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Short communication

Increasing the reliability of solution exchanges by monitoring solenoid valve actuation

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ABSTRACT

Solenoid valves are a core component of most solution perfusion systems used in neuroscience research. As they open and close, they control the flow of solution through each perfusion line, thereby modulating the timing and sequence of chemical stimulation. The valves feature a ferromagnetic plunger that moves due to the magnetization of the solenoid and returns to its initial position with the aid of a spring. The delays between the time of voltage application or removal and the actual opening or closing of the valve are difficult to predict beforehand and have to be measured experimentally. Here we propose a simple method for monitoring whether and when the solenoid valve opens and closes. The proposed method detects the movement of the plunger as it generates a measurable signal on the solenoid that surrounds it. Using this plunger signal, we detected the opening and closing of diaphragm and pinch solenoid valves with a systematic error of less than 2 ms. After this systematic error is subtracted, the trial-to-trial error was below 0.2 ms.

1. Introduction

As neuroscience starts to tackle the complexity of dynamic responses in neuronal circuits (Langenkamp et al., 2000; Engel et al., 2001), there is a need for better kinetic information about chemical receptors (Cannon and D'Alessandro, 2006). One of the factors that determine the quality of the measured kinetic information is the precision of the timing of the chemical stimulations (Liu and Dilger, 1991; Moffatt and Hume, 2007). The effects of chemical compounds on biological preparations are commonly tested using solution perfusion systems. Solenoid valves are a key component of most solution perfusion systems as they are used to time the relevant solution exchanges. Kinetic studies increase their analysis power by increasing the amount of available information about the time course of the solution exchange (Dudel et al., 1988; Maconochie and Knight, 1989; Moffatt, 2007; Cannell and Nichols, 1991). Therefore, there is a strong interest in the ability to determine the delay between the application of the voltage to the valve and the time when the valve actually opens.

Two types of valves are used in perfusion systems: direct valves for fast switching and pinch valves that ensure internal valve parts will never come into contact with the solution. Both types feature three elements: (1) a solenoid coil, (2) a plunger that moves inside the coil and (3) an obstruction mechanism that is operated by the plunger. Solenoid valves are actuated by applying an electric potential across the coil. This potential induces an electric current that, in accordance with Ampere's Law, will generate a magnetic field; this field moves the ferromagnetic plunger from its resting position to its activated position inside the coil (Brauer, 2006). In normally closed valves, the movement of the plunger opens the passage of fluid whereas in normally open it closes it.

In some direct valves this movement triggers the opening of a diaphragm; on others, not analyzed here, the plunger commands a direct occluding mechanism. In normally closed (open) pinch valves, the activation of the plunger will release (constrict) the pinched elastic tube. Once the electric potential is removed, the plunger returns to its initial position with the aid of a spring.

Each of the steps contributes a certain delay before the valve opens (Brauer, 2006). First, the current does not increase instantaneously, but only after a delay equal to its inductive time constant. Second, the change in magnetic flux is delayed by the magnetic diffusion time. Third, the magnetic flux requires some time to accelerate the plunger. Finally, the valve mechanism takes time to act. Obstruction mechanisms have their own particular delay times. The amplification mechanism of the diaphragm has its characteristic time as well as the occluding mechanism of the pinched elastic tubing.

In this communication, we propose a simple method for monitoring whether and when the valves open and close based on measuring the plunger signal, which is generated by the motion of

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the ferromagnetic plunger, using a small resistance placed in series with the solenoid coil.

2. Materials and methods

We tested the normally closed tube of a 3-way solenoid pinch valve (coil Z036S, Sirai Elettromeccanica, Bussero, MI, Italy) and a normally closed, 2-way, solenoid diaphragm-based valve (LFAX0524100AB, The Lee Company, Westbrook, CT, US). Both tested valves are custom manufactured for ALA perfusion systems (ALA Scientific Instruments, Westbury, NY). In order to test whether each valve was open or closed, we set the valve to connect a pressurized nitrogen tank to a differential pressure sensor (ASCX30DN, Honeywell, Freeport, IL). The reduction valve of the nitrogen tank was set to 1 bar; the nitrogen escaped to the environment only through a 1.2-mm hole in the tube that connected the sensor to the valve. When the valve was open, the pressure as recorded by the sensor was only 0.15 bar, since most of the pressure drop occurs through the smaller diameter of the pinched elastic tubing and its connectors. When the valve was closed, the pressure recorded by the sensor equalized with atmospheric pressure over a time constant of about 1 ms. We estimated this time constant by dividing the dead volume between the valve and the sensor (0.3 mL) by the nominal gas flow rate at 1 bar (0.3 L/s), which was obtained from tubing flow charts by assuming that the main flow restriction measured 0.8 mm in internal diameter and was 30 mm long.

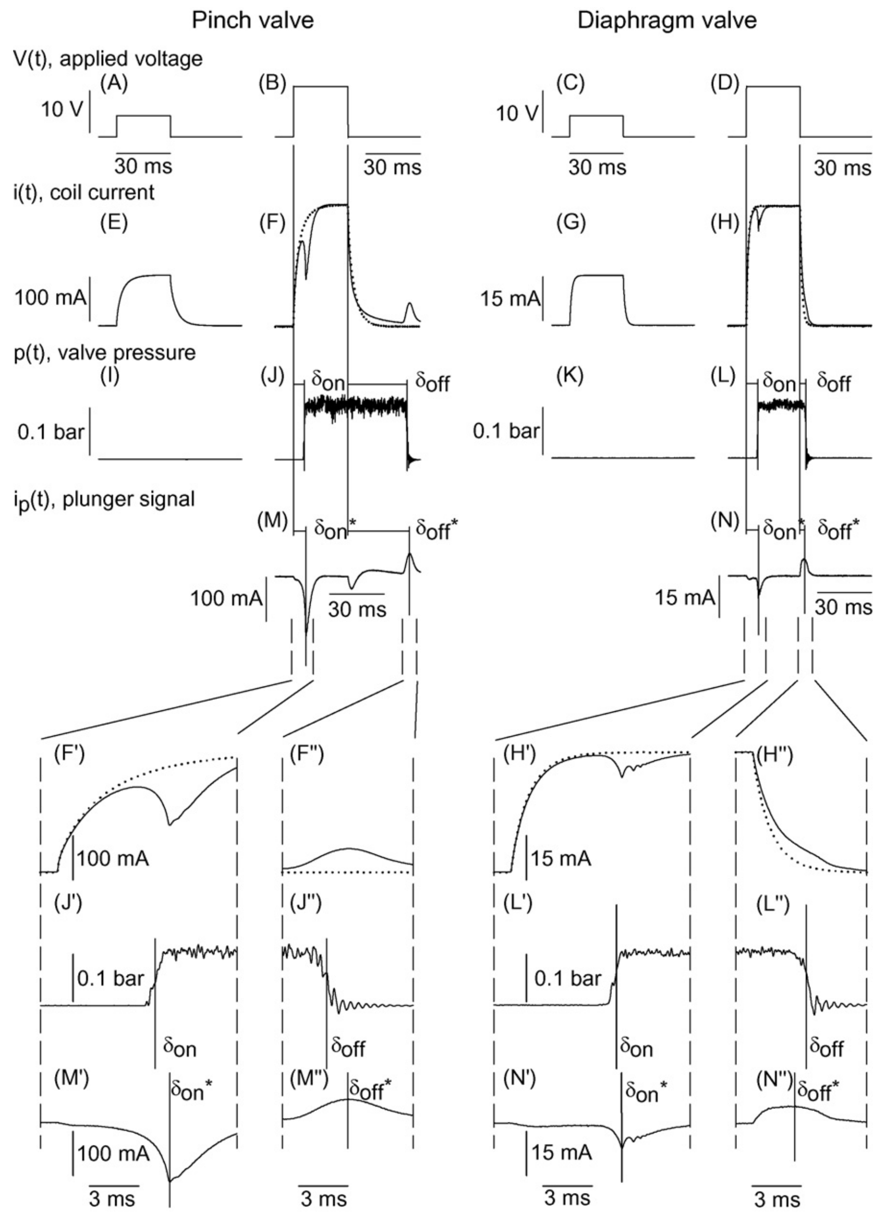

Fig. 1. Opening and closing (measured and estimated) delays associated with pinch and diaphragm solenoid valves. The measuring circuit of the solenoid coil for each valve is a series resistor: 1 Ω for the pinch valve and 6 Ω for the solenoid valve. (A)–(D) The voltage applied to the measuring circuit. (A) and (C) pulse of a sub-threshold voltage V_0. (B) and (D) Pulse of a supra-threshold voltage V_1. (E)–(H) Current flowing through the measuring resistor. (E) and (G) $i_0(t)$, for sub-threshold pulses, the measured current showed the time course expected for a regular RL circuit. (F) and (H) $i_1(t)$, for supra-threshold pulses, the measured current showed not only the time course expected for a regular RL circuit but also the current induced by the movement of the plunger. (I)–(L) Pressure recorded by a sensor downstream of the pinch valve. (I) and (K) no change in pressure: the valve failed to open. (J) and (L) the pressure increased to P_1 as the valve opened and decreased back to zero when it closed. δ_{on}: delay between the application of V_1 and the system reaching half of P_1. δ_{off}: delay between the removal of V_1 and the pressure subsiding back to half P_1. (M) and (N): $i_p(t)$, plunger motion signal calculated according to $i_p(t) = i_1(t) - V_1/V_0 \times i_0(t)$. δ^*_{on} : delay between the application of V_1 and $i_p(t)$ reaching its minimum value. δ^*_{off} : delay between the removal of V_1 and $i_p(t)$ reaching its maximum value. Vertical dashed lines represent the time of the expanded scales. (J′), (J′′), (L′), (L′′), (M′), (M′′), (N′) and (N′′)—$i_1(t)$, $p(t)$ and $i_p(t)$ at greatly expanded time scales at the beginning and end of the voltage pulses.

We used a NI PCI 6229 multifunction data acquisition card (National Instruments, Austin, TX) to synchronously drive the valve (we amplified the analog output signal 10 times using a 50 kHz bandwidth custom-made amplifier) and we measured both the output of the pressure sensor and the current that flows through the valve coil at 250 kHz. The signal was filtered at 10 kHz.

The circuit driving the solenoid valves consisted of a sense resistor (1 Ω for the pinch valve and 6 Ω for the diaphragm valve) in series with the solenoid coil (34 Ω for the pinch valve and 293 Ω for the diaphragm valve) and in parallel with a protective diode and a 47 V Zener diode.

3. Results

On Fig. 1, we show the response of a pinch and a solenoid valve to a sub- and a supra-threshold voltage pulse. When the sub-threshold step voltage was applied, no change in pressure was detected by the sensor (Fig. 1A, C, I and K). However, a significant current passed through the sense resistor zero of both valves (Fig. 1E and G). Its temporal course was consistent with the expected response of an RL circuit (a resistance in series with an inductance). Specifically, we observed the system to exponentially approach a steady-state current after the voltage step was applied and exponentially decay to zero when the voltage was removed (Brauer, 2006).

After a supra-threshold step voltage (12 V, the nominal working voltage) was applied to the pinch and the solenoid valves (Fig. 1B and D), the sensor recorded an increase in pressure (Fig. 1J and L), which indicated the times when the gas circulated through the open valve. There was a delay between the time when the voltage was applied and the time when the gas started to flow (δ_{on}), and between the time the voltage was removed and the time the gas flow ceased (δ_{off}).

In Table 1 we summarize the results of 100 repetitions of the experiment in Fig. 1 for two pinch valves and one diaphragm solenoid valve. When we look at the duration and variability of the closing delay, the performance of diaphragm valves clearly seems superior. For diaphragm valves, closing delays were even shorter than the opening delays and they differed between trials by less than 6%. However, for pinch valves, closing delays were 4–5 times longer than the opening delays. The variability of the delay in opening was 0.2–0.4 ms, and the variability of the delay associated with closing was 2–9 times greater. However, when we examine the opening delay and the rise and decay times, both valves showed similar performance

We found no changes in the closing delay with increasing duration of the voltage pulse while we did record changes in the opening and closing delays with applied voltage and air pressure (data not shown).

Table 1
Accuracy and sensitivity of the proposed method in the estimation of opening and closing delays. The table shows two pinch valve and one diaphragm-based valves. All measurements are in ms and given as mean ± S.D. Command voltage was 12 V for 30 ms; air pressure was 1 bar. Opening and closing delays (δ_{on} and δ_{off}) and estimated open and close delay (δ^*_{on} and δ^*_{off}) are defined in Fig. 1. Rise time and decay times refer to the time the pressure sensor took to go from 0.1 of P_{max} to 0.9 of P_{max} and the reverse.

	Pinch valve #1	Pinch valve #2	Diaphragm valve
δ_{on}	6.53 ± 0.19	6.51 ± 0.28	6.51 ± 0.35
δ^*_{on}	7.33 ± 0.14	7.33 ± 0.26	6.92 ± 0.37
$\delta^*_{on} - \delta_{on}$	0.8 ± 0.04	0.82 ± 0.03	0.41 ± 0.02
Rise time (10–90%)	1.31 ± 0.12	0.97 ± 0.12	0.76 ± 0.06
δ_{off}	30.38 ± 0.53	38.42 ± 2.41	3.27 ± 0.07
δ^*_{off}	31.39 ± 0.53	39.60 ± 2.42	2.51 ± 0.13
$\delta^*_{off} - \delta_{off}$	1.01 ± 0.04	1.18 ± 0.10	−0.74 ± 0.16
Decay time (90–10%)	0.84 ± 0.03	0.69 ± 0.15	0.75 ± 0.10

The aim of the present paper was to detect the plunger signal, namely the departures from the regular RL response as generated by the plunger movement. The plunger signal was quite evident from examining the uncorrected current consumed by the pinch valves (Fig. 1F), but this was not the case for the solenoid valves (Fig. 1H). Two departures are obvious in the case of the pinch valves: (1) a decrease in the current (Fig. 1F′) at the same time the increase in pressure due to the valve opening (Fig. 1J′) and 2) an increase in current (Fig. 1F″) at the same time the drop in pressure due to the valve closing (Fig. 1J″). By subtracting the appropriately normalized RL response (showed in dotted lines in Fig. 1F; equation in caption of Fig. 1), we obtain the plunger signal (Fig. 1M). The times when the plunger signal reached the minimum and maximum values reflects the time of maximal velocity for armature movement, which should be close to the time of opening or closing. Therefore, they were used to estimate the delays associated with opening and closing, respectively (δ^*_{on} and δ^*_{off}). Our estimates delays exhibited systematic errors (Table 1) in the 0.8–1.2 ms range. However, the variability of these errors was 10–20 times lower, in the 0.4–0.1 ms range. This variability was similar to the uncertainty in the opening delay but, if used for detection, the uncertainty on the closing delay can be 10–40 times lower (Table 1). The plunger signal shows a transient at the time the applied voltage is removed (Fig. 1M). This transient is related to an uncorrected change in the coil inductance, which in turn depends on the position of the plunger inside the coil (Brauer, 2006).

In the case of the solenoid valve, the plunger signal represented a smaller fraction of the coil current (Fig. 1H), consistent with the smaller plunger movement necessary to open the diaphragm. The signal generated by the return of the plunger to its resting position was obscured by the exponential decay in the current after the voltage had been removed (Fig. 1H). However, after the RL response (Fig. 1H, dotted line) was subtracted and the plunger signal was plotted (Fig. 1N), the negative and positive peaks of the opening and closing of the valve were apparent; we thus calculated estimates for the opening and closing delays (Table 1). These estimates exhibited systematic errors that were asymmetric: a positive 0.7 ms error for opening and a negative 0.7 ms error for closing (Table 1). When we look at an expanded time scale (Fig. 1L″ and N″), we see that the plunger signal starts to change some time before we start to see a change in the pressure that indicates a restriction in the air flow. It is likely that the plunger signal might be distorted by uncorrected changes in the coil inductance because of the position of the plunger and that the actual movement of the plunger occurs a little later. The variability of the systematic errors was low (less than 0.1 ms), but it was still greater than the near-undetectable variability associated with the actual delays. There were some differences in the tubing connection geometry of pinch and diaphragm valves that might be responsible for the differences found in the variability of the pressure signal.

4. Discussion

In this communication we propose a simple method for detecting solenoid valve openings and closings by measuring the plunger signal. With the plunger signal it is possible (1) to determine the absolute time of opening and closing with a systematic error in the 0.4–1.2 ms range and (2) to determine the relative changes in the time required for opening and closing over a series of successive trials with a random error in the 0.04–0.16 ms range.

4.1. Rationale to support the method

The motion of the ferromagnetic plunger of the solenoid valve causes a change in the electric potential of the solenoid coil that is proportional to the velocity of the plunger as described by Faraday's Law (Brauer, 2006). This change can be detected by placing a small resistance in series with the valve and measuring the resulting electric potential across it. After subtracting the inductive response of the coil (determined by measuring the response to a sub-threshold voltage application), we determined the response of the coil to the movement of the plunger, i.e., the plunger signal. Movements of the plunger towards the inside of the coil appeared as a transient decrease in the plunger signal and the opposite movement was evident as a transient increase. Similar changes in current were also evident after manually operating the plunger of the pinch valve while applying zero voltage potential to the coil (data not shown). Our proposed method uses the time when the plunger signal reaches the minimum and/or maximum values as proxies for the opening and closing times of the valve.

4.2. Pinch or diaphragm valves?

Pinch valves are widely used since their internal components do not come into contact with the tested solution. If there are concerns about possible contamination, it is easy to change the elastic tubing. Diaphragm valves, on the other hand, feature internal parts that necessarily come into contact with the solution; extra care has to be taken to avoid salt crystal accumulations or any kind of contamination. Diaphragm valves have the advantage that they feature a much shorter closing delay with much less trial-to-trial variability. Solenoid valves use a diaphragm amplification mechanism that is not present in pinch valves, which exhibit higher power consumption.

4.3. Applications where the plunger signal might be useful

Valves are a core component of perfusion solution systems and, as such, any improvements to their performance have the potential to be useful in many contexts, not all of them which requiring time resolutions on the millisecond scale. We consider three illustrative contexts where this plunger signal might be of interest.

The plunger signal can be used for failure detection. Pinch valves occasionally fail to open or to close, and these failures can be detected by the absence of a plunger signal. Failure detection is especially useful where failure of the preparation to respond to the signal might be expected—for instance, at threshold conditions.

Another application involves preventing the solution mixing that occurs after solution switching consistent with pinch valve operation. Pinch valves exhibit asymmetric delays for opening and closing: they open much faster than they can close. Therefore, if we simultaneously send the command to close one pinch valve and open another, solution will start flowing out of the opening valve before the other valve actually closes. Therefore, solution will flow from both valves for the time that the closing delay exceeds the opening delay (30–40 ms in the conditions we used). Whether the solution mixing is harmless, annoying or problematic would depend on the particular use case. This problem can be prevented either by using solenoid valves (that show almost symmetric delays) or by measuring the difference between the opening and closing delays using the plunger signal and taking that information into account when designing the test protocols.

A third context involves the use of pinch valves for ultrafast applications with excised patches (Maconochie and Knight, 1989; Liu and Dilger, 1991; Maconochie et al., 1994). It is for this particular application that our approach may be especially valuable. In such scenarios, two tubes are arranged at 20–50°, close to the patch pipette (Liu and Dilger, 1991; Maconochie and Knight, 1989). A single pinch valve is used to activate the flow at one tube while simultaneously deactivating the other. The plunger signal may be very useful to accelerate valve optimization. The time courses of applications are usually assessed by destroying the patch at the end of an experiment, without moving the pipette (Maconochie and Knight, 1989). Nevertheless, the exact timing of the solution switch during each trial varies with the intrinsic variability of the solenoid pinch valve time constants (0.5–2.4 ms for closing). By simultaneously recording the plunger signal, it should be possible to correct for this variability and consequently to decrease the uncertainty of the solution exchange timing by a factor greater than 10 (from 0.5–2.4 ms to 0.04–0.12 ms, in the case of valve closing), thus enhancing the temporal resolution of the kinetic analysis.

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