

Intraoperative monitoring of femoral head perfusion in adult femoral neck fractures

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Abstract

Objectives: To validate a novel intraoperative method of quantifying femoral head perfusion in adult patients with femoral neck fractures and to determine whether the lack of a perfusion waveform correlates with the development of osteonecrosis, nonunion, or reoperation.

Design: Prospective cohort.

Setting: Level 1 trauma center.

Patients/Participants: Nineteen patients with 20 acute femoral neck fractures treated with hip-preserving surgical fixation. All patients underwent intraoperative quantification of femoral head perfusion.

Intervention: Intraoperative quantification of femoral head perfusion pressure and waveform utilizing an intracranial pressure monitor.

Main outcome measurements: Radiographic union, avascular necrosis, revision surgery.

Results: Nineteen patients (8 male, 11 female, average age 56 ± 21 years) with 20 femoral neck fractures were enrolled. Eight fractures were stable (Garden 1-2/OTA B1.1-1.3) and 12 were unstable (Garden 3-4/OTAB2.1-3.3). A waveform was present in 12 of 20 cases. The average pressures were systolic 36.8 mm Hg, diastolic 30.8 mm Hg, pulse pressure 6.0 mm Hg. A perfusion waveform was significantly associated with advanced age ($P=0.02$) and accompanied by trend toward stable fracture patterns. There were 4 deaths during the 1-year follow-up period (20%), and there were 5 conversions to total hip arthroplasty (25%). There was no significant association between revision surgery or death with the absence of a waveform.

Conclusions: Our study demonstrated the feasibility of a relatively low cost, minimally invasive, technique to quantify femoral head perfusion. In our limited sample, the absence of perfusion did not correlate with our main outcomes; however, the trend toward correlation with increased fracture displacement was as expected. A larger cohort of patients will be needed to detect a significant difference between those with and without a perfusion waveform with regards to our primary outcomes. Further study is needed to delineate the role such data may play in medical decision making at the time of index surgery.

Level of Evidence: Prognostic Level II.

Keywords: avascular necrosis, femoral neck fracture, intraoperative monitoring, nonunion, surgical fixation

1. Introduction

Femoral neck or intracapsular fractures of the hip represent a significant source of morbidity and mortality to the health care

system worldwide. Current management practices vary but generally focus on internal fixation in the physiologically young for any fracture pattern and for minimally displaced fracture patterns in older adults.^[1] Internal fixation techniques can vary by implant type and position, without significant differences in outcome.^[2,1] Arthroplasty, either total hip arthroplasty or hemiarthroplasty, are used for active and more sedentary individuals, respectively.^[3] Within this paradigm, younger patients who undergo internal fixation are still burdened with an extremely high number of reoperations (18%),^[4] as well as complications, including nonunion (9–10%) and avascular necrosis (18–23%).^[4,5] While every effort to preserve the femoral head in very young patients should be made, there remains a subset of borderline patients (ages 40–65) in whom damage to the femoral head from displacement and fracture make the likelihood of reoperation large enough to possibly warrant arthroplasty rather than internal fixation.

The blood supply of the femoral head derives primarily from the medial femoral circumflex artery with secondary contributions from the foveal (ligamentum teres), lateral femoral circumflex, and inferior gluteal arteries.^[6,7] There are several factors, not all of which are under a surgeon's control, that contribute to revision surgery. These include age, smoking, sex,

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obesity, open procedure, fracture displacement, and implant placement.^[8,9] While interruption of the blood supply to the femoral head is thought to be a contributing factor,^[10] there are no routine intraoperative methods that may be taken to assess blood flow during surgical stabilization. If a consistent intraoperative measurement of femoral head vascularity could be assessed and evaluated, it may prove useful in determining if primary arthroplasty is a better choice for an individual of indeterminant age.

Femoral head perfusion has been measured using a percutaneous method in the pediatric population that has undergone surgery for slipped capital femoral epiphysis.^[11] This method utilizes a readily available pressure monitoring to detect blood flow in the femoral head and presents this as a perfusion waveform, similar to the data generated by an arterial line. This method has not been used to date to evaluate blood flow in adult femoral neck fractures. The purpose of this study was to evaluate a novel percutaneous method of monitoring femoral head perfusion in adult patients with femoral neck fractures and correlate that intraoperative perfusion with subsequent development of osteonecrosis, nonunion, or reoperation. Our hypothesis was that fractures demonstrating decreased perfusion would have an increased rate of reoperation or complications of nonunion and avascular necrosis. As a pilot study with a low number of initial patients due to funding constraints, we also hoped to use the pilot data to estimate a post-hoc power analysis to estimate the patient sample size needed to detect a significant difference between perfused and nonperfused groups, if no significant difference was detected.

2. Materials and methods

2.1. Patient selection

Between June 2018 and April 2019, we performed a prospective case series of 8 minimally displaced (Garden 1–2/OTA B1.1–1.3) and 12 displaced hip fractures (Garden 3 or 4/OTA B2.1–3.3) in 11 patients who were undergoing either dynamic hip screw with antirotation screw or cannulated screw fixation. Patients were excluded if they had prior ipsilateral hip pathology or surgery, were being treated with arthroplasty, were below the age of 18, or did not consent to the procedure. We obtained Institutional review board approval and all 19 patients provided informed consent. The investigation involving human subjects reported in the manuscript was performed with informed consent and following all the guidelines in place at WellStar Atlanta Medical Center, Atlanta, Georgia.

Femoral neck fracture was diagnosed by clinical and radiographic evaluation. Prospectively collected data included patient characteristics, fracture characteristics, intraoperative data, and follow-up data. Follow-up data were collected for 12 months or until reoperation, whichever came first. Reoperations were only considered to be major reoperations to include osteotomy or arthroplasty for avascular necrosis or femoral neck nonunion with implant failure. Patient characteristics collected included sex, age, BMI, and any history of hip pathology. Fracture characteristics included the Orthopedic Trauma Association (OTA) and Garden classification of the hip fracture. Intraoperative data included the type of fixation construct, type of reduction performed (open vs closed), reduction quality (per Lowell's Criteria), time to surgery (in hours), the waveform data including the patient blood pressure at the time of recording, the systolic, diastolic, and mean arterial pressure (MAP) of the

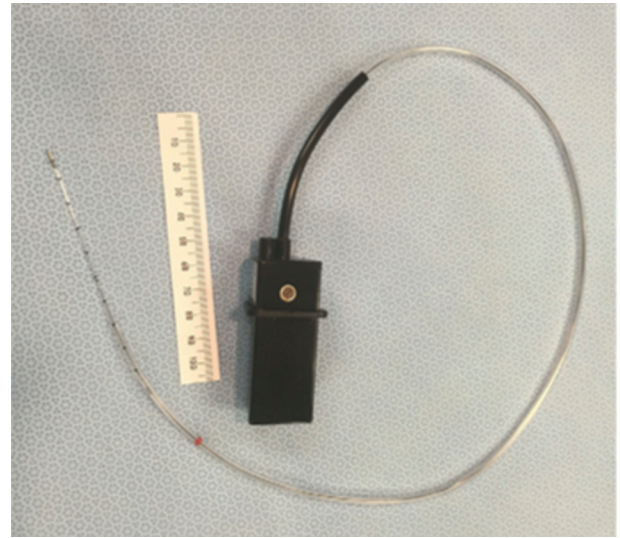


Figure 1. Camino Intracranial Pressure (ICP) Monitor probe (Integra Camino; Integra LifeSciences Corporation, Princeton, New Jersey).

waveform from the Camino probe. Follow-up data included major reoperation, fracture union at 12 months if reoperation had not occurred, avascular necrosis (AVN) classification at 12 months if reoperation had not occurred, and Harris Hip Scores and Short Musculoskeletal Functional Assessment Scores (SMFA) at 12 months for all patients not undergoing reoperation.

2.2. Surgical technique

Surgery was performed in an expeditious manner upon presentation to our facility. The exact technique (open vs closed), approach (anterior with lateral widow for implant or antero-lateral approach), and construct [dynamic hip screw (DHS) with antirotation screw vs 3 cannulated screws] was left up to the operating physician. In all cases, an anatomic reduction was the goal to minimize postoperative complications and reoperations. Once reductions had been obtained and provisionally fixed with the chosen construct, a stainless-steel 7.0mm cannulated screw (Smith & Nephew) was inserted past the fracture site but incompletely into the femoral head.^[12] Fluoroscopic imaging was used to monitor rotation and/or displacement of the fracture as the screw was advanced past the fracture site and then the guidewire was removed. A sterile Camino Intracranial Pressure (ICP) Monitor probe (Integra Camino; Integra LifeSciences Corporation, Princeton, New Jersey) (Fig. 1) was inserted into the femoral head and position verified with fluoroscopy (Fig. 2). Intraoperative femoral head perfusion pressure and waveforms were recorded (Fig. 3). Waveforms with measurable, arterial-like pulsations synchronous with the heart rate of the patient were believed to represent femoral head perfusion. The probe was then removed, and a guidewire replaced and the cannulated screw advanced to its final depth. All hips in this study were treated with at least a single screw, and only a 7.0mm screw would allow passage of the probe.

The Camino is an FDA-approved device used to rapidly determine and continuously monitor intracranial pressure and perfusion. It uses a sterile transducer-tipped pressure-monitoring catheter to produce an artifact free, high-fidelity waveform

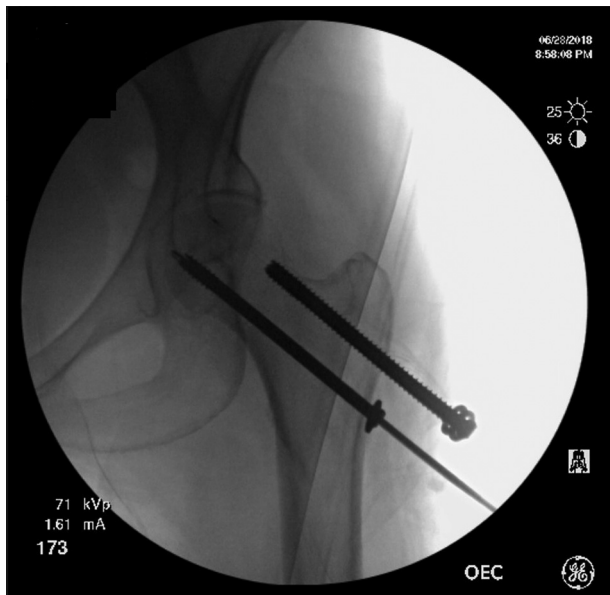


Figure 2. Fluoroscopy verification image of Camino Intracranial Pressure (ICP) Monitor probe (Integra Camino; Integra LifeSciences Corporation, Princeton, New Jersey) inserted into the Femoral head.

tracing without the need for a “fluid-filled” system. In the study application, the monitor quantified perfusion pressure in the femoral head rather than cerebral tissue pressure. The use of the ICP probe in the present study was off label as the device has not been approved for this application by the US Food and Drug Administration.

2.3. Postoperative management

Patients were typically discharged from the hospital after demonstrating mobility with partial weight bearing using crutches or a walker. The use of assistive devices was continued for 6 weeks. Anteroposterior and frog-leg lateral pelvic radiographs were made at every postoperative clinic visit at 2 weeks, 6 weeks, 3 months, 6 months, and 1 year. At 1 year, for those patients who had not undergone revision surgery (no osteotomies were performed in our cohort but 5 patients did undergo total hip arthroplasty), a Harris Hip Score, SMFA, evaluation of union on radiographs and Ficat classification of any AVN was performed.

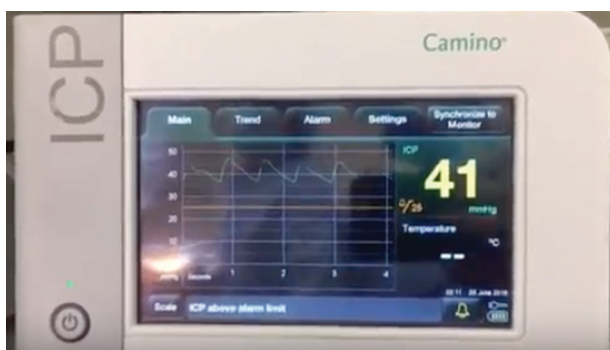


Figure 3. Recording of intraoperative femoral head perfusion pressure and waveforms.

2.4. Statistical analysis

Descriptive statistics were calculated for all variables. Differences in variables between the stable and unstable fracture groups, as well as the perfused and nonperfused patients were performed using a Fisher exact test for dichotomous variables and a Student *t* test for continuous variables. All statistics were analyzed at the 95% significance level. A power calculation using a Pearson Chi-Square test was performed set at 80% nominal power to estimate sample sizes required to detect a 5-point and 20-point percentage difference between the waveform and nonwaveform groups, with regards to major revisions.

3. Results

There were 19 total patients with 20 total femoral neck fractures. The data for patient demographics are shown in Table 1. The sex distribution was 11 females and 9 males; while the average age of the cohort was 56 ± 21 years and the average BMI was 26 ± 7 . Overall, the cohort arrived in the operating theater within 28.9 ± 27.9 hours of presentation. There were 8 stable fracture patterns (Garden 1 or 2/OTA B1.1–1.3) in 8 patients and 12 unstable fracture patterns (Garden 3 or 4/OTAB2.1–3.3) in 11 patients. An open technique was used in 7 cases while a reduction was obtained closed in 13 cases. A waveform was present in 12 of 20 cases. There were 4 deaths during the yearlong follow-up period and 5 revision surgeries (defined as a major revision, all 5 were total hip arthroplasties). All major revision surgeries were performed for nonunion, there were no cases on avascular necrosis. There were 2 minor revisions that consisted of implant removal.

In comparing patients who had a waveform versus those who did not (Table 2), there were no significant differences found. Overall, 5 of the 12 unstable hips did not have a pulsatile waveform, while 7 of the 8 stable fracture patterns did. This data reflects a trend toward not having a waveform being associated with an unstable fracture pattern ($P = .07$), but this did not reach statistical significance. Of note, there was no significant association with the absence of a waveform and revision surgery, or even death and revision surgery if the portion of patients who died within a year would be considered together. No difference was found between follow-up scores (SMFA, SMFA-Bother, and Harris Hip Score) in either group.

When comparing the demographic characteristics of the stable and unstable fracture cohorts (Table 3), there were statistically significant differences between sex ($P = .0014$), and both reduction technique and construct selection ($P = .015$). A nonsignificant trend toward older age ($P = .079$) was noted. One would expect the minimally displaced cohort tended to be female, older and treated using a closed technique with a 3-screw construct, as younger patient femoral neck fractures tend to be higher energy with greater displacements. There was again no significant difference between stable and unstable fracture cohorts with regards to revision surgery of any definition nor any difference between follow-up scores (SMFA, SMFA-Bother, and Harris Hip Score).

Waveform characteristics are shown in Table 4. The average systolic pressure was 36.8 mm Hg and the average diastolic pressure was 30.8 mm Hg, with an average pulse pressure of 6.0 mm Hg. There was no significant difference between stable and unstable fracture pattern pressures of any kind.

Follow-up data is also shown in Table 5. Overall, there were 4 deaths during the 1-year follow-up period (20%), and there were 5 conversions to total hip arthroplasty (25%). There was 1 patient lost to follow-up. Of the remaining patients who went on to union by a year their average Harris Hip Score was 72.5 ± 12.9 , their average SMFA score was 32.7 ± 23.6 , and SMFA-B score was 27.2 ± 12.7 .

Table 1
Patient demographics, fracture pattern, and operative findings

Patient number	Sex	Age	BMI	Garden class	OTA class	Construct used	Reduction technique	Reduction quality (Lowell's)	Time to surgery (hours)	Waveform
1	F	39	17.6	1	31-B1.1	3 screws	Closed	Acceptable	4	No
2	F	56	17.9	2	31-B1.2	3 screws	Closed	Anatomic	9	Yes
3	F	80	22.1	1	31-B1.1	3 screws	Closed	Acceptable	15	Yes
4	M	59	20.6	4	31-B2.2	DHS + Screw	Open	Borderline	61	No
5	F	85	24.4	2	31-B1.2	3 screws	Closed	Anatomic	16	Yes
6	M	48	23.3	3	31-B3.1	3 screws	Closed	Acceptable	10	Yes
7	F	84	22.2	1	31-B1.1	3 screws	Closed	Acceptable	13	Yes
8	F	99	25.6	4	31-B2.1	DHS + Screw	Closed	Acceptable	36	No
9	M	56	28.3	3	31-B3.1	DHS + Screw	Open	Acceptable	12	Yes
10	M	34	18.1	4	31-B2.3	3 Screws	Open	Acceptable	75	No
11	M	58	18.3	4	31-B2.2	DHS + Screw	Closed	Acceptable	15	Yes
12	F	37	45.6	4	31-B3.3	DHS + Screw	Open	Anatomic	96	Yes
13	M	42	33	4	31-B3.2	3 Screws + Plate	Open	Acceptable	90	No
14	M	59	22.8	3	31-B3.1	3 Screws	Open	Anatomic	14	Yes
15	M	38	30.4	4	31-B3.3	3 Screws	Closed	Borderline	16	No
				4	31-B3.3	DHS + Screw	Closed	Borderline	16	No
16	F	77	22.2	1	31-B1.1	3 screws	Closed	Acceptable	19	Yes
17	F	72	26.9	2	31-B1.3	3 Screws	Closed	Anatomic	18	Yes
18	F	23	35.5	4	31-B3.3	DHS + Screw	Open	Anatomic	24	No
19	F	35	28.6	2	31-B1.2	3 screws	Closed	Anatomic	19	Yes

BMI = body mass index; DHS = dynamic hip screw; OTA = Orthopedic Trauma Association.

Setting our power at the 80% level and using a Pearson Chi-Square test, an estimated sample size was determined to detect a significant difference between the waveform and nonwaveform group. A 5-percentage point improvement in major revision, with

80% likelihood to reject the null at a 5% significance level, would require a sample size of at least 1094 per group. A more powerful 20-percentage point improvement in major revision, with 80%

Table 2
Comparison between patients with and without a waveform

	Waveform	No waveform	P value
Sex			
Male	4	5	.362
Female	8	3	
Age	62.25 ± 17.34	46.5 ± 23.4	.1
BMI	25.21 ± 7.25	26.4 ± 6.96	.719
Reduction technique			
Open	3	4	.356
Closed	9	4	
Construction Technique			
3 Screw	9	4	.356
DHS	3	4	
Time to surgery	21.33 ± 23.73	40.25 ± 31.36	.142
Fracture pattern			
Stable	7	1	.0697
Unstable	5	7	
Major revision			
Yes	3	2	1
No	9	6	
Major revision or Death			
Yes	7	2	.197
No	5	6	
Any revision or death			
Yes	8	3	.3618
No	4	5	
Harris Hip Score	72 ± 18.27	74.5 ± 9.89	.7839
SMFA	40.25 ± 26.56	27.67 ± 22.34	.4403
SMFA-Bother	32.5 ± 14.11	23.67 ± 11.71	.3098

BMI = body mass index; DHS = dynamic hip screw; SMFA = Short Musculoskeletal Functional Assessment Scores.

Table 3
Comparison between stable and unstable patterns

	Stable	Unstable	P value
Sex			
Male	0	9	.0014
Female	8	3	
Age	66 ± 20	49 ± 19	.079
BMI	23 ± 4	28 ± 8	.124
Reduction Tech.			
Open	0	7	.0147
Closed	8	5	
Construct Tech.			
3 Screw	8	5	.0147
DHS	0	7	
Time to surgery (hours)	38 ± 33	14 ± 5	.051
Waveform			
Yes	7	5	.069
No	1	7	
Major revision			
Yes	1	4	.603
No	7	8	
Major revision or death			
Yes	1	6	.158
No	7	6	
Any revision or death			
Yes	5	6	.67
No	3	6	
Harris Hip Score	72 ± 14.2	74.14 ± 13.5	.826
SMFA	42.3 ± 29.7	28.6 ± 21.7	.429
SMFA-Bother	23.7 ± 17.6	28.7 ± 11.5	.6

Bold numbers indicate significant P values, P < .05.

BMI = body mass index; DHS = dynamic hip screw; SMFA = Short Musculoskeletal Functional Assessment Scores.

Table 4
Waveform characteristics

	Overall	Unstable fractures	Stable fractures	P value
Systolic (mm Hg)	36.8 ± 16.9	40.2 ± 12.7	34 ± 20.6	.57
Diastolic (mm Hg)	30.8 ± 15.8	34.8 ± 10.5	27.5 ± 19.5	.47
MAP (mm Hg)	33.6 ± 16.2	37 ± 11.3	30.8 ± 20	.55
Pulse pressure (mm Hg)	6.0 ± 3.3	5.4 ± 3.4	6.5 ± 3.4	.59

MAP = mean arterial pressure.

likelihood to reject the null at a 5% significance level, would require a sample size of at least 49 per group.

4. Discussion

Femoral head perfusion has been studied in patients with femoral neck fracture in small case series using noninvasive means such as superselective arteriography,^[13] digital subtraction angiography,^[14] and injection CT scan.^[15] In addition, other imaging modalities including PET/CT^[16] have been attempted. The diagnosis of AVN is typically made late in the patient's postoperative course utilizing plain radiographs or MRI. Other studies have investigated the utility of select imaging studies at predicting femoral head perfusion and found single photon-emission CT scan to be accurate yet not easily available and MRI to be superior to XR in early detection, but still not reliable in the early weeks after injury.^[17,18] All these techniques have had, to date, no long-term clinical correlation with outcomes such as revision surgery or functional outcome scores.

Real-time intraoperative measures such as Laser Doppler Flowmetry have been attempted, but they require drilling into the femoral head to subchondral bone and placing a laser probe. Its use has primarily been during surgical dislocation procedures and not during femoral neck fractures.^[19,20] Utilizing a technique initially reported for use in pediatric orthopaedics,^[11] we report on a minimally invasive (no more invasive than the underlying surgery) technique to obtain a measured pressure using an ICP

probe directly from the femoral head, which is recorded as a pulsatile pattern with peaks and troughs when flow is present. There is no drilling of extra holes into the proximal femur required compared with that for planned implants, and the ICP system is readily available in most hospitals and does not require additional personnel or training. As interruption of blood flow to the femoral head may be indicative of complications such as nonunion and avascular necrosis, it may be predictive of the need for secondary major procedures such as osteotomies or arthroplasties. This knowledge during the initial surgical adventure may allow surgeons to tailor their operative plans in cases where patients have a plethora of risk factors for failure of internal fixation.

Our study demonstrated the utilization of this technique to measure blood flow in both nondisplaced and displaced fractures. Given the prior use of this technique in the pediatric population,^[11] and the clinical reproducibility observed in our study, we believe this technique to be reliable and accurate in demonstrating femoral head perfusion. While the presence or absence of blood flow was not correlated to revision surgery, there was a trend toward correlation with increased displacement of fracture, which would be expected. The lack of significant correlation of pulsatile waveform to revision surgery may well be due to the low number of patients in this pilot study. The estimated sample size needed to detect a 20% point difference in revision rates is approximately 49 in each arm, while the sample size needed to detect a more conservative effect of a 5% point difference in revision rates is approximately 1094 patients in each arm. These sample sizes are the minimum for 80% power at 5% significance. Any concerns about loss to follow-up or attrition, nonparticipation, and so on may require an increase of these base numbers. Of course, there is no guarantee that either one will observe any difference, or that the difference will go in the direction one hopes (ideally a decrease in the revision rate with those patients who have a waveform), or one will find a significant result even if a difference is seen. Despite the lack of certainty regarding what may be found with further investigation, we feel that our study has demonstrated a reliable and reproducible technique effective in quantifying femoral head perfusion in the operating room. The absence of perfusion did not correlate with our main outcomes; however, the trend toward correlation with increased fracture displacement was as expected. Further study with larger patient cohorts will be necessary to assess the tool's ability to predict major complications when perfusion is absent in the femoral head. Ideally, adequately powered future work will provide an objective quantification of the intuitive relationship between a lack of perfusion and the development of major complications.

Our study had several limitations. There is the inherent difficulty of matching the patient characteristics of minimally displaced fractures to those of severely displaced fractures since there is a bias in treatment depending on age. Older patients undergo arthroplasty, so the blood flow to the femoral head is

Table 5
One-year follow-up data

Patient number	Waveform	Harris hip	SMFA	SMFA-Bother
1	No	77	9	4
2	Yes	Deceased		
3	Yes	Deceased		
4	No	Arthroplasty		
5	Yes	Arthroplasty		
6	Yes	Lost to Follow up		
7	Yes	Deceased		
8	No	61	68	38
9	Yes	92	4	15
10	No	82	37	23
11	Yes	Arthroplasty		
12	Yes	Arthroplasty		
13	No	Arthroplasty		
14	Yes	57	39	48
15	No	82	13	22
	No	82	13	22
16	Yes	56	52	38
17	Yes	Deceased		
18	No	63	26	33
19	Yes	83	66	29

SMFA = Short Musculoskeletal Functional Assessment Scores.

information that is superfluous and does not factor into the treatment algorithm. There is also the confounding nature of fracture displacement, which is an independent variable for complications and interruption of blood flow. Similarly, we did not have a reliable method to assess the effect quality of reduction may have had on our perfusion readings. Our cohort had small numbers, which was by design, since this was a pilot study demonstrating the feasibility of the technique in an adult trauma population. In addition, the technique is limited by uncertainty regarding the 5 patients converted to total hip arthroplasty for nonunion. Two of the 5 patients had no evidence of perfusion in their index operation, however, at the time of revision none of the femoral heads demonstrated avascular necrosis. This leaves open the potential for a false-negative reading in these patients and requires further study.

There is also the issue of cost, as each Camino probe does have an associated cost of around \$600 USD. The limited number of patients makes it difficult to make firm conclusions about the correlation between interruption of blood flow as measured by the Camino ICP probe technique and long-term outcomes of medical and financial significance (those requiring major revision surgery). We estimate that a larger cohort of patients (numbering at least 100 for a large effect size of 20% difference in revision rates) would be required to find a significant difference between those with blood flow and those without, with regards to revision surgery. Finally, further studies would benefit from follow-up data extending beyond the 1-year timeframe of this work to observe cases of AVN occurring beyond the first 12 months.

Despite the study's limitations, it does demonstrate the feasibility of a relatively low-cost, minimally invasive technique to obtain real-time feedback on the blood flow of the femoral head in an adult population with femoral neck fractures. Further research is needed to delineate the role that such data may play in long-term outcomes and the impact it may make on medical decision making at the time of index surgery.

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