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Intraosseous Infusion Rates under High Pressure: A Cadaveric Comparison of Anatomic Sites

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14. ABSTRACT

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 compared the performance of IO devices placed in the sternum, humeral head, and proximal tibia utilizing a fresh human cadaver model. 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-mmHg pressure over 5 minutes was measured. Rates of successful initial IO device placement and subjective observations related to the devices were also recorded. This is the first study comparing the rate of flow at the three most clinically utilized 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 to the humeral and tibial insertion sites.

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Intraosseous access, resuscitation, infusion, cadavers

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1.0 SUMMARY

When traditional vascular access methods fail, emergency access through the intraosseous route can be lifesaving. Fluids, medications, and blood components have all been delivered through these devices. Intraosseous (IO) access for emergency resuscitation is recommended when conventional peripheral vascular access is not readily achievable. The aim of this research is to determine which of three possible sites for IO access is the most effective for volume resuscitation, defined in terms of flow volumes achievable for resuscitation fluids. A cadaver model was used, as to date there have been no conclusive studies in human subjects.

Sixteen cadavers were obtained within 72 hours of death in collaboration with the Maryland State Anatomy Board from March 15, 2012, to June 21, 2013. IO infusion devices were placed in the proximal tibia (EZ-IO), humeral head (EZ-IO), and sternum (FAST-1). Sequentially, the volume of 0.9% saline infused into each site under 300-mmHg pressure over 5 minutes was measured. Rates of successful initial IO device placement and subjective observations related to the devices were also recorded.

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

This is the first study comparing the rate of flow at the three most clinically utilized adult intraosseous infusion sites in an adult human cadaver model. Our results showed that the sternal site for intraosseous access provided the most consistent and highest flow rate compared to the humeral and tibial insertion sites. The average flow rate in the sternum was 1.6 times greater than the humerus and 3.1 times greater than the tibia.

2.0 INTRODUCTION

Modern combat injuries often involve multiple injuries to the extremities and torso, limiting the ability of medics to obtain intravenous (IV) access for resuscitation. Therefore, combat medics are trained in the use of intraosseous (IO) devices for the delivery of resuscitative fluids after combat injury. However, the optimal site of insertion for these devices (tibia, humerus, or sternum) has not been well established. Potential complications of insertion, both those common to all sites and unique to each individual site, must be weighed against the need for resuscitation, with limited data to guide these decisions. Data on the efficacy, reliability, and ease of use of these devices have been published. Descriptions of flow rates and IO pressure measurements after infusion have also been published but are very limited.

3.0 BACKGROUND

Intraosseus 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 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 still most frequently used for pediatric resuscitation, the potential use of IO catheters 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 utilized by field combat medics for resuscitation of traumatically injured patients, to include the infusion of resuscitation fluids as well as blood products [15,16].

Intraosseous 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. Although there is widespread consensus that the optimal IO access point in children is the proximal tibia, the optimal site for insertion of these devices in adults is not similarly established. In adults, IO insertion into the proximal tibia, humeral head, and sternum is most commonly practiced. Placement into the medial malleolus, iliac crest, distal femur, radial head, clavicle, and calcaneus is also described [1,17-19].

Animal studies as well as a few limited human series have attempted to determine which IO access site is optimal for adult 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 to human anatomy. Human studies are limited due to concerns about insertion complications. We hypothesized that fresh human cadavers offer an alternate study model for comparison of infusion rates at various IO sites that is comparable to living patients.

4.0 METHODS

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

4.1 Cadaver Selection and Preparation

Eligible “fresh” cadavers aged 18-65 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 34-36°F until use within 24 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 due to excessive tissue, and evidence of median sternotomy or other surgical procedures involving the upper thorax. Sixteen “fresh” cadavers were identified during the study period.

Prior to 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 was left open to gravity drainage throughout the experiment to avoid any increase in central venous pressure that might influence flows at the later IO infusion sites.

4.2 Devices and Placement

In each cadaver, commercial IO infusion devices were inserted at three locations: (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) (Figure 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: (1) sternum – the midpoint of the manubrium, (2) proximal tibia – the antero-medial surface of the tibia 2 to 3 cm below the tibial tuberosity, and (3) 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 prior to infusion by confirming 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 all three IO sites further visually confirmed correct device placement for each cadaver.

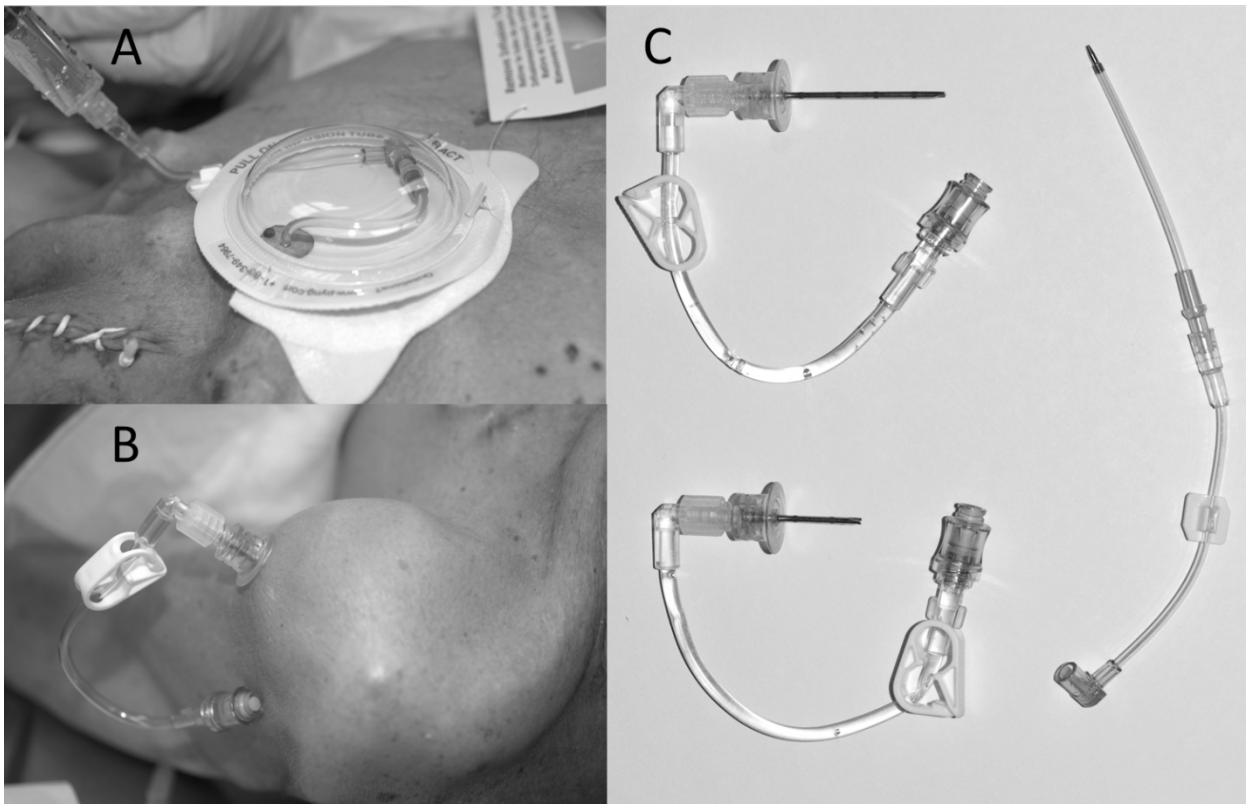

Figure 1. FAST-1 and EZ-IO Devices. *(A) FAST-1 inserted in the midpoint of the manubrium of the sternum; (B) 25-mm EZ-1O inserted into the most prominent aspect of the greater tubercle of the humerus; (C) clockwise from the upper left hand corner, 15-gauge x 45-mm EZ-IO, 14-gauge-inner-diameter x 155-mm FAST-1 IO, and 15-gauge x 25-mm EZ-IO*

4.3 Flow Rate Determination

A standard IV infusion tubing set was connected to a 1-liter bag of 0.9% saline and the tubing was primed. The pre-infusion 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 mmHg using a manual pressure infuser. An infusion was then delivered for 5 consecutive minutes. The tubing was clamped and disconnected from the IO device, and the post-infusion weight of the saline bag and attached tubing was measured and recorded. The total infusion volume was determined by the difference of the pre- and post-infusion weights with the assumption that 1 mg 0.9% saline correlated to 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.

4.4 Data Analysis

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

5.0 RESULTS

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

5.1 Flow Rates in Cadavers

The mean volume of crystalloid infused per minute at each site was as follows: (1) sternum 93.7 mL/min ± 37.9, (2) humerus 57.1 mL/min ± 43.5, and (3) tibia 30.7 mL/min ± 18.7 (Figure 2). Over the 5-minute infusion period, the total volume of fluid infused was 469 mL ± 190 for the sternum, 286 mL ± 218 for the humerus, and 154 mL ± 94 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 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 humerus and sternum and 81% for tibia.

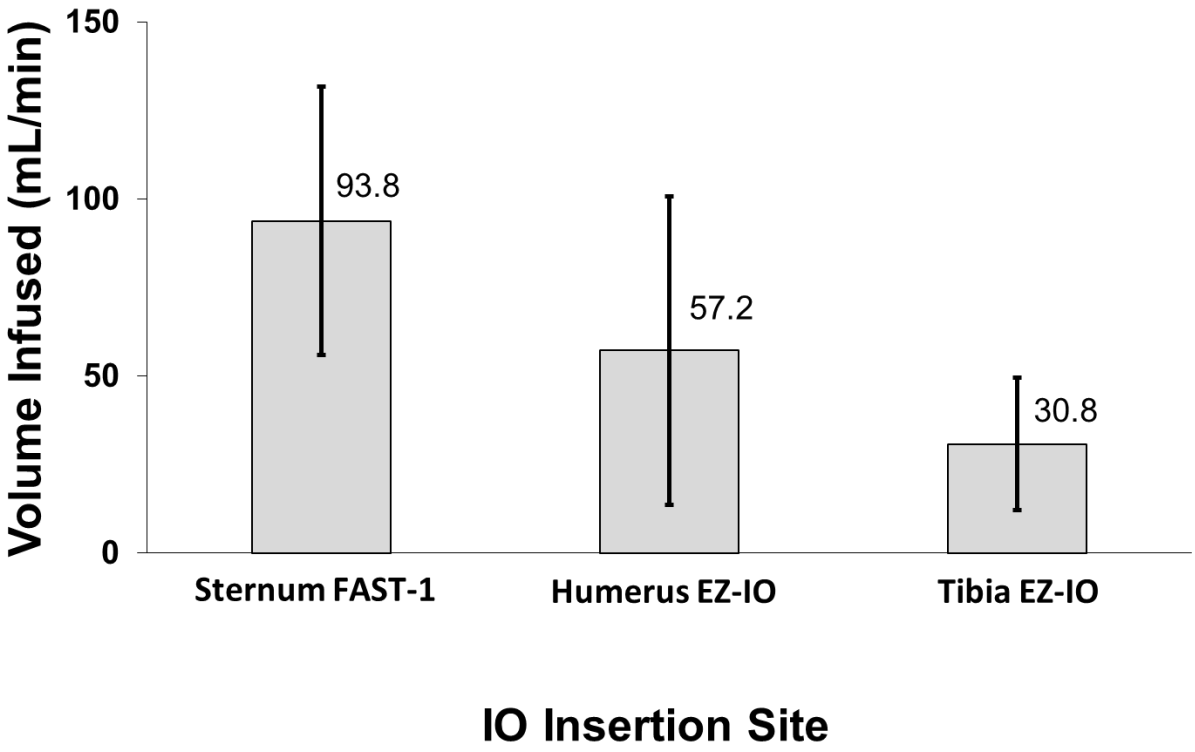

Figure 2. Average Infusion Rate into the Three IO Devices
(*fluid infused sequentially)*

5.2 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 mL/min ± 3.45, (2) EZ-IO [25 mm] 295 mL/min ± 8.43, and (3) EZ-IO [45 mm] 277 mL/min ± 4.3 ($p<0.01$).

6.0 DISCUSSION

When traditional vascular access methods fail, emergency access through the IO route can be lifesaving. Fluids, medications, blood components, and intravenous 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 utilizing a fresh human cadaver model. We hypothesized that there might be a difference in bolus flow rates between these three most commonly utilized 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 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 x 155 mm) and the two lengths of the EZ-IO (15 gauge x 25 mm) and (15 gauge x 45mm) (Figure 2). Predictably, the FAST-1 device has the highest intrinsic resistance to flow. Even so, the sternal access point utilizing the FAST-1 demonstrated significantly faster flow than the other sites tested utilizing the EZ-IO likely due to more limiting differences in the physiology and bony structure at these infusion sites.

In this study, IO catheters were successfully placed in the sternum, humerus, and tibia with high initial rates of success. Macnab et al. previously reported an overall success rate for sternal IO placement by paramedics and emergency medicine physicians of 84%. First-time users were successful on 74% of attempts and experienced users on 95%, with "experience" defined as one previous successful placement [30]. Paxton, Knuth, and Klausner showed, in a prospective observational study in patients requiring vascular access for resuscitation, the humeral IO site had an 81% first attempt placement success rate, compared to 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 [31]. Similarly, Leidel et al. 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 [32]. 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.

In a prospective observational study comparing flow rates between the humeral and tibial IO sites, Ong et al. 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 versus 84.4 mL/min without a pressure bag and 165.3 versus 153.2 mL/min with a pressure bag [33]. 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 the tibia. Flow rates at both sites were slower in the present study compared to the Ong study. The Ong study did not evaluate the sternal IO access site.

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 not only be related to initial placement but also 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 as with 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 a 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 that 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 versus 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 due to differing viscosities, we identified that the highest crystalloid flow rate was achieved at the sternal IO site using the FAST-1 device.

7.0 CONCLUSIONS

Rapid vascular access remains a life-threatening challenge in the resuscitation of severely injured trauma patients. Intraosseous 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 to 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 to 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 appears to be an optimal IO site for most adult resuscitations. Further study is required to confirm this assessment.

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LIST OF ABBREVIATIONS AND ACRONYMS

CVC central venous catheter

IO intraosseous

IV intravenous