

Intraosseous infusion rates under high pressure: A cadaveric comparison of anatomic sites

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BACKGROUND: When traditional vascular access methods fail, emergency access through the intraosseous (IO) route can be lifesaving. Fluids, medications, and blood components have all been delivered through these devices. We sought to compare the performance of IO devices placed in the sternum, humeral head, and proximal tibia using a fresh human cadaver model.

METHODS: Commercially available IO infusion devices were placed into fresh human cadavers: sternum (FAST-1), humeral head (EZ-IO), and proximal tibia (EZ-IO). Sequentially, the volume of 0.9% saline infused into each site under 300 mm Hg pressure over 5 minutes was measured. Rates of successful initial IO device placement and subjective observations related to the devices were also recorded.

RESULTS: For 16 cadavers over a 5-minute bolus infusion, the total volume of fluid infused at the three IO access sites was 469 (190) mL for the sternum, 286 (218) mL for the humerus, and 154 (94) mL for the tibia. Thus, the mean (SD) flow rate infused at each site was as follows: (1) sternum, 93.7 (37.9) mL/min; (2) humerus, 57.1 (43.5) mL/min; and (3) tibia, 30.7 (18.7) mL/min. The tibial site had the greatest number of insertion difficulties.

CONCLUSION: This is the first study comparing the rate of flow at the three most clinically used adult IO infusion sites in an adult human cadaver model. Our results showed that the sternal site for IO access provided the most consistent and highest flow rate compared with the humeral and tibial insertion sites. The average flow rate in the sternum was 1.6 times greater than in the humerus and 3.1 times greater than in the tibia. (*J Trauma Acute Care Surg.* 2015;78: 295–299. Copyright © 2015 Wolters Kluwer Health, Inc. All rights reserved.)

KEY WORDS: Intraosseous infusion; resuscitation; sternum; sternal IO.

Intraosseous (IO) access for the administration of fluids and medications was first described in 1922, and sternal IO access was widely practiced during World War II. With the introduction of plastic intravenous (IV) catheters in the 1950s, IO access fell into disfavor.^{1,2} In the 1980s, a resurgence in IO use occurred primarily for pediatric resuscitation.^{3–5} Beginning in the 1990s, the technique expanded to again include adults^{6,7} and then for prehospital infusions as well.^{8–11}

Although IO catheters are still most frequently used for pediatric resuscitation, its potential use includes any patient with difficult IV access from shock or other medical conditions.

The IO route is recommended in the Advanced Cardiac Life Support, Pediatric Advanced Life Support, and Advanced Trauma Life Support courses for second-line access.^{12–14} Recently, IO access has been widely used by field combat medics for resuscitation of traumatically injured patients, to include the infusion of resuscitation fluids and blood products.^{15,16} For continuous fluid administration and resuscitation, pressure bags are used with a recommended pressure of 300 mm Hg.

IO access has been demonstrated to be safe and reliable for the delivery of resuscitative fluids and medications. Several factors potentially impact the effectiveness of IO access including (1) success rate of placement into the marrow cavity, (2) timeliness of successful placement, (3) frequency of needle dislodgement, (4) absorption of medications, (5) complications of insertion, and (6) flow rates for IV fluids and blood products. Widespread consensus for optimal IO access point in children is the proximal tibia because of the ease of landmark identification and lack of additional sites. The optimal site for IO access in adults has not been clearly defined, and practice patterns are different in military and civilian practices. In the United States, IO insertion for adults is performed most often into the proximal tibia and humeral head, with very occasional sternal placement. The humeral head and sternum are more commonly used in recent military practice because of the high rate of lower extremity wounds. Placement into the medial malleolus, iliac crest, distal femur, radial head, clavicle, and calcaneus is also described.^{1,17–19}

Animal studies and a few limited human series have attempted to determine which IO access site is optimal for adult

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infusion of resuscitation fluids.^{20–27} Animal models are limited by differences in bony and vascular architecture, which vary considerably in scale and structure compared with the human anatomy. Human studies are limited because of concerns about insertion complications. In a fresh human cadaveric model, we sought to ascertain the optimal site for IO device placement and infusion.

MATERIALS AND METHODS

All experiments occurred at the Maryland State Anatomy Board laboratory from March 15, 2012, to June 21, 2013.

Cadaver Selection and Preparation

Eligible “fresh” cadavers aged 18 years to 65 years at time of death were screened for potential inclusion in collaboration with the Maryland State Anatomy Board. *Fresh* is defined as a cadaver flushed with intravascular detergent solution immediately after arrival to the morgue and subsequently stored at 34°F to 36°F until use within 24 hours to 72 hours. Exclusion criteria included bony or myeloproliferative malignancy, fracture of targeted bone, previous orthopedic procedures near insertion site, recent IO placement, prosthetic limb or joint, infection at the insertion site, inability to locate landmarks because of excessive tissue, and evidence of median sternotomy or other surgical procedures involving the upper thorax. Sixteen appropriate fresh cadavers were identified during the study period.

Before commencing fluid infusion on the cadaver model, central venous access was gained by surgical cut-down of the internal jugular vein and placement of an 8 Fr introducer sheath. The sheath remained open to gravity drainage throughout the experiment to decompress the central venous system, so as to avoid any increase in central venous pressure that might influence flows at the later IO infusion sites.

Devices and Placement

In each cadaver, commercial IO infusion devices were inserted at three locations as follows: (1) the sternum (FAST-1, Pyng Medical Corp., Richmond, British Columbia, Canada), (2) the proximal tibia, and (3) the humeral head (EZ-IO, VidaCare Corp., San Antonio, TX) (Fig. 1). EZ-IO needle lengths were selected according to manufacturer recommendations for the proximal tibia (25 mm or 45 mm) and the humeral head (25 mm or 45 mm) based on body habitus. The access sites were identified using anatomic landmarks as follows: (1) for the sternum, the midpoint of the manubrium; (2) for the proximal tibia, the anteromedial surface of the tibia 2 cm to 3 cm below the tibial tuberosity; and (3) for the humeral head, the most prominent aspect of the greater tubercle of the humerus with the arm positioned with internal rotation. Correct needle placement was confirmed before infusion by visualizing aspiration of bone marrow, firm placement of the needle in the bone, and ability to smoothly flush 10 mL of fluid. Surgical dissection at the end of the experiment of the IO sites further visually confirmed correct device placement for each cadaver.

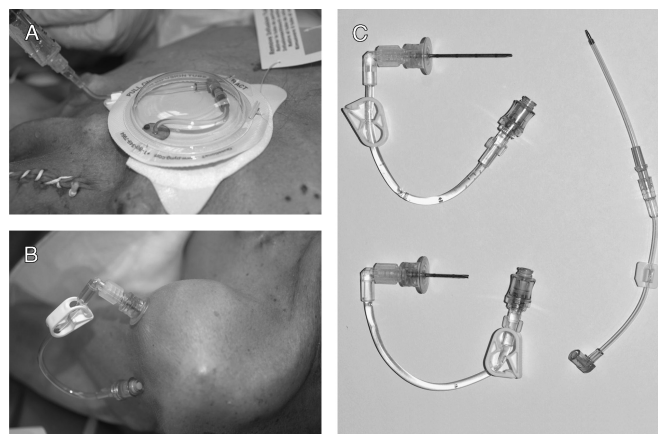


Figure 1. FAST-1 and EZ-IO devices. *A*, FAST-1 inserted in the midpoint of the manubrium of the sternum. *B*, EZ-IO 25 mm inserted into the most prominent aspect of the greater tubercle of the humerus. *C*, Clockwise from the upper left hand corner, 15 gauge \times 45 mm EZ-IO, 14 gauge inner diameter \times 155 mm FAST-1 IO, and 15 gauge \times 25 mm EZ-IO.

Flow Rate Determination

A standard IV infusion tubing set was connected to a 1-L bag of 0.9% saline and was primed. The preinfusion weight of the saline bag and attached tubing was measured and recorded. The tubing was connected to an IO device, and the saline bag was pressurized to 300 mm Hg using a manual pressure infuser. An infusion was then delivered for 5 minutes. The tubing was clamped and disconnected from the IO device, and the postinfusion weight of the saline bag and attached tubing was measured and recorded. The total infusion volume was determined by the difference of the preinfusion and postinfusion weights with the assumption that 1-mg 0.9% saline correlated to a 1-mL volume. Thus, flow rate simply equaled the total volume infused divided by the 5-minute infusion time.

Flow rates were determined sequentially for each IO infusion site. The sequence of the infusion sites was purposefully varied randomly to avoid bias.

Intrinsic flow rates were also determined for the IO devices themselves in an analogous manner without infusion into a cadaver. Measurements were repeated for each device five times.

Data Analysis

The mean flow rates for the sternum, proximal tibia, and humeral head were compared using an analysis of variance. Continuous variables were expressed as means with SDs. Data were compared between groups with the use of the analysis of variance. All tests were two tailed, and a $p < 0.05$ was considered to indicate statistical significance.

RESULTS

The 16 cadavers used were predominantly white (90%) and male (80%), with an average age of 58 years at death.

Flow Rates in Cadavers

The mean (SD) volume of crystalloid infused per minute at each site was as follows: (1) sternum, 93.7 (37.9) mL/min; (2) humerus, 57.1 (43.5) mL/min; and (3) tibia, 30.7 (18.7) mL/min (Fig. 2).

During the 5-minute infusion period, the total volume of fluid infused was 469 (190) mL for the sternum, 286 (218) mL for the humerus, and 154 (94) mL for the tibia. All of these infusion volumes were significantly different from each other ($F_{2,47} = 13.025, p < 0.001$). The humeral site had the greatest variability in volumes infused, ranging from 30.0 mL to 730 mL. The tibial site experienced the greatest number of insertion difficulties. On three occasions, the initial tibial IO access required replacement to the opposite tibia for the purposes of the study. First attempt IO placement success was 93% overall (100% for the humerus and sternum, and 81% for the tibia).

Flow Rates via IO Devices

To exclude for the potential differences in IO site flow rates resulting primarily due to resistance through the IO devices, the fluid volume infused through the devices alone was measured. The flow rate through each IO device was as follows: (1) FAST-1, 219 (3.45) mL/min; (2) EZ-IO (25 mm), 295 (8.43) mL/min; and (3) EZ-IO (45 mm), 277 (4.3) mL/min ($p < 0.01$).

DISCUSSION

When traditional vascular access methods fail, emergency access through the IO route can be lifesaving. Fluids, medications, blood components, and IV contrast can all be safely delivered through these devices.^{25,28,29} We sought to evaluate the performance of IO devices placed in the sternum, humerus, and tibia using a fresh human cadaver model. We hypothesized that there might be a difference in bolus flow rates among these three most commonly used adult access sites and that this difference may influence selection of the “optimal” site for acute resuscitation. In our model, the average flow rate at the sternal site was the highest of the three—1.6 times greater than the humeral site and 3.1 times greater than the tibial site.

Flow rates are influenced not only by resistance to flow through the IO device but also by resistance to flow through the

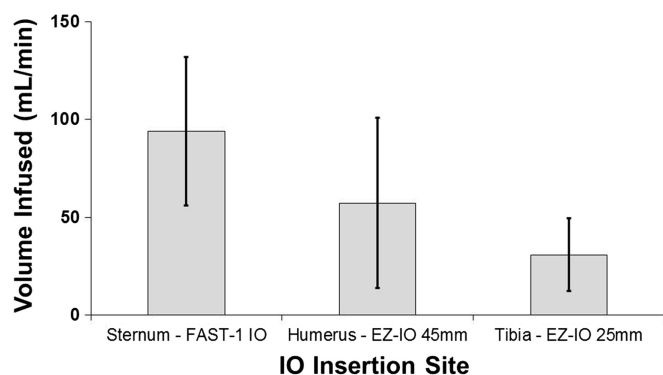


Figure 2. Fluid was infused sequentially into the three sites. Average infusion rate (mL/min) is shown for the three IO devices.

bone marrow space. By Poiseuille’s Law, resistance to flow through the device is directly proportional to its length and inversely proportional to its radius to the fourth power. The three commercial IO devices vary in length and diameter: FAST-1 (14 gauge inner diameter \times 155 mm) and the two lengths of the EZ-IO (15 gauge \times 25 mm, 15 gauge \times 45 mm) (Fig. 2). Predictably, the FAST-1 device has the highest intrinsic resistance to flow. Even so, the sternal access point using the FAST-1 demonstrated significantly faster flow than for the other sites tested using the EZ-IO likely because of more limiting differences in the physiology and bony structure at these infusion sites. In this study, we used the recommended 300 mm Hg for volume infusion since this is the standard practice of centers using these lines for resuscitation. Based on our study, we cannot comment of the exact flow rates without pressure bags.

Our cadaver population, for this study, was 80% male, with a mean (SD) age of 58.1 (9.12) years. Our youngest cadaver was 33 years, and our oldest was 69 years. The cause of death in nine of the patients was cancer. Age, sex, and cadaver “health” are potential limitations of our study population and may contribute to the high degree of variability seen in our study, particularly in the flow rates through the humerus. Bone density is known to decrease with age, which may have influenced the results of our study. The younger cadavers used in this study typically experienced a chronic illness, such as cancer. Cancer treatments are potentially myoablative and may have led to abnormal bone marrow that could have contributed to variability in our model.

Our study population was 80% male (13 males, 3 females). Although this ratio is representative of and similar to trauma patient populations, bone density between sexes is potentially another factor contributing to the variability of our results. Because of the small number of female cadavers, it was not possible to obtain statistically significant results between the male and female cadavers.

We used a novel cadaver model in this study because of the ethical concerns of performing this study in living humans. This model has not previously been validated for physiologic relevance and is a potential limitation to our study. Cadavers were obtained as close as possible to death, thoroughly flushed to limit the effects of coagulation postmortem, and fluid was seen to accumulate and drain out of the central line in all cadavers.

In a prospective observational study comparing flow rates between the humeral and tibial IO sites, Ong et al.³⁰ enrolled seriously ill or injured patients after two failed IV attempts. Twenty-four patients received tibial and/or humeral IOs, and flow rates for normal saline were compared with and without pressure bags. They determined that there was no significant flow difference between the two sites, 73.0 mL/min versus 84.4 mL/min without a pressure bag and 165.3 mL/min versus 153.2 mL/min with a pressure bag. In the current study, we found that with pressure infusion, there was a significant difference in flow rate between these sites, with the humeral site achieving, on average, 1.8 times greater volume than in the tibia. Flow rates at both sites were slower in the present study compared with the study of Ong et al. The study of Ong et al. did not evaluate the sternal IO access site.

In this study, IO catheters were successfully placed in the sternum, humerus, and tibia with high initial rates of success. Macnab et al.³¹ previously reported an overall 84% success rates for sternal IO placement by paramedics and emergency medicine physicians. First-time users were successful on 74% of attempts; and experienced users, on 95%, with “experience” defined as one previous successful placement. Paxton et al.³² showed in a prospective observational study in patients requiring vascular access for resuscitation that the humeral IO site had an 81% first-attempt placement success rate, compared with peripheral IV and central venous catheter (CVC) placements rates of 74% and 20%, respectively. The mean time to achieve flow of fluid was also much faster, with an average of 1.5 minutes for IO versus 3.6 minutes for peripheral IV and 15.6 minutes for CVC. Similarly, Leidel et al.³³ showed that for vascular access in adults undergoing resuscitation, first-attempt success rate for IO catheter versus CVC placement was 85% versus 60% and procedural time was 2.0 minutes versus 8.0 minutes. In our current study, the first-attempt placement success rate was 93%. We did not attempt to record the time required to place each device or to initiate fluid infusion in our protocol.

Complications from IO placement have been documented to include iatrogenic bone fracture, osteomyelitis, compartment syndrome, growth plate disruption, hematoma formation, fat embolization, and tissue necrosis.^{34–37} These complications can be related not only to the initial placement but also to the duration of placement and the fluid infused. Our cadaveric model allows very limited assessment of initial placement complications only. There were no identified difficulties with the sternal or humeral device placements, but there were three placement issues with the tibial site. In one cadaver, the tibial infusion flowed slowly, seemed to be related to device positioning, and improved with replacement of the device. In the other two cases, no marrow returned with aspiration at the initial placement. After switching to the other extremity, good marrow aspiration was noted and flow rates were much improved.

An “ideal site” for adult IO access would have a high first-attempt success rate, be easily protected from inadvertent dislodgement even during patient transport, and allow rapid infusion of resuscitation fluids, including blood products, and rapid absorption of medications. In our study, the sternum and humerus both demonstrated high first-attempt success rate, whereas the tibia had a lower first-attempt success rate and encountered problems with inadequate flow. The consistency of anatomic landmarks may play a factor in the high success rate of sternal placements facilitated by the FAST-1’s adhesive target patch along with guided depth release. Excessive, redundant soft tissue in the shoulder area at times makes IO placement into the humeral head more challenging, a condition which is less significant at the sternal and tibial sites. Factors such as the needle tip, the orientation of the needle to the body (humeral oriented laterally outward vs. sternal and tibial oriented upward), and thickness of soft tissue overlying the site may contribute to the risk of needle dislodgement. Realizing that flow rates for crystalloid and blood products may differ because of differing viscosities, we identified that the highest crystalloid flow rate was achieved at the sternal IO site using the FAST-1 device.

CONCLUSION

Rapid vascular access remains a life-threatening challenge in the resuscitation of severely injured trauma patients. IO access is proven as a valuable alternative in establishing initial access for fluids, blood components, and medications until definitive venous access can be achieved. In our fresh human cadaver model, the sternal IO site provided the highest flow rates compared with the humeral and tibial insertion sites. The sternal site was also associated with a 100% success rate for initial placement facilitated by its consistent anatomy. Because of its central position, the sternal site likely requires shorter infusion tubing length compared with the tibia site, is less vulnerable to inadvertent dislodgement compared with the humeral site, and is less frequently compromised by traumatic injury. Based on this analysis, the sternal site seems to have the optimal flow rate for most adult resuscitations. The sternal site, in addition to the humerus, should be used over the tibial site when conventional venous access is unobtainable.

AUTHORSHIP

J.P. contributed to the study data acquisition and analysis and drafted the article. C.H.T.M., S.A.S., and R.F. contributed to the study design, data acquisition and analysis, and critical review of the article. K.B., M.M., J.C., and J.J.D. contributed to the study design and data acquisition. C.H., M.C., and N.R. contributed to the data acquisition and analysis. N.T.T. and D.M.S. contributed to the study design and data analysis and critical review of the article. All listed authors approved the final version of the article.

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DISCLOSURE

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