vertical droplet trajectory according to eq. **(2)**:

$$v_{av} = \frac{\Delta y}{\Delta t} \quad (2)$$

where Δy is the distance covered by the drop between two light barriers and Δt the time of flight between those positions. **Figure 4** shows the measurement setup with the highlighted measuring section Δy = 100 mm. After identification of pressure and opening time values yielding stable formation of a single droplet per valve operation, we proceeded to experimentally determine the influence of those

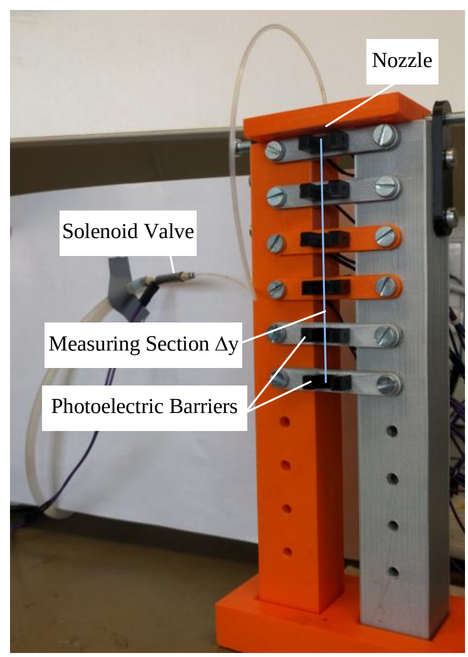

Figure 4: Optoelectronic droplet velocity measurement setup

parameters on average droplet flight velocity.

3 Results

In the first part of this section, we discuss our observations regarding the influence of fluid system relative pressure on the average droplet velocity along a vertical trajectory between two points that are 100 mm apart. The second subsection presents results concerning the impact of exemplary valve opening times on measured average droplet velocity levels.

3.1 Influence of fluid system pressure and working fluid properties

In **Figure 5**, the relationship between working fluid pressure and average droplet velocity for a constant valve opening time of 5 ms is displayed in a comparative boxplot. The influence of colorant addition has been evaluated for a concentration of 1:10 v/v of 150c Ammonia food colorant.

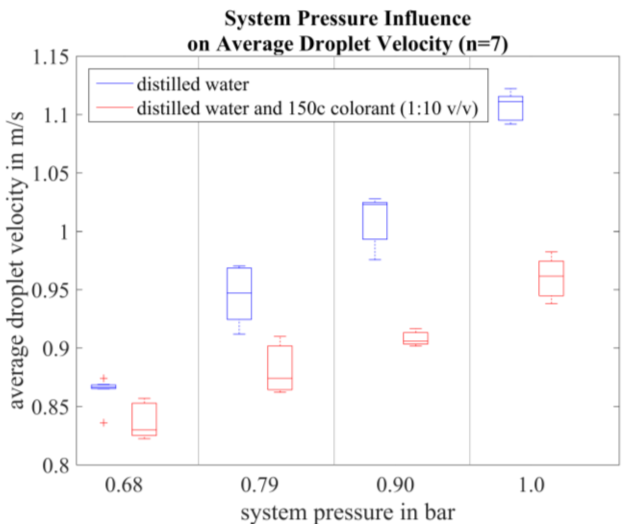

Figure 5: Influence of fluid system pressure and fluid properties on average droplet velocity

3.2 Influence of valve opening time

The impact of valve opening time variation is visualized in **Figure 6** for three exemplary values resulting in stable droplet formation with no observation of satellite droplets. System pressure was kept at a constant level of 0.79 bar. Distilled water with addition of 150c colorant (1:10 v/v) was used as working fluid.

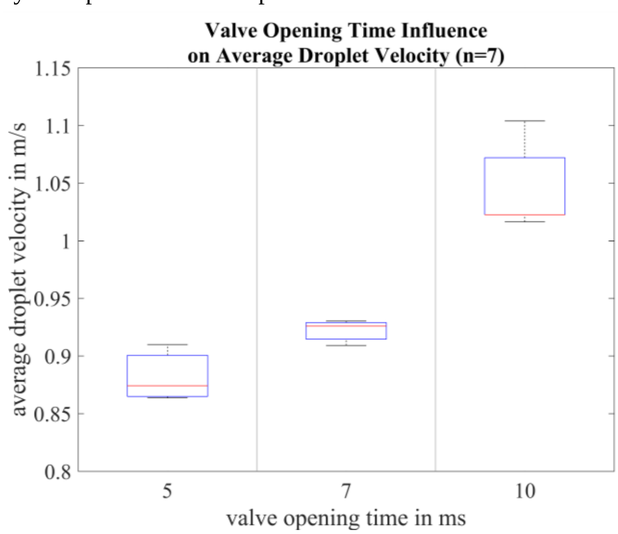

Figure 6: Influence of valve opening time on average droplet velocity

4 Conclusions and outlook

Our results indicate that the newly developed mechatronic system is capable of dispensing droplets at different average velocities by adjusting the fluid system pressure upstream of the microcontroller-operated valve. Valve opening time could be identified as a parameter influencing the average droplet velocity as well. Addition of a sugar-based colorant leads to lower average velocities, provided that all other parameters are left unchanged. This could be due to an increased fluid viscosity that results in higher internal friction and thus, dissipation of kinetic energy. **Figure 6** indicates that higher valve opening times yield higher average droplet velocities. However, the underlying cause has still to be identified. In further work, we plan to implement a parameter identification approach based on a model of the forces acting on the droplet during flight as depicted in **Figure 1**. By stepwise numerical integration of eq. **(1)**, the initial droplet velocity $\boldsymbol{v_0}$ will be determined with higher precision. This approach should also yield the droplet mass needed to calculate the kinetic droplet energy that has to be restrained to avoid mucosal injury.

Author's Statement

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