

Understanding Infusion Pumps

Jeff E. Mandel, MD, MS

Infusion systems are complicated electromechanical systems that are used to deliver anesthetic drugs with moderate precision. Four types of systems are described—gravity feed, in-line piston, peristaltic, and syringe. These systems are subject to a number of failure modes—occlusion, disconnection, siphoning, infiltration, and air bubbles. The relative advantages of the various systems and some of the monitoring capabilities are discussed. A brief example of the use of an infusion system during anesthetic induction is presented. With understanding of the functioning of these systems, users may develop greater comfort. (Anesth Analg 2017;XXX:00–00)

Infusion pumps are increasingly central to the practice of modern anesthesia. Just as it is possible to utilize the square root of time model to inject liquid volatile agents in a closed circle,¹ it is possible to deliver a total intravenous (IV) anesthesia by intermittent bolus. While such pedagogical exercises may be extended to clinical scenarios, most practitioners opt for calibrated vaporizers over copper kettles and particularly over glass syringes. The transition from copper kettle to calibrated vaporizer was easy; it reduced the amount of mental arithmetic, and because it was purely mechanical, it did not add an alarm. As long as there was a visible meniscus and the knob turned, an anesthetic could be delivered. Conversely, the desflurane vaporizer needs to be plugged in to operate, and even if we do not know which physical property of desflurane is responsible for this requirement,^a we understand how to operate the Tec 6 design vaporizers. The difference among the volatile agents is trivial—their vapor pressure, densities, heats of vaporization, and minimum alveolar concentration vary by at most a factor of 5. IV drugs are different: delivery rates can span more than 3 orders of magnitude, drugs can vary in viscosity, bubbles can be introduced into the tubing, catheters can become obstructed, and tubing can vary in elastance. Because they must address these issues, infusion pumps are different from vaporizers—they have numerous operating modes, different failure modes, and many alarms. While I have never been confronted by a resident asking for a glass syringe to avoid the annoyance of a vaporizer, I frequently encounter pushback from residents when I suggest using an infusion pump instead of intermittent boluses. This review will attempt to demystify infusion pumps to increase the comfort of the practitioner with these devices.

TYPES OF PUMPS

Drug delivery requires moderate precision in delivering solutions into relatively low-resistance sinks (a place where flow disappears without a significant increase in pressure,

such as a blood vessel) with relatively low-pressure heads (the height difference between the fluid reservoir and the point of exit) at relatively low infusion rates. Although there is no single standard for flow accuracy in infusion pumps, a value of $\pm 5\%$ is fairly typical, but, as discussed further, this number may only apply under laboratory conditions. There are several design constraints that apply to medical devices such as pumps. IV solutions must be sterile, so wetted surfaces are typically composed of inexpensive materials intended for a single use. Infusion devices must move with the patient and are usually battery powered, which constrains the power available to drive delivery. Some drugs are not stable in polyvinylchloride bags.² Many elegant designs have foundered on the rocks of clinical practicality, and no single design is best for all applications.

While applications such as cardiopulmonary bypass may utilize centrifugal pumps and implantable pumps incorporate a number of designs such as elastomeric and osmotic pumps, such systems are not typically used for IV drug delivery. Several approaches are discussed—gravity feed, in-line piston, peristaltic drive, and syringe pumps.

Gravity Feed

An early form of regulated delivery was a gravity feed system with flow interruption. The IVAC 260 was an example of such a system. It utilized an optical counter that detected the number of drops from a standard IV set and a pinch clamp to stop the flow when the specified number of drops was detected; accuracy was limited due to the variation in drop size. While these systems are no longer widely used in the developed world, they were an advance over pinch rollers and the Dial-a-Flow (Hospira Inc, Lake Forest, IL), and they have advantages in “off the power grid” settings—a human operator lifting a liter bag 1 m is a simple power source available the world over. Another advantage of gravity feed is that it is a pressure source, rather than a flow source, and flow begins instantaneously when the pinch clamp opens, rather than requiring a drive train to come into tension.

In-line Piston Drive

In-line piston drives have a reservoir that is compressed to generate flow and refill from an upstream container; 1 or more 1-way valves are incorporated to avoid sending drug back to the reservoir or filling the piston from the patient side. With a single piston, there is no flow while the piston refills,³ but flow is otherwise constant. Two pistons in a

From the Department of Anesthesiology & Critical Care, Perelman School of Medicine at the University of Pennsylvania, Philadelphia, Pennsylvania.

Accepted for publication July 7, 2017.

Funding: None.

The author declares no conflicts of interest.

Reprints will not be available from the author.

Address correspondence to Jeff E. Mandel, MD, MS, 7003 Dulles Bldg, 3400 Spruce St, Philadelphia, PA 19063. Address e-mail to jemandel@verizon.net.

Copyright © 2017 International Anesthesia Research Society

DOI: 10.1213/ANE.0000000000002396

^aPotency.

seesaw configuration avoid this issue but increase the complexity of the valve control. Piston drive systems require specialized infusion sets and have largely been supplanted by peristaltic drive systems, but the Hospira Plum series (Hospira, Lake Forest, IL) is still available. These pumps utilize a dome-shaped membrane that is compressed by a disk to form the piston. Due to the valve configuration, piston drives are less susceptible to siphoning, as discussed further with syringe pumps.

Peristaltic Drive

Most volumetric infusion pumps found in the developed world utilize some form of peristaltic drive. The majority are linear drives, although Delphi IVantage pump (Delphi Medical Systems, Troy, MI) utilizes a rotary cassette. Linear drives contain a stack of plates with holes mounted on a corkscrew shaft; as the shaft rotates, the plates massage the fluid down a tube, typically composed of an elastic material such as Silastic (Dow Corning, Midland, MI). Because each plate expresses a small volume of fluid, flow is phasic, and there can be a brief pause in flow during the transition from the bottom to the top plate. These effects are the most noticeable during low infusion rates.⁴ Additionally, the performance of a peristaltic drive can be significantly altered by using tubing that differs from that with which the pump was designed to work.

Syringe Pumps

Syringe pumps are widely available due to their simplicity. Most syringe pumps approved for clinical use use a side-mounted ratchet that disengages to permit a filled syringe to replace an empty one. Syringe pumps use stepper motors to produce a constant rate of linear travel that is translated to a flow rate by the cross-sectional area of the syringe. Many pumps attempt to sense this by measuring the outer diameter of the syringe; others may require the user to specify this dimension of the syringe. Syringe pumps are susceptible to siphoning; the pressure head of a syringe pump can expand the compressible volume of the infusion system and even drive the motor, particularly when moving the pump on the pole⁵ or when placing a loaded syringe in a pump, with the primed tubing dangling to the floor (which can produce a puddle of drug and an empty syringe). Syringe pumps are subject to several effects that delay the start of drug delivery. First, all elements of the drive train must be brought into tension before flow starts.⁶ Second, syringe pumps typically use motors that are adequate for continuous infusion but may be underpowered during startup, when syringe stiction (the force required to cause 1 body in contact with another to begin to move) must be overcome.⁷ These delays occur every time a new syringe is placed into a pump.

Many more syringes are destined for manual administration than in syringe pumps, so it should come as no surprise that syringe design is driven by the needs of the user handling the syringe. An important property of a syringe is stiction—the coefficient of static friction should be much larger than the coefficient of dynamic friction to prevent backfilling of the syringe from the IV. One means to achieve this is to have a compressible pocket between the rubber grommet and the plunger (Figure 1); the air pocket must be compressed before any movement occurs. Just as it is easier

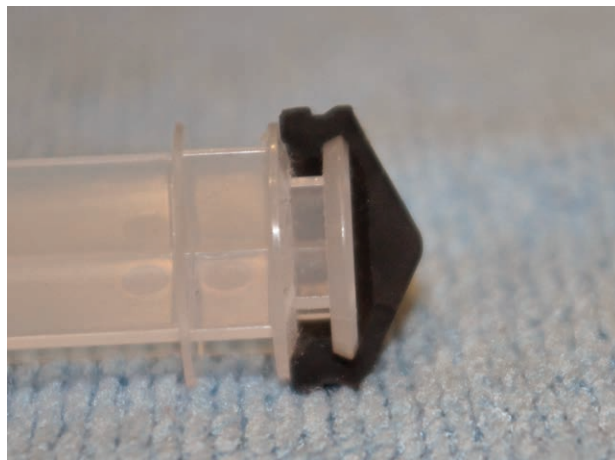


Figure 1. BD 20-mL syringe (Becton Dickinson, Franklin Lakes, NJ) with rubber grommet bisected to demonstrate the air pocket.

to “burn rubber” with stiff shock absorbers than soft ones, this air pocket increases the force required to overcome the tendency of the grommet to stay in place. Different designs among manufacturers lead to differences in compliance.⁸ Greater syringe stiction increases startup time, as the motor must run longer to develop the force needed to overcome the static friction. Increases in compliance may also exacerbate siphoning, because a lower head of pressure is required to expand this volume. We have found that measures that decrease the negative pressure applied to the grommet, such as venting vials (inserting a second needle into the vial to admit air while filling the syringe) or removing their cap prior to filling syringes, and measures that increase the pressure in the syringe, such as pressing the plunger with an occluded outflow path, allow the grommet to better seat, improving startup time and reducing compliance.

There are 2 approaches to sensing pressure in syringe pumps—by measuring the force applied to the plunger and by measuring the pressure in the infusion line. While the second method is more accurate, it requires a wetted surface, typically a disk with a membrane. Small air bubbles lodged in the sensing disk can alter the pressure seen by the controller, leading to erratic behavior.⁹ Newer approaches that permit accurate measurement of flow in the line are available but have not yet been widely adopted.

ERROR DETECTION

Occlusion

When the outflow of a pump is occluded, the pressure will rise until it exceeds a specified pressure. The time required to achieve this pressure is determined by the elastance of the tubing and the flow rate. The resistance of an occluded system should be nearly infinite; however, adding a secondary infusion may provide a pressure relief, particularly if the tubing does not include a check valve. When highly compliant extension sets are used to extend drug infusion lines, a considerable volume can be infused before the alarm threshold is reached. Use of such extension sets should be avoided.

Alarms can be intrusive and interfere with the anesthesiologist attending to critical functions¹⁰; manufacturers have responded with a range of features that are intended

to improve usability. The Alaris SE system (Carefusion, San Diego, CA) has a special “Anesthesia” mode that allows the user to deliver boluses and set extended alarm limits: in this mode, the occlusion alarm threshold on the 8100 module is 525 mm Hg, which is useful when delivering boluses. A better approach is to use the “pump” setting, which increases the threshold to 525 mm Hg at high flow rates, but returns to 300 mm Hg at low flow rates. An explanation of occlusion detection with the Alaris SE is available from Carefusion.¹¹

Infiltration

Detection of infiltration requires estimation of hydraulic resistance, which can be performed by measuring the pressure at 2 or more flow rates and determining the slope of the line. The ability to detect infiltration by estimation of resistance is incorporated into the Alaris SE pump system. When the status light is cycling from green to yellow, the pump is assessing resistance, and it may be prudent to examine the IV site.

Disconnection

When a pump is connected to a vein, venous pulsations can be observed, and the absence of these pulsations may indicate disconnection. Newer B. Braun syringe pumps (B. Braun Medical, Allentown, PA) provide 3 ranges of amplitude below which the pump will issue an alarm.

Siphoning

Detection of siphoning requires sensing abrupt changes in the pressure in the line, and, while newer pumps such as

the B. Braun syringe pumps may detect this problem, the user should be aware of the potential for transient changes in drug delivery when the pump is moved vertically relative to the patient.

Air Bubbles

Infusion pumps are not common sources of venous air emboli, and the International Electrotechnical Commission standard states that infusion of <1 mL air in a 15-minute period is not a safety issue.¹² Bubbles of <50 μ L are not considered to be a safety hazard; bubbles of this size are about 7 mm long in standard IV tubing. Bubbles are typically detected by optical methods. Twisting the IV tubing while seating it in the bubble detector may result in spurious alarms.

CALIBRATION

Infusion systems should be periodically checked for accuracy by a designated professional, typically the local clinical engineering department. The process is relatively simple and utilizes a gravimetric scale to measure the volume of fluid infused at a specified rate.

MODES OF DELIVERY

Pumps marketed in the United States do not have the capability to perform target-controlled infusion, but that does not mean that the clever clinician cannot achieve some measure of pharmacokinetic control by using modes that are available. By combining modes, it is possible to provide more control over anesthetic induction.

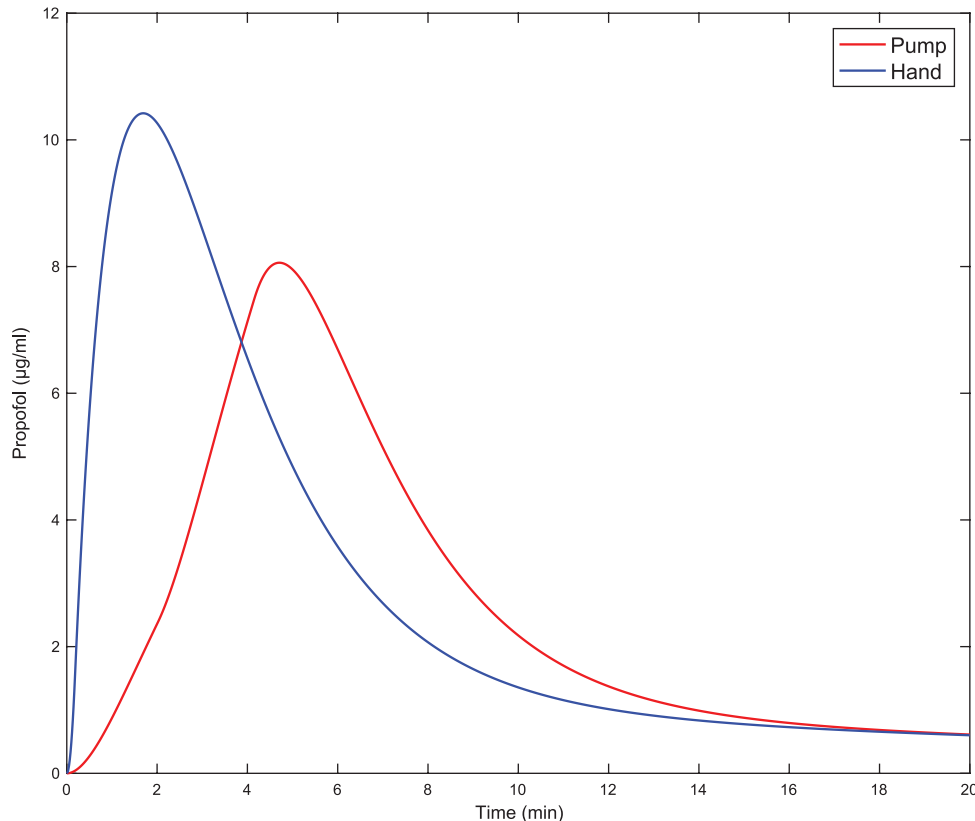


Figure 2. Computer simulation of the concentration of propofol in the effect site resulting from delivering 200 mg either by hand over 10 s (blue) or by an infusion pump as an 800 μ g/kg bolus over 2 min followed by an infusion of 800 μ g/kg/min (red).

For this example, we use the Alaris Medley SE pump, which permits setting a bolus over a specified period, followed by a specified infusion rate that will proceed until the volume limit is reached. The effect of the boluses is depicted in Figure 2, which uses the Cortínez model¹³ with an adjoined effect compartment to estimate effect-site concentrations for propofol. The k_{e0} was chosen to yield a time-to-peak effect of 1.6 minutes. The MATLAB code for this model is available on the OpenTCI website.¹⁴ We will deliver 200 mg propofol to a 50-year-old, 80-kg patient in 2 ways: a hand bolus over 10 seconds (blue) and using the pump to deliver a bolus of 800 µg/kg over 2 minutes followed by 800 µg/kg/min until the volume limit of 20 mL is reached (red). The hand-delivered bolus achieves a peak effect-site concentration of 10.4 µg/mL in 103 seconds, while the pump induction requires 284 seconds to achieve a peak of 8.1 µg/mL. But what if the patient only requires an effect-site concentration of 4 µg/mL for loss of consciousness? The entire 200-mg hand-delivered bolus has already been delivered by that time, but with the pump induction, the concentration of 4 µg/mL is achieved after 168 seconds when only 113.6 mg propofol has gone in. Using the pump, we can expect less hypotension during induction¹⁵ and are compliant with the propofol package insert, which states that propofol “should be titrated (approximately 40 mg every 10 seconds) against the response of the patient until the clinical signs show the onset of anesthesia.”¹⁶

SUMMARY

Infusion systems are a common feature of modern anesthesia but are complicated electromechanical systems that vary in design and performance. There is a tendency to consider these systems as interchangeable, but a system that is acceptable for delivering 100 mL/h normal saline may be inadequate for delivering the same rate of phenylephrine or 1/10th the rate of remifentanyl. Clinicians should understand the safe use of these systems. Among these, the use of high-elastance tubing and antireflux valves are simple measures that can avoid problems. With familiarity comes comfort. As I tell my residents, “the only thing you’ll see me injecting by hand is air into the cuff of the endotracheal tube.” ■■

DISCLOSURE

Name: Jeff E. Mandel, MD, MS.

Contribution: This author is solely responsible for the manuscript.
This manuscript was handled by: Maxime Cannesson, MD, PhD.

REFERENCES

1. Lowe HJ, Ernst EA. *The Quantitative Practice of Anesthesia: Use of Closed Circuit*. Baltimore, MD: Williams & Wilkins, 1981.
2. Stewart JT, Warren FW, Maddox FC, Viswanathan K, Fox JL. The stability of remifentanyl hydrochloride and propofol mixtures in polypropylene syringes and polyvinylchloride bags at 22 degrees-24 degrees C. *Anesth Analg*. 2000;90:1450–1451.
3. Mann HJ, Fuhs DW, Cerra FB. Effect of infusion pump fill-stroke flow interruption on response to sodium nitroprusside in surgical patients. *Clin Pharm*. 1988;7:214–219.
4. Stull JC, Erenberg A, Leff RD. Flow rate variability from electronic infusion devices. *Crit Care Med*. 1988;16:888–891.
5. Donald AI, Chinthamunee MP, Spearritt D. Effect of changes in syringe driver height on flow: a small quantitative study. *Crit Care Resusc*. 2007;9:143–147.
6. Neff T, Fischer J, Fehr S, Baenziger O, Weiss M. Start-up delays of infusion syringe pumps. *Paediatr Anaesth*. 2001;11:561–565.
7. Sarraf E, Mandel JE. Time-delay when updating infusion rates in the Graseby 3400 pump results in reduced drug delivery. *Anesth Analg*. 2014;118:145–150.
8. Weiss M, Fischer J, Neff T, Baenziger O. The effects of syringe plunger design on drug delivery during vertical displacement of syringe pumps. *Anaesthesia*. 2000;55:1094–1098.
9. Davey C, Stather-Dunn T. Very small air bubbles (10–70 microl) cause clinically significant variability in syringe pump fluid delivery. *J Med Eng Technol*. 2005;29:130–136.
10. Quinn ML. Semipractical alarms: a parable. *J Clin Monit*. 1989;5:196–200.
11. Monitoring and detection of IV line occlusions - Alaris® SE pump. Available at: http://www.carefusion.com/documents/white-paper/IF_Alaris-SE-Pump-Monitoring-IV-Occlusions_WP_EN.pdf. Accessed June 21, 2017.
12. Wilkins RG, Unverdorben M. Accidental intravenous infusion of air: a concise review. *J Infus Nurs*. 2012;35:404–408.
13. Cortínez LI, Anderson BJ, Penna A, et al. Influence of obesity on propofol pharmacokinetics: derivation of a pharmacokinetic model. *Br J Anaesth*. 2010;105:448–456.
14. Cortínez model. Available at: <http://opentci.org/code/matlab/mandel-propofol-cortinez-2010>. Accessed June 21, 2017.
15. Bilotta F, Fiorani L, La Rosa I, Spinelli F, Rosa G. Cardiovascular effects of intravenous propofol administered at two infusion rates: a transthoracic echocardiographic study. *Anaesthesia*. 2001;56:266–271.
16. Propofol Package Insert 451094F/Revised: February 2014. Available at: https://www.accessdata.fda.gov/drugsatfda_docs/label/2014/019627s062lbl.pdf. Accessed June 21, 2017.