Original Article

Comparison of effectiveness of the piston-pump method versus the pressure-infusor method for rapid infusion of crystalloids: A bench study

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Submitted: 15-Jul-2020
Revised: 11-Aug-2020
Accepted: 29-Sep-2020
Published: 12-Dec-2020

Access this article online

Website: www.ijaweb.org

DOI: 10.4103/ija.IJA_864_20

Quick response code

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ABSTRACT

Background and Aims: The piston-pump method is a simple method for rapid administration of fluids but some problems are unsolved. We compared the effectiveness of using the piston-pump method with that of the pressure-infusor method. **Methods:** Twelve anaesthetists were classified randomly into the piston-pump and pressure-infusor groups. They were asked to infuse 500 ml of saline three times successively through a 16-G intravenous cannula as rapidly as possible using a pump with a 50-ml syringe or a pressure-infusor at 300 mmHg. The time taken for infusion and the maximum or minimum pressure in the infusion circuit and substitute vessel were measured. Bacterial culture of the saline infused sterilely was performed to estimate bacterial contamination. **Results:** The pressure-infusor group led to faster infusion of 500 ml of saline (233 ± 19 s) than the piston-pump group (301 ± 48 s) ($P < 0.01$). The infusion time at the third attempt (316 ± 43 s) was significantly longer than that at the first attempt (285 ± 53 s) only in the piston-pump group ($P < 0.05$). The maximum pressure (mmHg) in the circuit was 131 ± 9 and > 200 ($P < 0.01$) and in the substitute vessel was 5 ± 1 and 17 ± 7 ($P < 0.01$) in the pressure-infusor and piston-pump groups, respectively. A pressure of <-200 mmHg occurred at all infusion attempts in the piston-pump group. Bacterial contamination was not observed in either group. **Conclusion:** If fluids must be administered rapidly, the pressure-infusor method is more efficient than the piston-pump method because the latter is less effective in infusing fluids rapidly and associated with excessive positive and negative pressure in the infusion circuit.

Key words: Flow rate, fluid therapy, infusor, intravenous infusions, syringes

INTRODUCTION

Fluid needs to be administered rapidly when unexpected blood loss has occurred during anaesthesia.[1,2] In this situation, manual syringing of fluid is often forced to increase the effect of a fluid load (piston pump method) because this is a simple method and special preparation is not required.[3,4] However, several problems have been pointed out in the piston-pump method. First, attempting a rapid push of the piston generates the excessive positive intravenous pressure, which is difficult to regulate and can lead to barotrauma. The barotrauma could lead to compartment syndrome.[5-9] Also, it might delay the resuscitation if a large volume was injected extravascular and waste a precious volume of blood that might not be available in large amounts. Second, negative pressure occurs when withdrawing the syringe plunger before refilling to administer blood rapidly, which can haemolyse red blood cells.[3,10,11]

How to cite this article: Hashimoto W, Takenaka I, Yasunami K, Minami T, Sano H. Comparison of effectiveness of the piston-pump method versus the pressure-infusor method for rapid infusion of crystalloids: A bench study. Indian J Anaesth 2020;64:1059-63.

Third, the effectiveness of increasing the flow rate of fluid administration has been reported to be variable.[3,4] Finally, repeated pumping of the piston can cause bacterial contamination of fluids.[12,13]

To increase the flow rate when rapid administration of fluids is necessary, use of a pressure infusor (pressure-infusor method) is a simple alternative to the piston-pump method.[3,14,15] Although time for attaching a pressure infusor to the fluid bag and inflating the infusor is required, the pressure-infusor method enables to save labour during infusion. Excessive positive intravenous pressure occurs in the piston-pump method but can be controlled in the pressure-infusor method. Therefore, we examined the effectiveness of increasing the flow rate of saline administration through an intravenous cannula, the circuit and substitute-vessel pressure, and bacterial contamination using the piston-pump and pressure-infusor methods.

METHODS

The requirement for ethical approval was waived by the Ethics Committee of our hospital (Kyushu Rosai Hospital, Kitakyushu, Japan) because no patients were involved in this study. The ethical approval was not obtained. This study was performed on 6th-14th April, 2019.

The infusion circuit was made as shown in Figure 1. It consisted of a sterile 180-cm Sure-Plug® infusion set (content 10.7 ml; Terumo, Tokyo, Japan), including three-way taps for connecting a syringe and measuring circuit pressure, together with a 32-mm 16-G intravenous cannula (B. Braun, Melsungen, Germany). A 50-cm polyvinyl-chloride extension tube (ID 3.1 mm; Terumo, Tokyo, Japan), including a three-way tap for measuring the pressure, was used as a substitute vessel, and a 16-G intravenous cannula was spiked to it in a sterile manner. The infusion circuit and substitute vessel were primed with sterile 0.9% saline (Terumo, Tokyo, Japan) of which 1 ml had been taken for bacterial culture. Then, a new 500-ml bag of 0.9% saline was spiked to the infusion circuit, and the total drop in height from the lowest part of the infusion bag to the intravenous cannula was 100 cm. Thirty-six infusion circuits were created. We took, in a sterile manner, 1 ml from the 500-ml bag of saline for bacterial culture before infusion.

Six male and six female anaesthetists were classified randomly using a sealed-envelope method into

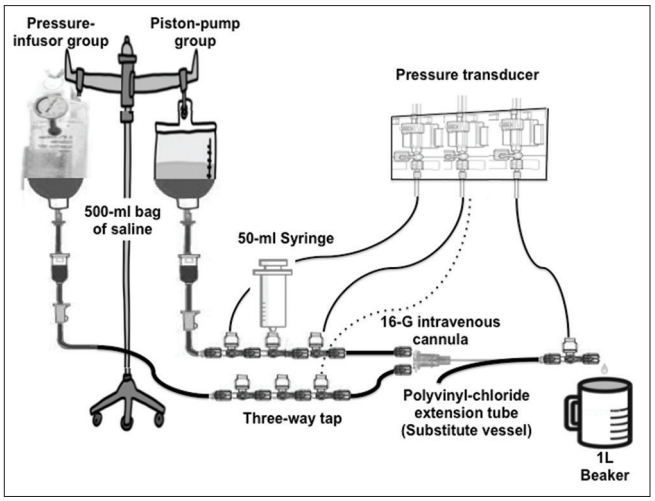

Figure 1: Diagram of infusion circuit and substitute vessel in the piston-pump and pressure-infusor groups

two groups: Piston-pump group (M/F = 3/3) and pressure-infusor group (M/F = 3/3). They washed their hands with alcohol gel (Saraya, Osaka, Japan) before experimentation. Experiments were carried out in an operating room at room temperature (25°C). Immediately after the timer was started, anaesthetists in the piston-pump group connected a 50-ml syringe (Terumo, Tokyo, Japan) to a three-way tap, pumped its piston as quickly as possible, and infused the remaining 499 ml of saline into a sterile 1-L beaker. The timer was then stopped. In the pressure-infusor group, after the timer was started, anaesthetists attached a pressure infusor (C-fusor®; Smiths Medical, Dublin, OH) to the fluid bag, inflated the infusor as quickly as possible to 300 mmHg, and infused the remaining 499 ml of saline into the beaker. The timer was then stopped. They maintained 300 mmHg by intermittent insufflation of air throughout infusion. The time required to administer 499 ml of saline in each group was recorded. Each anaesthetist in each group infused the saline successively three times in the same fashion. One ml of the saline collected in the beaker was taken for bacterial culture. To examine the standard infusion time of the circuit used in this study, the time using the gravity-fed infusion was measured. Other anaesthetists blinded to the study aims infused 499 ml of saline by gravity from a height of 100 cm with the same infusion circuit and substitute vessel used in this study and repeated it 10 times.

The maximum pressure in each group was measured immediately upstream of the cannula and the distal end of the substitute vessel using pressure transducers (Edwards, Irvine, CA, USA)

connected to the side port of the three-way tap. In addition, in the piston-pump group, the minimum pressure was measured immediately upstream of the syringe because a negative circuit pressure was generated while pumping the piston. The pressure measurements (range, 0 to 200 or –200 to 0 mmHg) were recorded by an Infinity Delta® monitor (Draeger, Telford, PA, USA) every 10 s until the end of each infusion. The anaesthetists blinded to the study aims selected the maximum (or minimum) value of the circuit and substitute-vessel pressure from these records. If the maximum pressure was >200 mmHg and <–200 mmHg, these were calculated as 201 mmHg and -201 mmHg, respectively.

The samples for bacterial culture, which were 1 ml of saline for priming, that in the 500-ml bag before infusion, and that collected in the beaker after infusion, were inoculated into the plates prepared with Standard Methods agar using aseptic techniques and mixed thoroughly. The plates were incubated at 36 ± 1°C for 7 days. During the incubation period, the plates were evaluated for bacterial growth every day and mixed daily. Final bacterial growth identification was carried out by standard reference methods.

The primary outcome of this study was the time required to infuse 499 ml of saline. The secondary outcomes were incidence of bacterial contamination and the pressure in the infusion circuit and substitute vessel. A minimum sample size was estimated on the basis of the time required for infusion. The time under gravity-fed infusion was 438 ± 10 s (mean ± SD). A "clinically important change" was defined as an absolute change of 20%. Hence, minimum sample size of five was required to detect such a change with $\alpha = 0.05$ and $\beta = 0.2$. The infusion time and maximum circuit and substitute-vessel pressures were compared using the unpaired *t*-test. Also, we compared the infusion times at the first and third attempts of infusion in each group with a paired *t*-test. The result of bacterial culture was compared with the Chi-square test. $P < 0.05$ was considered significant. Statistical analyses were carried out using StatView 5.0 (SAS Institute, Cary, NC, USA).

RESULTS

Age of the twelve anaesthetists who were participants of this study was 37 ± 13 years. Table 1 shows the infusion time and maximum or minimum pressure in the circuit and substitute vessel in the piston-pump and pressure-infusor groups. The pressure-infusor group led to faster infusion of 499 ml of saline (233 ± 19 s) than the piston-pump group (301 ± 48 s) ($P < 0.01$). There was no significant difference in the infusion time between the first and third attempts in the pressure-infusor group (242 ± 24 s and 236 ± 12 s, respectively). However, in the piston-pump group, the infusion time at the third attempt was significantly longer than that at the first attempt (316 ± 43 s and 285 ± 53 s, respectively) ($P < 0.05$).

Table 1: Infusion time and maximum or minimum pressure in the circuit and substitute vessel in the piston-pump and pressure-infusor groups

	Piston-pump	Pressure-infusor
Infusion time (s)	301±48	233±19*
1st attempt (s)	285±53	242±24
3rd attempt (s)	316±43**	236±12
Maximum or minimum circuit pressure		
Positive (mmHg)	>200	131±9*
Negative (mmHg)	<-200	-
Maximum substitute-vessel pressure (mmHg)	17±7	5±1*

Values are mean±SD. *P<0.01 vs piston pump group, **P<0.05 vs. 1st attempt in piston-pump group

The maximum pressure in the infusion circuit was 131 ± 9 mmHg in the pressure-infusor group and >200 mmHg in the piston-pump group: The latter was significantly higher than the former ($P < 0.01$). A pressure of -200 mmHg or less occurred at all infusion attempts in the piston-pump group. Despite a high circuit pressure, the maximum pressure in the substitute vessel was 5 ± 1 mmHg and 17 ± 7 mmHg in the pressure-infusor and piston-pump groups, respectively. A significant difference in the substitute-vessel pressure was found between both groups ($P < 0.01$) but the clinical change was small. There was no bacterial contamination of the saline solution before and after infusion attempts in both groups.

DISCUSSION

The approximate mean flow rate (in ml min^{-1}) in the pressure-infusor group and piston-pump group was 130 and 100, respectively. Use of the pressure infusor doubled the flow compared with that using gravity-fed infusion. However, a commercially available rapid-infusion system, such as the Level 1® H-1000 (Smiths Medical, Dublin, OH), can infuse more than 400 ml min^{-1} of crystalloids rapidly when used in conjunction with a 16-G intravenous cannula.[16] The anaesthetists should change to this system if it can be prepared.

Smart *et al*. and Stoneham reported that the flow rate of saline through a 16-G intravenous cannula was 240 ml min^{-1} and 340 ml min^{-1} using a pressure infusor at 300 mmHg, respectively, which are not in accordance with our results.[3,14] The manufacturers of the infusion circuits that they used were different from that in this study. The effect of a difference in the infusion circuits across manufacturers on the flow rate needs to be studied. In addition, a substitute vessel was not used in their studies.[3,14] The substitute-vessel pressure was remarkably lower than the circuit pressure because it was downstream of the resistance of a thin intravenous cannula. We considered that the combination of a difference in manufacturers of the infusion circuits and use of a substitute vessel could have affected considerably the flow rate. In the Stoneham's study, the flow rate by gravity from a height of 100 cm (which was the same height used in this study) was 190 ml min^{-1}, compared with 70 ml min^{-1} in this study.[14] A difference in the flow rate by gravity may support our opinion. Moreover, the flow rate by gravity in the Stoneham's study was more rapid than that in the pressure infusor group in this study.[14] The cause also seems to be the same. However, Stoneham has clarified that use of pressure infusor doubles the flow compared with that using the gravity-fed infusion, which is similar to our results.[14] We believe that the result in the present study is close to the flow rate seen in the clinical setting.

Among the piston-pump groups, the infusion time at the third attempt of infusion was significantly longer than that at the first attempt. A possible reason for the variation in infusion time is the fatigue elicited by infusing 500 mL of saline three times successively because this task was hard work. Also, increased friction due to repeat pumping of the piston may cause the variation because of use of the same syringe when infusing 500 mL of saline three times. Further studies are needed. The effort devoted to pumping by the anaesthetist when unexpected massive bleeding, which is a life-threatening emergency situation, occurs is another cause for concern in this method. Conversely, in the pressure-infusor method, the variation in the infusion time was not observed when infusing 1500 mL of saline, which was an obvious advantage of the pressure-infusor method.

The maximum pressure was ~ 150 mmHg in the pressure-infusor group, which was approximately identical to the systolic arterial pressure. The pressure of the substitute-vessel, which was a polyvinyl-chloride extension tube, was as low as 5 mmHg in the pressure-infusor group. Venous pressure will be lower than this because the vein wall is much more flexible than the polyvinyl-chloride substitute-vessel. In the piston-pump group, the maximum circuit pressure was too high to measure in this study. Smart *et al*. have demonstrated that the piston-pump method generates more than 600 mmHg when attempting rapid push of the piston, which can cause barotrauma.[3] In contrast, the substitute-vessel pressure was less than 20 mmHg. Although no data are available about the threshold value that can make the vein rupture, neither the piston-pump method nor the pressure-infusor method will cause barotrauma. However, even if the cannula is placed appropriately in a vein and the proximal run-off from the vein is occluded, the venous pressure can increase markedly.[17] Moreover, there have been some case reports of extravasation and compartment syndrome resulting from pressurised infusion and forceful manual syringing.[5-9] Thus, intravenous sites should be checked closely to avoid compartment syndrome and extravasation caused by barotrauma when fluids are administered rapidly.

A unique problem in the piston-pump method was excessive negative pressure (<-200 mmHg) when withdrawing the syringe plunger before refilling. Use of the pressure infusor can avoid this problem. Negative pressure can haemolyse red blood cells. Studies have shown that haemolysis is not caused by negative pressure alone.[3] Conversely, De Villiers *et al*. have demonstrated that forceful manual syringing caused significant haemolysis but use of the pressure-infusor induced no haemolysis.[11] Moreover, Pohlmann *et al*. showed a combination of negative pressure and an air-blood interface to be associated with haemolysis.[10] Thus, the anaesthetists should avoid the piston-pump method to expedite red blood cell transfusions.

Bacterial contamination of the infused saline was not observed in this study. Huey *et al*. showed that bacteria were not detected in the drainage after five reciprocations by grasping the protruding part of a disposable-syringe plunger with dry hands that were not disinfected; their data are consistent with our results.[18] Conversely, previous studies have demonstrated bacterial contamination of syringe contents after repeated refilling.[12,13] Bacterial contamination of a syringe may not always result in bacterial contamination of fluids. We used a Terumo 50-ml syringe but the risk of bacterial contamination may differ if other types of syringes are employed. The

effect of a difference in syringes across manufacturers on bacterial contamination needs to be studied.

There are some potential limitations of our experimental design. First, venous pressure measured in this study may be different from that in humans because a 50-cm polyvinyl-chloride extension tube was used as a substitute vessel. A study based on a simulation technique using human veins is needed, for example, a cadaver study. Second, we used a 50-ml syringe in the piston-pump group to minimise the number of pumpings of the piston. Results in this study may not be applied when using a 10-ml or 20-ml syringe because its size can affect both negative and positive pressures in the infusion circuit. Finally, six anaesthetists in each group carried out experiments and the sample size was small. They may have learned to give the fluid via a syringe pump and the results may have got affected. Also, a sample size was estimated on the basis of the infusion time that was the primary outcome. The pressure in the infusion circuit and substitute vessel, which is the secondary outcome, is as important as the primary outcome but it was not taken into consideration in calculating the sample size.

CONCLUSION

If fluids must be administered rapidly, use of the pressure-infusor method is more efficient than that of the piston-pump method. The latter is less effective in infusing fluids rapidly, and associated with excessive positive and negative pressure in the infusion circuit, which can cause barotrauma of intravenous sites and haemolysis. However, these methods should be considered as first aid until a commercially available rapid transfusion and infusion system has been prepared.

Data availability

The datasets analysed in this study are available from the corresponding author on reasonable request.

Acknowledgements

We thank Arshad Makhdum, PhD, from Edanz Group (www.edanzediting.com/ac) for editing a draft of this manuscript.

Financial support and sponsorship

Financial support was provided solely from institutional and/or departmental sources. The authors have no affiliation with any manufacturer of any devices described in the manuscript.

Conflicts of interest

There are no conflicts of interest.

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