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Simulation Study on Flow Rate Accuracy of Infusion Pumps in Vibration Conditions During Emergency Patient Transport

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Abstract:	<p>Infusion pumps are frequently used when transferring critically ill patients via patient transport cart, ambulance, or helicopter. However, the performance of various infusion pumps under these circumstances has not been explored. The aim of this study was to evaluate the flow rate accuracy of infusion pumps under various clinical vibration conditions. Experiments were conducted with four different types of pumps, including two conventional syringe pumps (Injectomat MC Agilia, Fresenius Kabi and TE-331, Terumo), one conventional peristaltic pump (Volumed μVP7000; Arcomed), and one new cylinder pump (H-100, Meinntech). The flow rate was measured using an infusion pump analyzer on a stable table (0 m/s²) for 1 hour with 1 ml/h and 5 ml/h. Experiments were repeated in mild vibration (2 m/s²) (representing vibration of patients in a moving cart or ambulance), and in moderate vibration (6 m/s²) (representing vibration in helicopter transport). Any accidental bolus occurrence in extreme vibration situations was also analyzed. Simulated vibrations were reproduced by a custom-made vibration table. In the resting state without vibration and in mild vibration conditions, all pumps maintained good performance. However, in moderate vibration, flow rates in syringe pumps increased beyond their known error ranges, while flow rates in peristaltic pumps remained stable. In extreme vibration, accidental fluid bolus occurred in syringe pumps but not in peristaltic pumps. The newly developed cylinder pump maintained stable performance and was unaffected by external vibration environments.</p>	

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	Mark A. Lovich, Md, Phd St. Elizabeth's medical center mark.lovich@steward.org He is an expert who has published many papers on my research field(infusion pump).

1 **Simulation Study on Flow Rate Accuracy of Infusion Pumps in Vibration Conditions During Emergency**

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3 **Patient Transport**

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7 **Abbreviated Title:** Infusion pumps in Vibration Conditions

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1 **Abstract**

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3 Infusion pumps are frequently used when transferring critically ill patients via patient transport cart,
4 ambulance, or helicopter. However, the performance of various infusion pumps under these circumstances has
5 not been explored. The aim of this study was to evaluate the flow rate accuracy of infusion pumps under various
6 clinical vibration conditions. Experiments were conducted with four different types of pumps, including two
7 conventional syringe pumps (Injectomat MC Agilia, Fresenius Kabi and TE-331, Terumo), one conventional
8 peristaltic pump (Volumed μ VP7000; Arcomed), and one new cylinder pump (H-100, Meinntech). The flow rate
9 was measured using an infusion pump analyzer on a stable table (0 m/s^2) for 1 hour with 1 ml/h and 5 ml/h.
10 Experiments were repeated in mild vibration (2 m/s^2) (representing vibration of patients in a moving cart or
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13 custom-made vibration table. In the resting state without vibration and in mild vibration conditions, all pumps
14 maintained good performance. However, in moderate vibration, flow rates in syringe pumps increased beyond
15 their known error ranges, while flow rates in peristaltic pumps remained stable. In extreme vibration, accidental
16 fluid bolus occurred in syringe pumps but not in peristaltic pumps. The newly developed cylinder pump
17 maintained stable performance and was unaffected by external vibration environments.
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34 **Keywords**

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37 Flow rate accuracy, Vibration, Emergency transport, Infusion pump, Cylinder pump
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1 **Declarations**

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3 **Financial Disclosures**

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6
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9 Institute (KHIDI)'.
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13 **Conflicts of interest/Competing interests**

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15 The authors declare that they have no conflict of interest.
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19 **Research involving human participants and/or animals:** This work did not to include research involving
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21 human participants and/or animals.
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25 **Authors' contributions**

26
27 KYH, JHL, DKK and JJM conception and design of research; KYH and YYK performed experiments; KYH,
28
29 YYK, SYY and JJM analyzed data; KYH, SYY, JHL, DKK and JJM interpreted results; KYH, SYY and JJM
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31 prepared figures; KYH and JJM drafted manuscript; KYH, SYY, JHL, DKK and JJM edited and revised the
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33 manuscript; KYH, YYK, SYY, JHL, DKK and JJM approved final version of manuscript.
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41 Medical Center.
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45 **Abbreviations:** none
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4 **Introduction**

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6 Infusion pumps are not only used for in-hospital patients in beds but also during intra-, inter-, and out-
7 of-hospital emergency transport of patients in critical conditions[1, 2]. Emergency transport involves limited
8 medical resources in a confined space with vibrations and unexpected movements that may adversely affect the
9 quality of resuscitation and patient management [3, 4]. Dosing errors of vasoactive drugs with narrow safety
10 margins may lead to fatal hemodynamic responses in vulnerable patients [5], and stable performance of infusion
11 pumps is essential to deliver correct volumes and ensure patient safety.
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16 As technical advancements continue to develop, conventional infusion pumps with demonstrated good
17 performance are widely used in daily clinical practice [6]. However, flow rate accuracy can be affected by
18 several factors [7, 8]. The performance of infusion pumps under various vibration conditions that may occur
19 during emergency patient transport has not previously been evaluated. A cylinder pump that provides precise
20 fluid injection by rotating two pistons inside a donut-shaped dedicated cylinder cartridge has recently been
21 developed [9]. Theoretically, the cylinder pump will be less affected by surrounding environments [10].
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30 In this experimental study, we compare the performance of infusion pumps under simulated vibrations
31 that may occur during emergency patient transport using transfer carts, ambulances, or medical helicopters.
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1 **Methods**

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3 *Study design*

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5 This is an experimental bench study observing the performance of four different infusion pumps under
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7 simulated vibration conditions mimicking patient transport situations. Ethics approval was not required for this
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9 study.

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11 Possible vibration situations during in- and out-of-hospital patient transport, such as a moving cart,
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13 ambulance, or helicopter flight, were reproduced using a custom-made vibration table (DMVT-400, Dongmyung
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15 vibro, Korea). With reference to the previous literature, vibration during patient transport in a moving cart or
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17 ambulance was defined as mild vibration with an acceleration force of 2 m/s², and vibration during helicopter
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19 transport including both takeoff and landing was defined as moderate vibration with an acceleration force of 6
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21 m/s² [11-13]. Infusion flow rates delivered by four different infusion pumps were analyzed in various vibration
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23 settings of resting state (0 m/s²), mild vibration (2 m/s²), moderate vibration (6 m/s²), and extreme shock
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25 conditions (20 m/s²).
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29 *Materials*

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31 Four different infusion pumps were used, including two conventional syringe pumps (Injectomat MC
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33 Agilia, Fresenius Kabi, France and TE-331, Terumo, Tokyo, Japan), one conventional peristaltic pump (Volumed
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35 μVP7000; Arcomed, Switzerland), and one new-generation cylinder pump (Anyfusion H-100, Meinntech, Korea).
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37 The operating principle of the new-generation cylinder pump has been described previously [14]. The cylinder
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39 pump has two different parts; main body and disposable part (a donut-shaped cylinder cartridge). In brief, the key
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41 technology of this pump is a continuous cross-cycling of two pistons inside a dedicated cylinder cartridge (with
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43 an independent motor for each piston). Differently programmed two pistons rotate in the cylinder by different
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45 manner and allow precise control of fluid infusion. Moreover, the additional sealing technology in the cylinder
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47 cartridge prevents any free flow or accidental bolus. (Figure 1). A multi-channel infusion pump analyzer (IDA 4
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49 Plus, Fluke biomedical, Cleveland, USA) was used to measure the actual flow rate delivered by infusion pumps.
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54 *Outcome parameters*

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56 Average flow rate delivered by each infusion pump with infusion settings of 1 ml/h and 5 ml/h was
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58 measured over 1 hour.
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1 *Experimental set-up*

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3 The experimental set-up is shown in Figure 2. The infusion system, composed of a 50 ml syringe
4 (Shinchang Medical Co, Korea) filled with normal saline installed in the infusion pump, was connected to the
5 infusion analyzer (IDA 4 Plus) through an intravenous tubing line and three-way stopcock. The infusion pump
6 was positioned on the vibrating table.
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11 Each experiment was performed for 1 hour to analyze the flow actually delivered to the infusion pump
12 analyzer with fluid infusion rate settings of 1 ml/h or 5 ml/h. Experiments were repeated under different simulated
13 vibrations, including resting state (0 m/s²), mild vibration (2 m/s²) (reflecting vibrations in moving cart or
14 ambulance), and moderate vibration (6 m/s²) (reflecting vibration during medical helicopter flight). Experiments
15 were also performed under extreme vibration situations (20 m/s²) to observe if accidental bolus infusion would
16 occur due to unexpected external shocks or irregular ground conditions, such as movement during an ambulance
17 ride or abrupt air turbulence during a helicopter flight. To verify adequate acceleration of vibration, the vibration
18 level was measured using a vibration meter (VM-6360, Hong Kong, China) (Figure 2). All experiments were
19 repeated five times, except for the extreme vibrations test, which was conducted only once.
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31 *Statistical Analysis*

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33 Data were tabulated and analyzed using SPSS 25.0 (SPSS, Inc., Chicago, IL) and GraphPad Prism 8
34 (GraphPad Software, Inc., La Jolla, CA). Changes of flow rate were considered significant if the error ranges
35 increased beyond the known (manufacturer-provided) error ranges. In general, infusion error range is reported as
36 less than 3% for syringe pumps[15, 16] and 5 to 10% for peristaltic pumps [17, 18]. To compare the flow rate
37 accuracy between different infusion pumps under each simulated vibration condition, flow rates for one hour were
38 analyzed with Kruskal-Wallis tests with post hoc pairwise Mann-Whitney analyses. The type I error rate for
39 pairwise comparisons between infusion pumps was adjusted by Bonferroni's correction using $p = 0.05$ as the
40 global level of significance with post- hoc p values set at $p < 0.008 (=0.05/6)$.
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1 **Results**

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3 A total of 128 1-hour experimental procedures were analyzed to provide 128 hours of data. In the resting
4 state and under mild vibrating conditions, all pumps showed good performance within the known error range at
5 both flow rates of 1 ml/h and 5 ml/h (Table 1). However, with both syringe pumps, flow rates increased over the
6 known error range with moderate and higher vibrating conditions (5% of error range in Fresenius Kabi Agilia and
7 8% in Terumo TE-331 syringe pump). In addition, inadvertent fluid boluses were injected with extreme vibration
8 (20 m/s²). In an peristaltic pump (Arcomed Volumed μ VP7000), flow rates remained stable within the known
9 error range with moderate vibration, but overall under-infusion was found than obtaining the target volume (Figure
10 3). This tendency was more pronounced at a lower flow rate (1 ml/h) under moderate vibration (Table 1, Figure
11 3). In the new generation cylinder pump, stable flow rate was recorded with less than 2% of the manufacturer-
12 provided error range under all simulated vibrations. No accidental bolus injection was observed with extreme
13 vibrating conditions for both infusion and cylinder pumps (Figure 4).
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1 **Discussion**

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3 We evaluated the performance of infusion pumps in various vibration conditions possible during
4 emergency patient transport. In mild vibration, all infusion pumps maintained good performance with accurate
5 flow rate. However, in moderate vibration, flow rates in syringe pumps increased beyond their known error
6 ranges, while flow rates in peristaltic pumps remained within the known error ranges. In extreme vibration
7 conditions, accidental fluid bolus was injected in the syringe pumps but not in the peristaltic pumps. The new
8 cylinder pump maintained stable performance without being affected by the external vibrations.
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17 **Importance of pump performance during emergency patient transport**

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19 Inter-hospital patient transports are common, and many patients may be critically-ill requiring
20 continuous drug infusion during transports [19-21]. Therefore, stable performance of infusion pumps, especially
21 flow rate accuracy, is important for patient safety because even small dosage errors for vasoactive drugs may
22 cause significant hemodynamic fluctuations in vulnerable patients [22-24]. Moreover, vibrations of varying
23 intensities can occur continuously or abruptly during transports due to irregular road surfaces, sudden air flow
24 turbulence during helicopter transport, and unexpected external shocks. However, the effects of these possible
25 vibrations on pump performance are not clearly demonstrated.
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35 **Conventional infusion pumps and possible flow rate variability**

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37 With continuing technical advancements, various syringe and peristaltic pumps are indispensable in
38 daily clinical practice. However, each infusion pump has distinct advantages and limitations. The entire infusion
39 system consists of several components, including the fluid bag/syringe, fluid tubing line, attachments to the
40 infusion pump, flow controller, and intravenous angio-catheter. Therefore, even if the electromechanical pump
41 performs well as expected, injection errors may occur due to various external factors [7, 25]. For example, the
42 flow rate of a syringe pump may be affected by vertical displacement of the devices; lowering the pump position
43 more than the patient temporarily reduces infusion volume [26], and raising the pump position above the patient
44 may generate an inadvertent bolus injection [27]. Compliance with tubing lines and syringe size also affects
45 flow rate accuracy [28-30]. Therefore, the vibration generated during patient transport is another important
46 environmental factor that may influence flow accuracy. We hypothesized that the effects vary depending on the
47 design and technology of different pump devices.
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1 **Our findings and Interpretation**

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3 Syringe and peristaltic pumps are two representative infusion pumps for continuous micro-infusion. A
4 peristaltic pump uses indirect operation in which a series of linear peristaltic actuators driven by a rotary stepper
5 motor exert peristaltic movement on fluid in the infusion line, resulting in a relatively high margin of error. This
6 is consistent with our results of around 5% under-infusion with peristaltic pumps. Syringe pumps use a
7 sophisticated method to directly push the syringe, and rotary motion is converted to linear movement. As a
8 result of its mechanics, this pump delivers fluid in small, precise volumes within 2-3% of the error range. The
9 precision of syringe pumps was recreated in resting and mild vibration conditions of this experiment. Unlike
10 with peristaltic pumps, however, unexpected bolus injections were observed with syringe pumps at 5 ml/h with
11 moderate vibrations. This was also reproduced in additional experiments using extreme vibrations. In the
12 peristaltic pump, two actuators on either side of the infusion line act like a safety valve to prevent inadvertent
13 bolus infusion even if a strong external shock is applied. With a syringe pump, accidental forward free flow can
14 occur through the open end in the absence of a locking device that acts as a check valve to prevent unintended
15 syringe movement from large external shocks.

16
17 A cylinder pump is a new concept infusion pump that combines the advantages of both infusion and
18 syringe pumps. The cylinder pump operates on the principle of sucking and discharging fluid via two rotating
19 pistons inside a dedicated cylinder cartridge. Due to the design of the dedicated cartridge, precise injection is
20 possible and any free flow or accidental bolus is prevented.

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22 **Clinical implications of our study**

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24 In a stable environment, all pumps showed good performance, and the syringe pump was more
25 beneficial for sophisticated flow control at lower error ranges compared to the peristaltic pump. However, in
26 environments with moderate or higher vibrations expected, the peristaltic pump is better at preventing accidental
27 bolus injection. When transferring small pediatric patients or critically ill patients with intravenous infusions of
28 highly potent drugs, the use of syringe pumps requires careful attention, including fastening the pump to fixed
29 racks to prevent sudden device movement or displacement. The new cylinder pump has combined advantages of
30 both accurate injection of the syringe pump and free flow prevention of the peristaltic pump. Therefore, the
31 cylinder pump should be considered in environments with moderate vibration expected.

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33 **Limitations**

1 This study involves limitations. First, as a laboratory-level experimental study, it is difficult to predict
2 the actual response in real patients. Clinical response may vary individually according to patient size and
3 underlying cardiopulmonary function. Responses may be more pronounced in small pediatric patients or elderly
4 patients with organ dysfunction. Second, simulated vibrations were used with reference to previous research[11-
5 13], and the experiments were not performed in actual ambulances or helicopters. However, the vibration
6 intensity during emergency transports is not fixed and varies from sitting in stable conditions (e.g., car 0.5 m/s²,
7 bus 0.6 m/s², helicopter 0.8 m/s²)[31, 32] to strong vibrations with unreported intensities (strong vibration-
8 generating conditions such as dropping the pump). Third, investigators were not blinded to the pump types
9 during experiments. Although this experiment could not be blinded by its very nature, the sequences of infusion
10 pump or vibration intensity were randomly selected to reduce selection bias [33]. In addition, all delivered flow
11 rates were automatically recorded by the flow analyzer. Fourth, 50-cc syringes were used for the syringe pump.
12 The performance results of syringe pumps using smaller syringes may differ. However, considering the clinical
13 inconvenience of frequent syringe replacements, the use of 50-cc syringes could be considered reasonable.
14 Finally, limited types of infusion pumps were used. Various commercially available infusion pumps would cause
15 wide variations in performance and the results may not be applicable to other models from the same or different
16 manufacturers.

35 **Conclusions**

37 In this experimental study evaluating the performance of various infusion pumps in clinically possible
38 vibrations, all infusion pumps maintained good performance with mild vibrations. However, the flow rate
39 variability of syringe pumps increased beyond the known error ranges with moderate vibration and accidental
40 bolus injection occurred with extreme vibrations, while the flow rate accuracy of peristaltic pumps was
41 maintained. The new cylinder pump showed stable pump performance and was unaffected by external
42 environmental vibration.

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Table 1 Performance of various infusion pumps.

	Syringe pump	Syringe pump	Peristaltic pump	Cylinder pump
	Kabi	Terumo	Arcomed	Meinntech
Infusion rate at 1 ml/h				
Resting (0 m/s ²)	1.01±1.03 (1%)	1.03±0.01 (3%)	0.96±0.02 (4%)	0.98±0.01 (2%)
Mild (2 m/s ²)	1.01±0.02 (1%)	1.01±0.05 (1%)	0.96±0.01 (4%)	0.99±0.02 (1%)
Moderate (6 m/s ²)	1.01±0.01 (1%)	1.03±0.03 (3%)	0.93±0.03 (7%)	0.99±0.03 (1%)
Inadvertent bolus at extreme vibrations (20 m/s ²)	Yes	Yes	No	No
Infusion rate at 5 ml/h				
Resting (0 m/s ²)	5.10±0.06 (2%)	5.04±0.06 (0.8%)	4.78±0.02 (4.4%)	4.96±0.04 (0.8%)
Mild (2 m/s ²)	5.03±0.01 (0.6%)	5.05±0.04 (1%)	4.79±0.09 (4.2%)	4.92±0.06 (1.6%)
Moderate (6 m/s ²)	5.25±0.43 (5%*)	5.40±0.68 (8%*)	4.77±0.07 (4.6%)	4.95±0.11 (1%)
Inadvertent bolus at extreme vibrations (20 m/s ²)	Yes	Yes	No	No

Data are presented as mean±SD of delivered flow rate (ml/h) with percent error (%).

*Beyond manufacturer-provided error range of 2-3% in syringe pump, 5-10% in peristaltic pump, and 2% in cylinder pump.

1 **Figure legends**

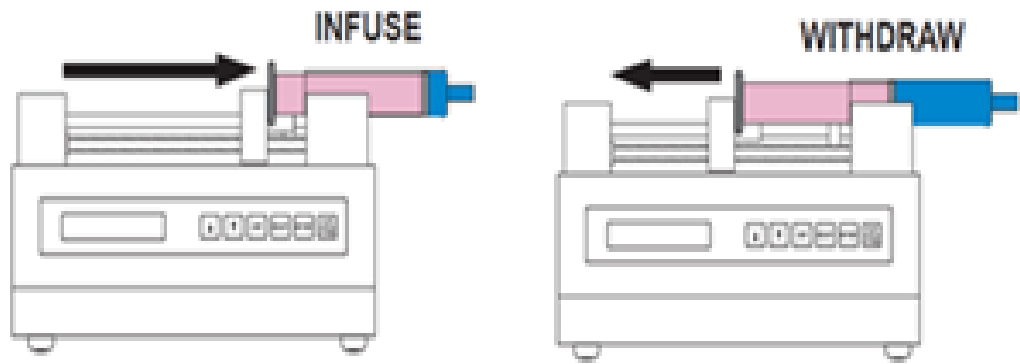
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3 **Fig. 1** Core technology of new-generation cylinder pump. Cross-cycling of two pistons inside a donut-shaped
4 dedicated cylinder cartridge allows precise control of fluid infusion and prevents any free flow or accidental bolus.

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7 **Fig. 2** Experimental set-up.

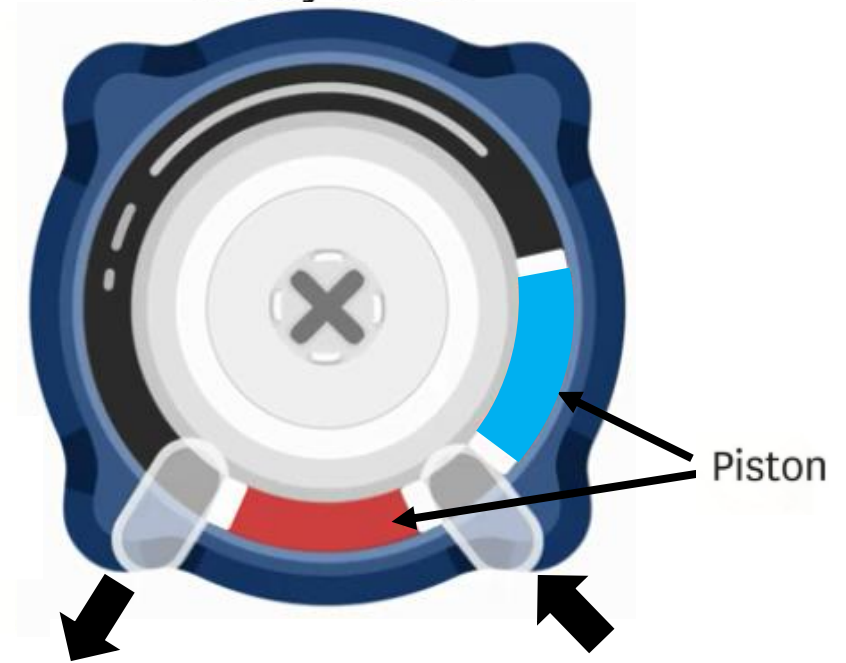
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9 **Fig. 3** Average flow rate for various infusion pumps with (a) 1 ml/h, (b) 5 ml/h. P-values are statistically significant
10 by Kruskal-Wallis test at both flow rates of 1 ml/h and 5 ml/h. Mann-Whitney test is conducted to calculate P-
11 values between groups; * indicates $P < 0.05$ and ** indicates $P < 0.01$ after adjustment by Bonferroni correction.

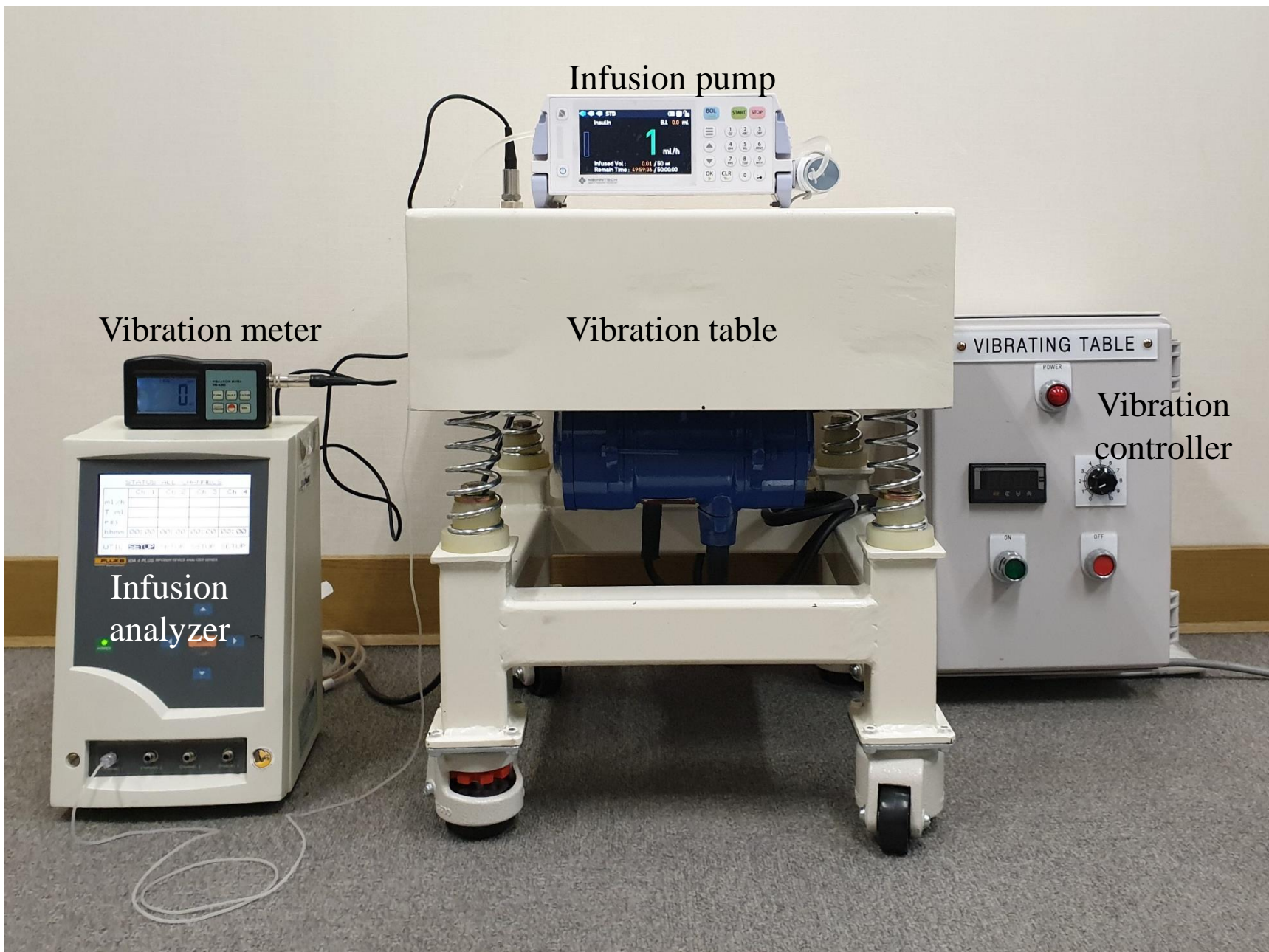
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14 **Fig. 4** Hydrograph of inadvertent bolus infusion with flow rate of 1 ml/h (left) and 5 ml/h (right). Blue line
15 indicates average flow rate and green line indicates delivered volume. (a) Kabi, (b) Terumo, (c) Arcomed, (d)
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Parallel motion



Rotary motion





Infusion pump

Vibration meter

Vibration table

VIBRATING TABLE

Vibration controller

Infusion analyzer

