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Validation of a Novel Electromagnetically Operated Free Flow Liquid Dispensing System

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ABSTRACT

Repeat dispensing of liquids is a common requirement in many industries, often performed using automated machinery. These instruments often use complex mechanisms requiring expensive parts that may not be readily available. In resource-constrained regions there is a need for a simple device capable of reproducibly dispensing a controlled volume of fluid accurately. We evaluated the performance of a semi-automated liquid dispenser made from readily available parts that utilizes a programmable timer to trigger the activity of an electromagnetic valve, which allows delivery of liquid from a storage tank to the delivery nozzle via a flexible tube. The device was programmed to deliver a wide range of volumes and a gravimetric analysis of dispensed liquid was performed. The dispensed liquid maintained a linear relationship with the delivery time within the tested delivery range of 0.05 gram to 1.8 gram. It demonstrated high accuracy (>95%) and precision (coefficient of variation of <10%) for dispensing quantities more than 0.2 gram. However, the accuracy and precision suffered significantly below 0.2 gram. By changing nozzle diameters, we found a similar linear relationship between time and dispensed water weight for all tested nozzle sizes. By using a wide range of nozzle diameters, we could increase the range of delivery weight from 0.03 gram to 28.4 gram, with a very similar precision. This simple instrument is a user friendly, cost-effective, resource-efficient and reliable alternative for repeatedly dispensing a wide variety of liquids with various industrial applications, within a given volume range.

Introduction

Free flow liquid repeat-dispensing systems are required in a wide variety of industries for the delivery of liquids such as water, oil, milk, chemicals, reagents, media, and more ranging from microliter to liter quantities. Automatic and semi-automatic liquid dispensers employing various actuating methods have been developed such as thermal-bubble, piezoelectric, pneumatic, and solenoid actuation. (1-5). These instruments aim to provide a rapid, flexible, and convenient method to dispense different types of liquids with high reliability and accuracy in a wide range of volumes. The principal limitation of these technologies is the high infrastructure requirement and related costs. Particularly in a setting with limited access to materials and expertise, purchasing or building such liquid handlers may not be feasible. There is a need for a low cost, low maintenance, user friendly plug and play device with an easily adjustable broad dispensing range without compromising accuracy and ensuring sample integrity.

In this work, we evaluate the performance of a simple new technology that offers long-term liquid storage, valving/pumping, and proportional reagent dispensing all in one instrument (Patent pending and manuscript in preparation). This simple device is designed to decrease complexity and allowing users to substitute components to meet the user's needs and available resources. The instrument consists of a storage tank from which liquid flows via a flexible tube. The tube passes through an electromagnetically operated valve. To operate the instrument, a timer connected to the electromagnet acts as a switch to open the valve and the liquid passes through the tube to the nozzle at the dispensing end. The user can dispense liquid with an easy click of a button and select a wide range of quantities by adjusting the timer duration and/or changing nozzles. A continuous tube system eliminates leaks, clogging or cross contamination. We aim to validate the function of this instrument; explore the delivery range it achieves and ascertain the accuracy and precision within this range.

Hypothesis

Since the timer activates the electromagnetic switch, we hypothesize that the delivered quantity is proportional to the time for which the valve is open. If this is true, the delivered volume (V) can easily be programmed by adjusting the timer duration (T), provided the cross-sectional area of the nozzle orifice (A) is kept constant. On the other hand, if the timer duration is kept constant, a change in nozzle cross sectional area would affect the delivered quantity. Thus, by adjusting the timer duration and nozzle gauge, this instrument could be capable of delivering a wide range of liquid quantities.

Materials and Methods

Experiments to validate the functioning, accuracy and precision were performed using a prototype of the novel dispensing instrument (Package Systems; Anant Vasahat, Bibvewadi, Pune, India. Patent pending and manuscript in progress). To validate the relationship between delivered quantity (V) and timer duration (T), the nozzle diameter (D) was kept constant and deionized water was dispensed into pre-weighed vials (Eppendorf, Catalog no. 022363352) for specified time durations. Nine timer (Selec.com, model UNIX-1; least count 0.001 second) durations were selected and thirty replicates each were obtained at room temperature (80º F) and 1 atmosphere pressure. Mass of the dispensed water was measured using a four-decimal place balance (Model 8068, AMICI Tools, amazon.com; least count of 0.006 g). To validate the relationship between dispensed quantity (V) and nozzle diameter (D), we did a similar gravimetric analysis of 5 replicate water deliveries at 5 specified timer durations, using 10 different nozzle diameters. Nozzle size was altered by using readily available syringe needles of varying gauges (Benton Dickinson regular bevel regular wall 1” needles, gauges 14 to 27; vitalitymedical.com), with gauge 14 being the largest and gauge 27 being the smallest cross-sectional area. These disposable needles easily attach to the flexible tubing at the dispensing end with no leakage. The resulting data was analyzed to validate our hypothesis and obtain accuracy and precision information.

Results

Relationship between timer duration and dispensed quantity

Figure 1. shows the linear relationship observed (R^2=0.9987, y =1.2433x + 0.0139) between delivery time (T) and dispensed quantity (V) over a range from 0.01 to 1.5 seconds, dispensing a corresponding range from 0.05 gram to 1.88 gram of water. This translates to 49.8345 µL to 1.87377 mL by volume (Volume = Density × Weight; density of water at 80 C = 0.99669 (6). Within this tested range, the time delivery T is directly proportional to the dispensed quantity, in agreement with the proposed formula.

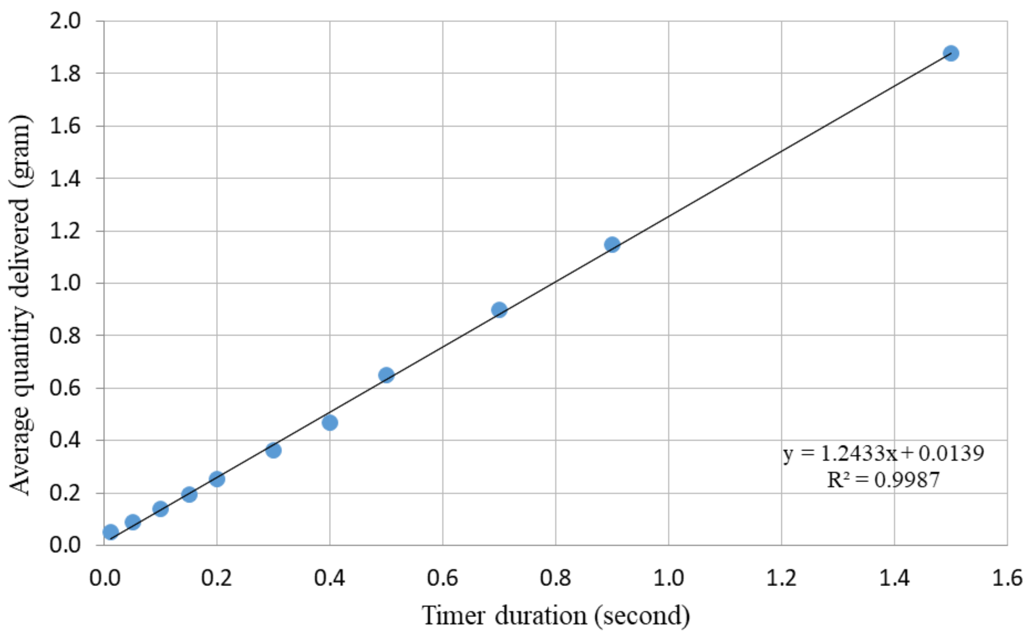

Figure 1. Relationship between timer duration (T) and dispensed quantity (V).

Accuracy

To test the accuracy of this instrument, we utilized the linear relationship to predict the expected volume delivery for given timer durations using the graph equation y=1.2433x+0.0139. 5 replicate measurements were taken and the % error was calculated based on the expected and observed values. As shown in Table 1, >95% accuracy was obtained beyond the 0.2-gram delivery quantity. However, the accuracy suffered significantly in the lower delivery range less than 0.2 gram.

Variability and precision

To study the variability among measurements of the machine, we analyzed 30 delivery replicates for each timer setting. Table 2 shows the mean, range, standard deviation (SD) and coefficients of variation (CV) obtained at each timer setting. We observed a similar range and SD of measurements for all timer settings. The CV was >10% at the lowest timer settings delivering <0.2 gram, however progressively reduced to 1% with longer timer durations. Thus, high precision was obtained for delivering larger quantities. This agrees with data available for small-volume delivery by hand-held manual pipettes (7).

Table 1. Accuracy of delivered quantity

Timer duration (s)	Predicted quantity (g)	Observed quantity (g)	Accuracy (%)
0.01	0.02633	0.06	44%
		0.05	53%
		0.04	66%
		0.05	53%
		0.07	38%
0.05	0.076065	0.1	76%
		0.09	85%
		0.090	85%
		0.110	69%
		0.090	85%
0.2	0.26256	0.270	97%
		0.290	91%
		0.27	97%
		0.27	97%
		0.27	97%
0.7	0.88421	0.88	100%
		0.88	100%
		0.9	98%
		0.91	97%
		0.9	98%
1	1.2572	1.28	98%
		1.27	99%
		1.3	97%
		1.26	100%
		1.29	97%

Table 2. Variability and precision of delivered quantity

Timer duration (Seconds)	Average delivery (gram)	Standard Deviation	Coefficient of Variation	Maximum delivery (gram)	Minimum delivery (gram)	Delivery range (gram)	Corresponding volume (mL)
0.010	0.052	0.008	15.526	0.067	0.040	0.027	0.0518
0.050	0.090	0.013	14.628	0.110	0.070	0.040	0.0897
0.100	0.141	0.013	9.044	0.160	0.120	0.040	0.1402
0.150	0.194	0.019	10.032	0.220	0.160	0.060	0.1929
0.200	0.255	0.011	4.396	0.270	0.220	0.050	0.2543
0.300	0.365	0.010	2.636	0.380	0.350	0.030	0.3636
0.400	0.467	0.011	2.292	0.480	0.450	0.030	0.4656
0.500	0.649	0.012	1.813	0.670	0.630	0.040	0.6466
0.700	0.899	0.012	1.296	0.930	0.880	0.050	0.8961
0.900	1.146	0.010	0.836	1.160	1.130	0.030	1.1420
1.500	1.877	0.018	0.984	1.900	1.830	0.070	1.8709

Response to change in nozzle

We propose that the delivered quantity depends on the cross-sectional area of nozzle orifice (A) if timer duration (T) is kept constant. As shown in Figure 2, we observed a linear relationship between timer duration and dispensed water weight for each of the 10 different nozzle sizes tested. By using a wide range of nozzle diameters, we were able to increase the range of delivery weight from 0.03 g to 28.4 g, which would translate to 30 μL-28 mL range of delivered volume. Figure 3 shows a heat map depicting the average, standard deviations, and coefficient of variance of quantities delivered by the different nozzle gauges. We observed that the smallest quantities <0.15 gram had the poorest variance depicted in orange color, the quantity range roughly between 0.2-1 g had better variance depicted in yellow color, while quantities greater than 1 gram had the best performance with coefficient of variance <1% as depicted in green.

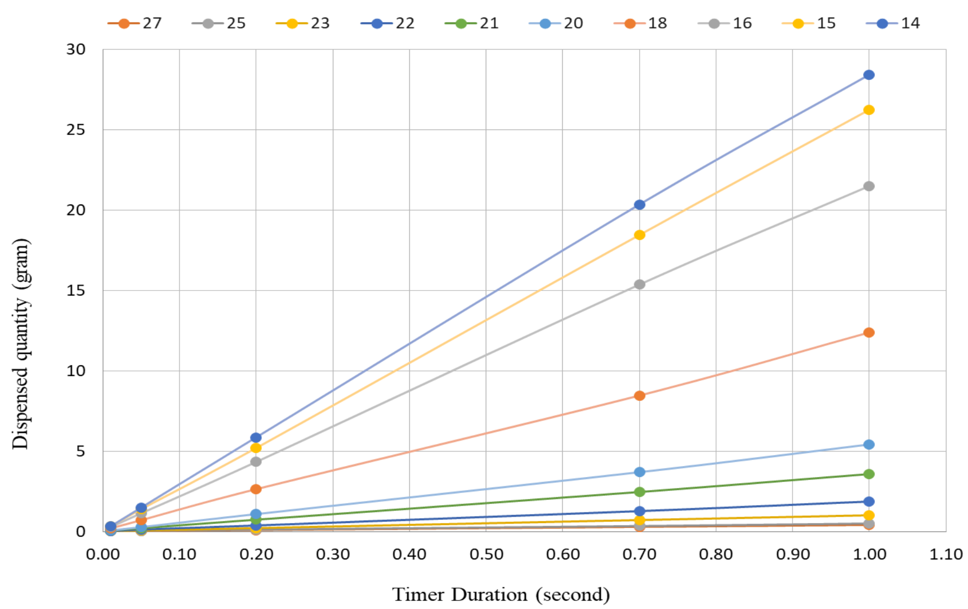

Figure 2. Relationship between nozzle gauge and delivered quantity

Discussion

We present the validation, calibration and precision of a low-cost semi-automated liquid dispenser that uses a novel electromagnet-driven mechanism. This instrument can be easily constructed using readily available parts and has a small footprint, which offers a distinct advantage in resource constrained settings. The technology may be utilized for delivery of a wide range of liquids used in chemical, biological, animal and horticulture industries. The instrument offers a controlled release of liquids for a volume set by the user. The device is user friendly since delivery occurs by easy click of a button. It allows for reagent storage and continuous operation, eliminating extra steps and time required for replenishing liquid such as with syringes or pipettes. This instrument utilizes surgical grade needles, an inexpensive, readily available, and easy option for nozzles without any need for nozzle customization and reduces chances of contamination.

Table 3. Heat map showing variability and precision of delivery using different nozzle gauges

Nozzle Guage	Timer Duration (second)	0.1	0.5	2	7	10
25	AVG	0.05	0.07	0.14	0.38	0.54
	SD	0.01	0.01	0.01	0.02	0.03
	CV	**11.91**	**12.30**	**6.21**	**5.18**	**5.56**
23	AVG	0.05	0.09	0.24	0.74	1.04
	SD	0.01	0.01	0.02	0.01	0.03
	CV	**29.17**	**10.40**	**7.52**	**1.76**	**2.52**
22	AVG	0.05	0.15	0.40	1.29	1.88
	SD	0.01	0.01	0.01	0.02	0.02
	CV	**16.09**	**7.40**	**2.08**	**1.41**	**1.26**
21	AVG	0.09	0.23	0.76	2.48	3.59
	SD	0.01	0.01	0.01	0.01	0.02
	CV	**14.82**	**3.67**	**0.72**	**0.46**	**0.53**
20	AVG	0.11	0.32	1.12	3.72	5.43
	SD	0.02	0.01	0.01	0.03	0.09
	CV	**15.75**	**3.61**	**1.09**	**0.68**	**1.71**
18	AVG	0.21	0.72	2.65	8.49	12.42
	SD	0.02	0.00	0.02	0.02	0.14
	CV	**8.60**	**0.62**	**0.73**	**0.21**	**1.16**
16	AVG	0.30	1.16	4.36	15.39	21.52
	SD	0.01	0.02	0.03	0.14	0.52
	CV	**3.75**	**1.44**	**0.64**	**0.91**	**2.40**
15	AVG	0.34	1.42	5.22	18.48	26.27
	SD	0.01	0.01	0.02	0.04	0.65
	CV	**2.08**	**0.81**	**0.41**	**0.21**	**2.47**
14	AVG	0.34	1.52	5.88	20.35	28.43
	SD	0.01	0.01	0.02	0.22	0.31
	CV	**3.20**	**0.75**	**0.34**	**1.08**	**1.10**

0-1	1-10	>10

Our results validate the proposed mechanism of action where the electromagnetic valve is activated by adjusting the timer controller. We observed that the opening of the valve is directly proportional to the timer duration, making it possible to program the machine easily and to adapt it to a large range of volumes. This is a distinct advantage and obviates the need for separate instruments for different delivery volumes. We observed efficient accuracy and precision within the tested range, except at the lowest microliter quantities. At all tested volumes we did not notice any droplet formation or leaking at the nozzle end. Since we used standard hypodermic needles as interchangeable nozzles, perhaps using needles with short barrels may reduce dead volume and increase the accuracy. Hence in the current form this instrument may not be an ideal substitute for micro-pipetting.

Future studies include re-testing in the smaller delivery range using a more sensitive timer and weighing scale of smaller least count. In addition, we would like to explore instrument adjustments for an even higher volume range as well. Adding a programmable logic controller (PLC) to facilitate programming can provide a very user-friendly interface. We envision a PLC that would calculate the appropriate timer duration and needle gauge for a desired volume delivery. Additionally, testing delivery of liquids of various viscosities will further help define device applications. We envision this instrument to have a wide range of applications in various industries, especially in resource-constrained settings.

Conclusion & Limitations

Our results establish a linear relationship between delivery time and dispensed mass for a given nozzle orifice. This can be further utilized to define the delivery times for desired quantities, within or beyond the tested range. The instrument exhibits high precision within part of the tested range. For standard micropipettes, the acceptable random error is <1%. Using the same standard, this novel instrument performs equally well for a corresponding liquid delivery of 750 µL to 18.5 mL, using various nozzle diameters. The instrument can deliver about 230 µL to 28 mL (maximum tested) with a precision of >95%. Precision is maintained even upon repeated delivery.

We have noted a few limitations for this instrument. First, there should be no electromagnetic force or elements in the close vicinity of this instrument to avoid any magnetic interference. Secondly, since the design utilizes liquid flow through using a flexible tube and nozzles, we expect that this technology may not work for high viscosity liquids that do not flow freely. Even though silicone tubing is very durable, it is possible that this will need replacing, especially if the nozzle end is not secure. Third, the tubing creates a corresponding minimum dead volume requirement, which poses a challenge for delivery of precious or expensive reagents. Lastly, this device is designed only to dispense liquids, and not perform liquid aspiration. The lack of aspiration precludes performing serial dilutions or other types of liquid transfers using this device.

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References

1. Amirzadeh Goghari, A., Chandra, S. Producing droplets smaller than the nozzle diameter by using a pneumatic drop-on-demand droplet generator. (2008). Exp Fluids, 44, 105–114. https://doi.org/10.1007/s00348-007-0378-z.
2. Arrabito G., Pignataro B. Inkjet printing methodologies for drug screening. (2010). Anal Chem, 82(8):3104-7. doi: 10.1021/ac100169w.
3. Keesey R., LeSuer R., Schrier J. (2022). Sidekick: A Low-Cost Open-Source 3D-printed liquid dispensing robot. HardwareX, 12:e00319. doi: 10.1016/j.ohx.2022.e00319.
4. Revia RA., Wagner B., James M., Zhang M. (2022). High-Throughput Dispensing of Viscous Solutions for Biomedical Applications. Micromachines (Basel), 13(10):1730. doi: 10.3390/mi13101730.
5. Kim J.D., Choi J.S., Kim B.S., Choi Y.C., Cho Y.W. (2010) Piezoelectric inkjet printing of polymers: Stem cell patterning on polymer substrates. Polymer, 51 (10) 2147-2154. https://doi.org/10.1016/j.polymer.2010.03.038
6. https://www.usgs.gov/special-topics/water-science-school/science/water-density
7. Hawthorne G., Dillen L., Barfield M., Cobb Z., Kandira A., Schroeter K., White S., Karp N.A., Love I., Boutet V., Rohde M., Kranenborgh M., Timmerman P. (2019). Feedback from the European Bioanalysis Forum liquid microsampling consortium: microsampling: assessing accuracy and precision of handheld pipettes and capillaries. Bioanalysis, 11(6):533-542. doi: 10.4155/bio-2019-0018.