Original Clinical Article

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The modified Dunn procedure can be performed safely in stable slipped capital femoral epiphysis but does not alter avascular necrosis rates in unstable cases: a large single-centre cohort study

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Abstract

Purpose The modified Dunn procedure for slipped capital femoral epiphysis (SCFE) remains controversial. We reviewed our series over ten years to report our learning curve, experience with intraoperative monitoring of femoral head perfusion and its correlation with postoperative Single-photon emission computed tomography (SPECT-CT) bone scan and femoral head collapse in stable and unstable SCFE.

Methods We retrospectively assessed 217 consecutive modified Dunn procedures performed between 2008 and 2018. In all, 178 had a minimum of one-year follow-up (mean 2.7 years (1 to 9.2)) including 107 stable and 71 unstable SCFE. Postoperative viability was assessed with a three-phase Tc99 bone scan and SPECT-CT. From 2011, femoral head perfusion monitoring was performed intraoperatively using a Codman Intracranial Pressure transducer and the capsulotomy was modified.

Results With intraoperative monitoring, the rate of non-viable femoral heads in stable SCFE decreased from 21.1% to 0% ($p < 0.001$). In unstable SCFE, the rate remained unchanged from 35.7% to 29.8% ($p = 0.669$). The positive predictive value (PPV) of pulsatile monitoring for no collapse was 100% in stable and 89.1% in unstable SCFE. Pulsatile monitoring and viable SPECT-CT bone scan gave a 100% PPV for all cases. A non-viable scan defines those hips at risk of collapse since 100% of stable and 68.2% of unstable hips with non-viable bone scans went on to collapse.

Conclusion Our protocol enables safe performance of this complex procedure in stable SCFE with intraoperative monitoring being a reliable asset. The avascular necrosis rate for unstable SCFE remained unchanged and further research into its best management is required.

Level of evidence: Level III

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Keywords: slipped capital femoral epiphysis; modified Dunn procedure; intraoperative monitoring; SPECT-CT bone scan; avascular necrosis

Introduction

In situ fixation is the conventional treatment for slipped capital femoral epiphysis (SCFE) due its non-invasive nature. In the setting of moderate to severe SCFE, however, there are ongoing concerns with this method of fixation due to the rates of residual deformity, gait disturbance and femoroacetabular impingement (FAI) which results in damage to the labrum and acetabular cartilage and subsequent degenerative changes.[1] With the increasing safety of advanced techniques there has been a trend towards treatment of higher grade SCFE using the modified Dunn subcapital realignment procedure through a surgical dislocation approach.[2,3] This procedure is complex and is designed to correct the deformity without compromising the blood supply of the femoral head.[4,5] Avascular necrosis (AVN) remains a significant concern with reported rates varying from 0% to as high as 67% in unstable SCFE.[4,6-22] Particularly in unstable SCFE, there is an inherent risk of AVN associated with the pathology itself, and the iatrogenic risk of AVN associated with the modified Dunn procedure remains unclear.[4,14] In stable SCFE, the AVN risk may be purely iatrogenic and several recent publications reporting high AVN rates for the modified Dunn procedure in stable SCFE advise against its use.[19,20]

As the trend toward modified Dunn subcapital realignment procedures for moderate to severe SCFE continues, the priority is to establish the safety of the procedure and reduce the rate of AVN. Intraoperative monitoring of femoral head perfusion is one technique that provides real-time intraoperative feedback and has the potential to increase the safety of this procedure. Available monitoring techniques include the use intracranial pressure (ICP) transducers, angiography, laser Doppler flowmetry or simple drill holes with observation of bleeding.[23-25] Since 2011 we have used an ICP transducer to monitor femoral head perfusion intraoperatively during the modified Dunn procedure. In an aim to further reduce the iatrogenic risk of damage to the femoral head blood supply, we modified the capsulotomy and capsular closure to avoid any tension on the supero-lateral capsular flap containing the retinacular vessel and allow a stable anterior capsular repair. Post-operative femoral head viability was assessed with a three-phase Tc99 bone scan and single-photon emission computed tomography (SPECT-CT).

The aim of this retrospective assessment is to review our series over ten years and document our learning curve including measures to increase intraoperative and postoperative safety, with particular reference to: 1) experience with intraoperative monitoring of the femoral head perfusion; 2) its correlation with postoperative SPECT-CT bone scan and; 3) radiological evidence of femoral head collapse.

Materials and methods

Study design

Institutional review board approval was obtained. Clinical and radiographic records were reviewed of all patients that underwent a modified Dunn procedure for SCFE from November 2008 to December 2018. Surgical treatment was provided by one of the three senior authors (OB, PJG, DGL). The minimum follow-up required was one year. Retrospectively collected data included patient characteristics, slip severity and stability, and the type of fixation utilized. Slip severity was assessed on the preoperative frog leg-lateral radiograph using the posterior sloping angle (PSA), as defined by Barrios et al.[26] Slip stability was defined according to the Loder classification.[27] Time from symptom onset to surgery was recorded for unstable SCFE only. The effect of time to surgery on AVN rates was evaluated by comparing delays of < 24 hours to ≥ 24 hours, and also comparing < 24 hours, 24 hours to seven days and greater than seven days to assess the 'unsafe window' as described by Kohno et al.[28] Anatomical restoration was assessed using the corrected PSA on intraoperative imaging.

Femoral head viability was assessed using intraoperative epiphyseal monitoring (see surgical technique) and postoperative SPECT-CT bone scan. AVN was defined as a non-viable SPECT-CT bone scan. Femoral head collapse was defined as any loss of sphericity of the femoral head on follow-up radiographs. The viability on postoperative SPECT-CT bone scan was then correlated with femoral head collapse on follow-up radiographs for both stable and unstable SCFE. One patient was excluded as the parents did not consent to a postoperative SPECT-CT bone scan.

All complications were recorded. Hip dislocation was classified as 'early' if it occurred less than three months postoperatively. Further procedures were recorded including total hip arthroplasty (THA), reconstructive procedures, revascularization procedures, other unplanned procedures and elective removal of hardware. Referral for consideration for THA was also recorded. Further searches were performed in state-wide radiological databases in order to identify patients who have undergone THA at alternative institutions. Postoperative clinical outcomes were beyond the scope of this study.

Surgical technique and postoperative management

All operations were performed similar to the technique described by Ganz et al[3,5] and Ziebarth et al[4] using the safe surgical dislocation of the hip via a trochanteric flip approach. It is crucially important to carefully develop the retinacular soft-tissue flap and thereafter completely resect the posterior callus, but only shorten the femoral neck enough to avoid tension on the vessel when repositioning the femoral head. We found, however, that the retinacular soft-tissue flap can be developed without full resection of the stable trochanter. After subperiosteal dissection we usually only partially resect the stable trochanter to preserve bone stock, which allows for better re-fixation of the trochanteric flip in an anatomical position. Additionally, we introduced intraoperative monitoring of femoral head perfusion and modified the capsulotomy to reduce tension on the retinacular flap following capsular closure. Fixation was performed using fully threaded cannulated screws in the vast majority (93.9%). Threaded Steinmann pins were used in the remainder, who were younger patients.

For the femoral head perfusion monitoring, a 1.5-mm drill hole is made anterolaterally into the centre of the epiphysis. Into this is placed a Codman ICP transducer (Codman Microsensor Basic Kit; Depuy Synthes, Raynham, MA, USA) which is then connected, via the ICP Express Monitoring System (Depuy Synthes, Raynham, MA, USA), to the anaesthetic monitor to produce a pulsatile trace. Monitoring is performed multiple times: prior to dislocation (unless the epiphysis is not accessible), after dissection of the retinacular flap, after realignment and fixation of the femoral head, and finally, after capsular closure. By performing intraoperative monitoring at these time points, any loss of the waveform can allow for intraoperative adjustments (for example, repositioning of the femoral head). We consider the quality of the ideally biphasic waveform to be more important than the absolute value of pressure since we have noted that the latter varies and can be influenced by multiple factors including blood pressure, vasoconstriction of the retinacular vessel and alteration in leg position (external rotation often compromises the blood flow). Figure 1 demonstrates an unstable moderate-severe SCFE with the pulsatile arterial waveform shown in Figure 1c.

We have modified the capsulotomy from the original Z-shape based on the observation that capsular closure following realignment sometimes compromises the femoral perfusion on intraoperative monitoring. We have changed the central limb of the Z from a straight capsular incision to one that is Y-shaped. This creates a V-shaped superior flap that facilitates a stable anterior closure and avoids tension on the vessel posteriorly (Figs 2 and 3).

In patients with positional intraoperative perfusion, or those considered to be at high risk of postoperative dislocation such as chronic severe slips with acetabular dysplasia,[29] a below knee broomstick cast or brace is applied postoperatively in optimal rotation and 20° to 30° abduction until the SPECT-CT is performed five to seven days postoperatively. If the SPECT-CT bone scan is viable, the patient is mobilized to touch weight bearing for six weeks before gradual progression of weight bearing. Graded progression of weight bearing may take place more slowly in the setting of severe epiphyseal osteopenia, as seen in chronic, severe SCFE. If the femoral head is non-viable, weight bearing is restricted for one year and bisphosphonate treatment is commenced in close collaboration with endocrinology.

Statistical analysis

Descriptive statistics were calculated for all variables. The positive and negative predicative values of intraoperative epiphyseal monitoring were calculated. For statistical purposes, the Shapiro-Wilk test was used to determine whether our data met the assumption of normal distribution required for a parametric test. For the data without normal distribution, the Mann-Whitney test was used. A chi-squared test was used to compare categorical data. The level of significance was set at $p < 0.05$. All analyses were performed with use of the SPSS statistics (version 23; SPSS, Chicago, Illinois).

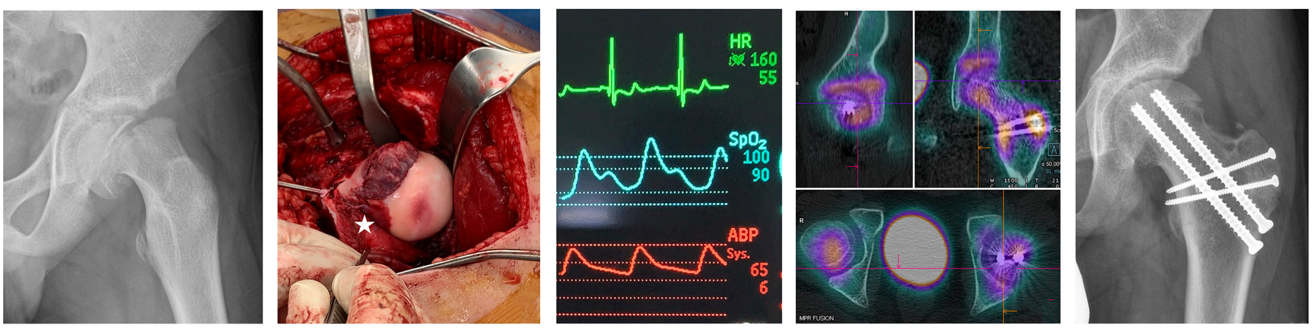

Fig. 1 a) Unstable moderate-severe slipped capital femoral epiphysis; b) with 'button-holed' appearance intraoperatively where the anterior periosteum was ripped right up to the retinacular vessel which was bruised and injected but remained intact (*); c) as confirmed by intraoperative monitoring with red pulse wave; d) a viable postoperative SPECT-CT bone scan; e) and healing with no signs of avascular necrosis or collapse.

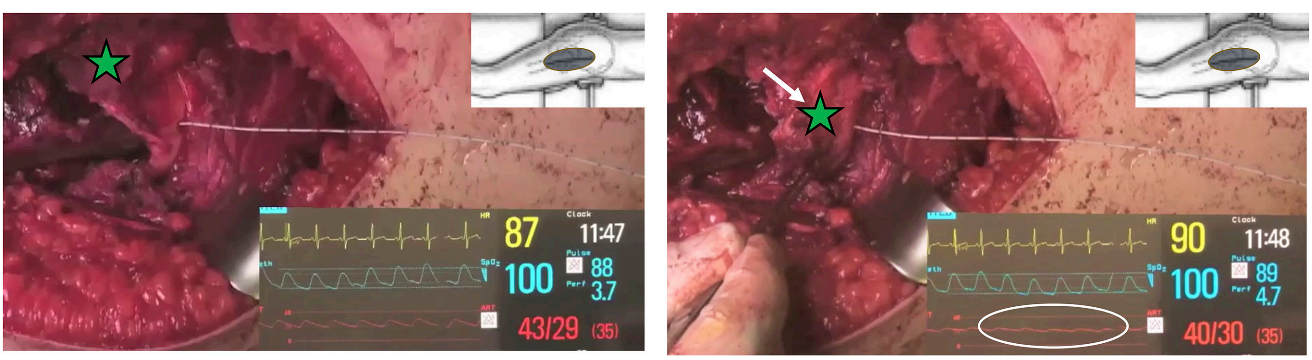

Fig. 2 Even gentle tension on the posterosuperior capsular flap of the Z-shaped capsulotomy (*) like shown here intraoperatively with a forceps (arrow) can flatten the waveform of the epiphyseal blood flow on Codman monitoring.

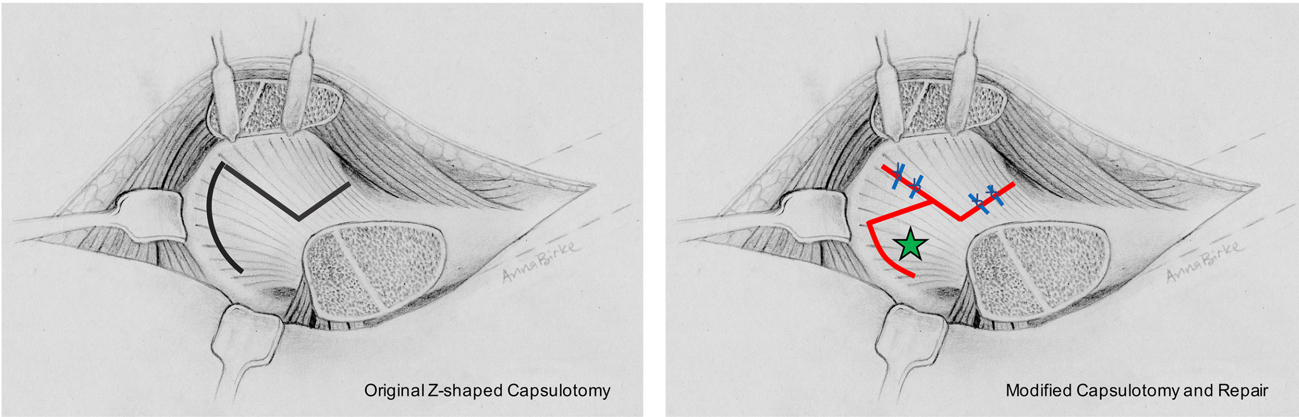

Fig. 3 Modified capsulotomy and repair: we have changed the central limb of the original Z-shaped capsulotomy from a straight incision to one that is Y-shaped. This creates a V-shaped superior flap that facilitates a stable anterior closure and avoids tension on the vessel posteriorly (*).

Results

Of the 217 modified Dunn procedures performed over the ten-year period, 178 hips (172 patients) met the minimum follow-up criteria (Fig. 4). Overall, the mean follow-up was 2.7 years (1 to 9.2). In all, 96 patients were male (55.8%) and 94 (52.8%) involved the left side. The mean age was 13.5 years (9.5 to 17.5) for male patients and 11.4 years (8.5 to 14.6) for female patients. All were moderate to severe with a mean PSA of 62° (35° to 90°). There were 107 stable (60.1%) and 71 (39.9%) unstable SCFE. A total of 117 (65.7%) were referrals from other hospitals. Five patients had undergone previous fixation at another institution, all of which were complicated by slip progression. Intraoperative monitoring was utilized in 145 hips (81.5%). The mean correction was 54° (23° to 86°) and slips were corrected to a mean PSA of 9° (30° to -7°).

There was a significantly higher rate of non-viable hips in the unstable group at 31.0% compared with 3.7% in the stable group ($p < 0.001$). In stable SCFE, the rate of non-viable scans decreased from 21.1% (4/19 hips) to 0% (0/88 hips) after intraoperative monitoring was introduced ($p = 0.001$). In the unstable group, however, the rates of non-viable scans were not significantly different at 35.7% (5/14 hips) prior to the introduction of monitoring compared with 29.8% (17/57 hips) after the introduction of monitoring ($p = 0.669$).

The sensitivity and positive predictive value (PPV) of intraoperative femoral head monitoring in predicting a viable bone scan was high (Table 1). Pulsatile monitoring had the most utility in predicting femoral head collapse in stable SCFE with a PPV of 100% and a negative predictive value (NPV) of 100%. In six unstable SCFE, a pulsatile trace was demonstrated but the postoperative imaging showed a non-viable femoral head. Pulsatile intraoperative monitoring combined with a viable SPECT-CT-bone scan had a 100% PPV for no collapse in both stable and unstable SCFE.

Overall, 26 hips (14.6%) had a non-viable postoperative SPECT-CT bone scan (AVN). A non-viable scan defines those hips at risk of collapse since the NPV for collapse in the stable and unstable groups was 100% and 68.2%, respectively. This means that 100% of stable and 68.2% of unstable hips with non-viable scans collapsed. Only one hip with a viable scan (0.6%) went on to collapse. This patient had a chronic severe stable SCFE, however, intraoperatively, severe osteopenia was noted, and no pulsatile trace could be established with intraoperative monitoring. Overall, the mean time to collapse was 7.4 months (4 to 14).

In the context of unstable SCFE, time to surgery made no significant difference to hip viability. The mean time to surgery in the viable group was 4.6 days (9 hours to

Table 1 Femoral head monitoring in predicting viability in stable and unstable SCFE (slipped capital femoral epiphysis)

	Stable SCFE*			Unstable SCFE†		
	Viable	Non-Viable	Total	Viable	Non-Viable	Total
Pulsatile	87	0	87	40	6	46
Non pulsatile	1	0	1	0	11	11
Total	88	0	88	40	17	57

*positive predictive value (PPV) 100%, negative predictive value (NPV) 0%, sensitivity 98.9%, specificity not available
†PPV 87.0%, NPV 100%, Sensitivity 100%, Specificity 64.7%

Table 2 Time to surgery in unstable SCFE (slipped capital femoral epiphysis)

	Viable, n (%)	Non-viable, n (%)	Total, n (%)
< 24 hrs	10 (*62.5*)	6 (*37.5*)	16 (*100*)
≥ 24 hrs	29 (*67.4*)	14 (*32.6*)	43 (*100*)
24 hrs to 7 days	23 (*65.7*)	12 (*34.3*)	35 (*100*)
> 7 days	6 (*75*)	2 (*25*)	8 (*100*)

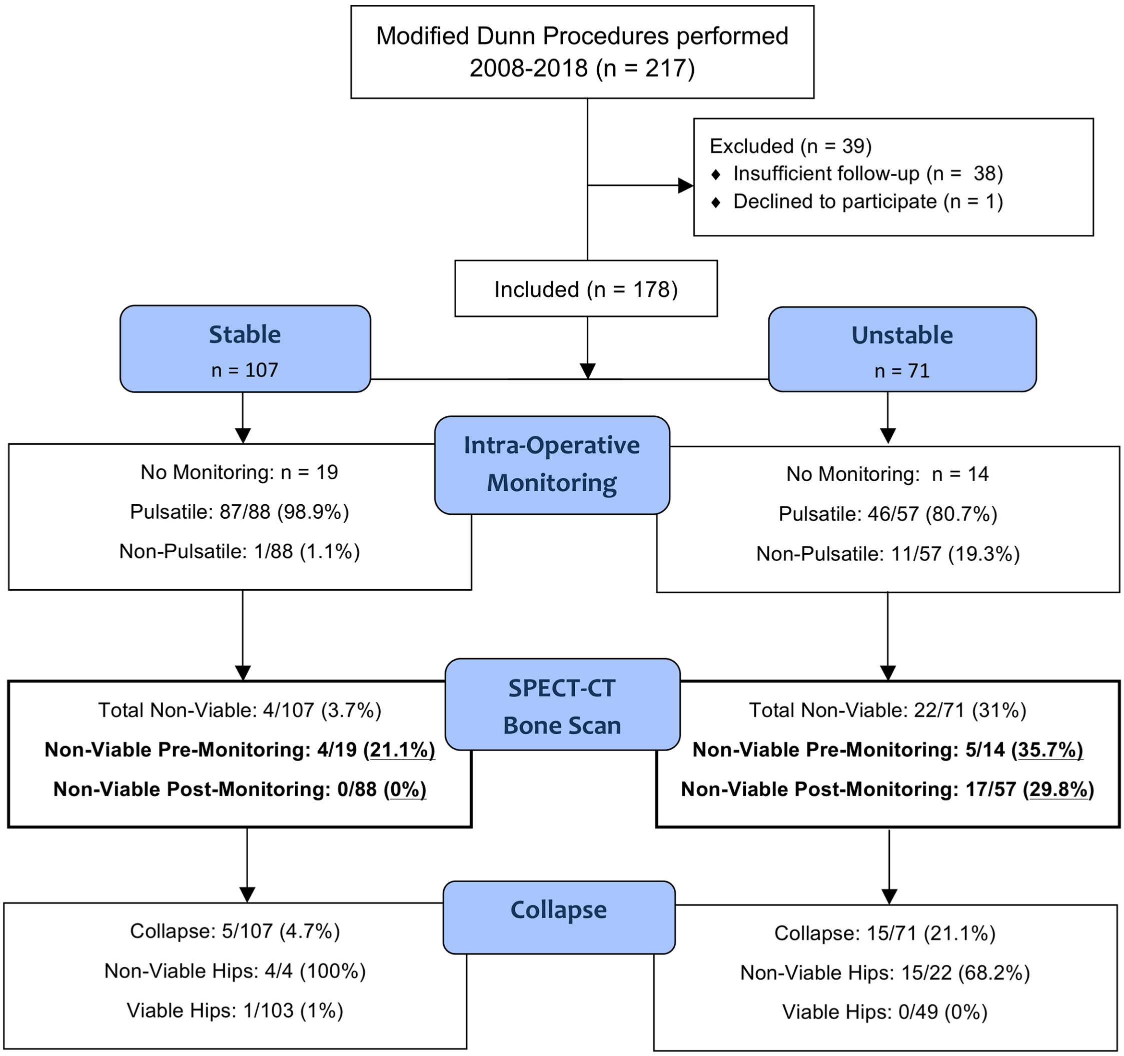

Fig. 4 Flow diagram of our patient series with correlation of intraoperative monitoring and postoperative SPECT-CT bone scan with radiological collapse for both stable and unstable slipped capital femoral epiphysis

23 days) compared with 2.7 days (16 hours to 8.9 days) in the non-viable group (p = 0.112). Time to surgery over 24 hours had no significant effect on AVN rates with 37.5% having a non-viable scan if the time to surgery was < 24 hours, compared with 32.6% if the time to surgery was 24 hours or greater (p = 0.468). With regards to the 'unsafe window', 16 hips underwent operative fixation in < 24 hours (27.1%) following symptom onset, whilst 35 underwent operative fixation between 24 hours and seven days (59.3%) and a further eight hips underwent operative fixation after seven days (13.6%). When comparing these three groups, there was no significant difference in the rates of non-viable bone scans at 37.5%, 34.3% and 25.0%, respectively (p = 0.828) (Table 2).

Complications occurred in 49 (27.5%) procedures. In total, 31 hips (17.3%) required at least one unplanned return to theatre. In all, 22 had a single return to theatre, whilst six hips required two unplanned procedures and three hips required three unplanned procedures. Just over half of unplanned returns to theatre (51%) occurred in non-viable hips. A total of 11 were referred for, and nine hips (5.0%) underwent THA for AVN. An additional six hips (3.4%) underwent revascularization procedures. Reconstructive procedures were performed in five hips (2.8%), two in the setting of collapse of the femoral head, one pelvic and femoral osteotomy for dislocation, and two for cam impingement (Table 3).

In addition, there were seven hip dislocations. Four occurred in the early postoperative period and three were late, post-traumatic dislocations. In all, 50% (2/4) of the early dislocations also had non-viable bone scans. Four were managed with a closed reduction alone. A further two hips failed closed reduction (one of which required an open reduction and one that required an open reduction and Salter and femoral osteotomies), and one hip was primarily managed with an open reduction. Further surgical management was performed to address instability, clinically significant leg-length discrepancy and hardware complications (Table 3). A total of 16 hips (9.0%) underwent planned elective removal of hardware. Other complications included four (2.2%) transient peroneal nerve palsies, one (0.6%) below knee deep vein thrombosis, one (0.6%) contralateral post-surgical inflammatory sciatic neuropathy, two (1.1%) superficial pressure areas, four (2.2%) superficial wound infections and no deep wound infections.

Discussion

The use of the modified Dunn procedure in the management of moderate to severe SCFE remains controversial. Both AVN and hip instability are a devastating consequence and remain a significant concern. We have reviewed our ten-year experience of the modified Dunn procedure in a relatively high volume centre with a large referral base. In any series over ten years there is an inevitable evolution of technique. We have identified several factors that we believe have made the procedure safer in our hands. Such techniques include femoral head pulse monitoring in stable slips; a modified capsulotomy and capsular closure technique; and control of instability in severe slips with acetabular changes.[29] However, we were unable to show any reduction in rates of AVN or femoral head collapse in unstable SCFE. Although we see it as an urgent procedure in the setting of an unstable SCFE, we could not show a difference in time to surgery with regards to rates of AVN or femoral head collapse and our rate of AVN and collapse is similar to that before we started using the modified Dunn procedure.

It is important to be clear what is meant by AVN in the context of SCFE. The pathophysiology is such that avascularity occurs at, or shortly after, the time of injury or surgery. In the current literature, femoral head collapse is often used as a marker for AVN and has been reported to occur no later than one year postoperatively in unstable SCFE.[30] In our series, collapse occurred in 73% of the non-viable femoral heads and ranged in severity from segmental collapse up to catastrophic collapse requiring THA in teenage years. We had one patient noted to collapse after the 12-month minimum follow-up period. In this particular case, the previous radiograph was performed six months postoperatively and demonstrated no evidence of collapse. We also believe that collapse occurs by one year and that this 14-month time-period represents the interval of follow-up rather than the true time to collapse. Overall, we feel that the rate of postoperative viability on SPECT-CT bone scan better captures the complete spectrum of AVN. It is possible that other series may underestimate their AVN rates by identifying AVN on plain radiographs alone as some hips may not go onto collapse despite AVN.

Table 3 Unplanned return to theatre

	Non-viable hips, n	Viable hips, n	Total, n (%)
Total unplanned procedures	25	18	43 (*24.2*)
Number			A
0	10	137	147 (*82.6*)
1	10	12	22 (*12.4*)
2	3	3	6 (*3.4*)
3	3	0	3 (*1.7*)
Reason			
Total hip arthroplasty	9	0	9 (*5.1*)
Revascularization	6	0	6 (*3.4*)
Reconstruction	1	4	5 (*2.8*)
Correction of LLD	1	1	2 (*1.1*)
Disclocation	2	5	7 (*3.9*)
Early adjustment of hardware	3	6	9 (*5.1*)
Other	3	2	5 (*2.8*)

Femoral head perfusion and monitoring in stable and unstable SCFE

There is no inherent risk of AVN preoperatively in stable SCFE[27] and, therefore, potentially all postoperative AVN and femoral head collapse is iatrogenic. Recent studies have now recommended the abandonment of the modified Dunn procedure for stable SCFE because of this high iatrogenic AVN risk.[19,20] Conversely, we feel that the modified Dunn procedure can be performed safely in stable SCFE. Since the introduction of intraoperative monitoring and the advancement in our surgical technique, we have had no cases of iatrogenic damage to the femoral head perfusion in stable SCFE (including those hips with insufficient follow-up). We believe that severe osteopenia noted intraoperatively accounted for the one stable SCFE that went onto collapse in this time period despite a viable scan.

For stable SCFE, given the reliability of pulsatile monitoring in predicting no collapse, we feel that intraoperative femoral head monitoring alone may be sufficient to assess femoral head vascularity and a postoperative SPECT-CT bone scan may not be required for all stable cases.

The role of the modified Dunn procedure in unstable SCFE remains unclear. In contrast to the promising results for Loder stable cases, in unstable SCFE our rate of non-viable cases did not significantly change with monitoring and remained relatively high. Given the absence of iatrogenic AVN with our surgical technique in the stable group, we assumed that our technique should be similarly successful and not cause iatrogenic damage in unstable slips. The inherent difference in unstable SCFE is that there is a higher likelihood of pre-injury to the retinaculum which may increases the risk of dissection of the retinacular flap, and some cases may already present with the retinacular vessels fully torn.

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Conversely, others have described low AVN rates in unstable SCFE.[4,31] We too had hypothesized that intraoperative femoral head monitoring would increase the safety of the modified Dunn procedure, particularly in unstable SCFE, as we could obtain real-time feedback as to the perfusion of the femoral head, allowing us to make intraoperative modifications such as femoral neck shortening or accepting more retroversion of the femoral head. Although intraoperative monitoring was very reliable in stable SCFE, in the unstable group, we had six cases in which the femoral head was non-viable despite a pulsatile trace being obtained at the end of the procedure. Based on these findings, we recommend both intraoperative femoral head monitoring and a postoperative SPECT-CT bone scan for all unstable SCFE in order to guide prognosis.

Time to surgery in unstable SCFE

Some authors advocate avoiding surgery within the 'unsafe window' from 24 hours to seven days post acute event in order to reduce the risk of a 'second hit' which may further contribute to vessel damage and, therefore, AVN.[28,31,32] In this study, there was no statistically significant relationship between the AVN rates for unstable SCFE and the timing to surgery, although due to the retrospective nature of this study, an accurate time of onset of symptoms was unable to be established in 12 of the 71 unstable SCFEs, which may have underpowered the analysis. We found, however, varying degrees of epiphyseal displacement and retinacular damage within the unstable group. In some of our cases the femoral head was completely separated, the retinacular vessels torn and a pulsatile trace was never recorded. In others only the anterior periosteum was torn, and even when the epiphysis was 'button-holed', the retinacular vessels were intact (Fig. 1b). The status of the retinaculum may explain wide variations in AVN rates between clinical series. There may also be cases where extensive dissection of a pre-injured retinaculum resulted in a detrimental 'second hit'. These observations occurred over time and were not specifically recorded. Ziebarth et al[33] reported the difference between clinical and intraoperative stability with Loder's clinical classification having a 37% sensitivity and 76% specificity of intraoperative physeal stability. We feel that our own intraoperative observations represent the spectrum of pathology found in unstable SCFE and that Loder unstable hips still represent those hips at risk of AVN. A prospective study of the state of the physis and retinaculum as well as time to surgery and its relationship to AVN is required.

Modified capsulotomy and capsular closure

Early in our series, two cases of 'unexplained' non-viable bone scans triggered the change to using formal intraoperative pressure monitoring with the Codman ICP pressure probe. In both these stable SCFEs the operation went well, and the femoral head showed pulsatile bleeding from a drill-hole at the end of the procedure, before capsular closure, but the postoperative bone scan was non-viable. A possible explanation is that the capsular closure compromised the femoral head perfusion by tensioning the retinacular vascular leash. Through the use of intraoperative monitoring, we were able to observe the impact of capsular closure, such that even gentle tension on the superior capsular flap after a Z-capsulotomy can flatten the waveform of the epiphyseal blood flow on Codman monitoring (Fig. 2). In our modification of the capsulotomy and capsular closure, the V-flap is not connected to the retinacular vessel and, therefore, a stable anterior capsular repair can be performed without tension and, therefore, without risking epiphyseal perfusion (see Fig. 3). Regardless of the type of capsular repair performed, we believe that it is vital to monitor epiphyseal blood flow until after capsular closure as this provides useful intraoperative feedback and can potentially prevent inadvertently compromising perfusion.

Control of instability

Other than AVN, the most significant postoperative complication we encountered was hip dislocation. This potentially devastating complication has been discussed in a few studies,[17,29,34] one of which included three of our seven cases as part of a multicentre study.[29] Excessive shortening and over-correction into valgus and anteversion should be avoided in order to maintain stability. In addition, soft-tissue contractures in external rotation can lead to antero-lateral hip instability postoperatively, particularly in chronic severe SCFE with significant preoperative obligatory external rotation. There can also be acquired acetabular dysplasia in chronic severe SCFE due to abnormal articulation of the femoral head. Instability is a difficult problem, and we are conscious to minimize shortening and optimize our reduction. In addition, we perform a stable anterior capsular repair of our modified V-flap capsulotomy and place all chronic severe SCFE and those with positional pulsatile monitoring in a broomstick cast or brace for one week postoperatively in an aim to maintain neutral or optimal rotation and 20° to 30° hip abduction.

Limitations

The limitations of this study are its retrospective design, lack of clinical and patient-reported outcome measures and a relatively high rate of patients lost to follow-up. The latter remains a significant challenge in our state healthcare system due to geographical barriers and significant cultural diversity of our SCFE patient population.

Conclusion

In our large, single centre experience of the modified Dunn procedure we have been able to eliminate the risk of AVN in stable SCFE using intraoperative monitoring. Over time, observations of the pulsatile trace during the procedure led to modification of the capsulotomy. Intraoperative monitoring should be used until after capsular closure. We have not been able to show any change in our AVN rate in unstable SCFE despite the introduction of intraoperative monitoring of femoral head vascularity. The theory of a 'second hit' has merit for further investigation based on our experience.

Pulsatile intraoperative monitoring combined with a viable postoperative SPECT-CT give a 100% PPV for no collapse in both stable and unstable SCFE. In stable SCFE intraoperative monitoring alone may be sufficient to assess femoral head vascularity. A non-viable postoperative SPECT-CT identifies the 'at risk group' for collapse in both stable and unstable SCFE. Further research into the best management of unstable SCFE is required.

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COMPLIANCE WITH ETHICAL STANDARDS

FUNDING STATEMENT

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

ETHICAL STATEMENT

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Because of its retrospective nature, the institutional ethics committee did not require informed consent from participants.

Informed consent: Not applicable.

ICMJE CONFLICT OF INTEREST STATEMENT

OB reports that he previously was a consultant for Orthofix; no direct biases were identified for this work. DGL reports that he is a consultant for OrthoPaediatrics; no direct biases were identified for this work. JStG and PJG declare they have no conflict of interest. There was no funding received for any component of this study.

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AUTHOR CONTRIBUTIONS

OB: Study design, Data acquisition, Analysis and interpretation of data, Drafting and critical revision of the manuscript, Final approval of the submitted manuscript.

JStG: Study design, Data acquisition, Analysis and interpretation of data, Drafting and critical revision of the manuscript, Final approval of the submitted manuscript.

PJG: Study design, Data acquisition, Analysis and interpretation of data, Drafting and critical revision of the manuscript, Final approval of the submitted manuscript.

DGL: Study design, Data acquisition, Analysis and interpretation of data, Drafting and critical revision of the manuscript, Final approval of the submitted manuscript.

REFERENCES

1. **Sink EL, Zaltz I, Heare T, Dayton M.** Acetabular cartilage and labral damage observed during surgical hip dislocation for stable slipped capital femoral epiphysis. *J Pediatr Orthop* 2010;30:26-30.

2. **Kim YJ.** CORR Insights(®): modified Dunn procedure is superior to in situ pinning for short-term clinical and radiographic improvement in severe stable SCFE. *Clin Orthop Relat Res* 2015;473:2118-2119.

3. **Ganz R, Gill TJ, Gautier E, Ganz K, Krügel N, Berlemann U.** Surgical dislocation of the adult hip: a technique with full access to the femoral head and acetabulum without the risk of avascular necrosis. *J Bone Joint Surg [Br]* 2001;83-B:1119-1124.

4. **Ziebarth K, Zilkens C, Spencer S, et al.** Capital realignment for moderate and severe SCFE using a modified Dunn procedure. *Clin Orthop Relat Res* 2009;467:704-716.

5. **Ganz R, Huff TW, Leunig M.** Extended retinacular soft-tissue flap for intra-articular hip surgery: surgical technique, indications, and results of application. *Instr Course Lect* 2009;58:241-255.

6. **Khalil AMM, Elsherif ORE.** Short-term outcomes of the modified Dunn procedure in the treatment of slipped capital femoral epiphysis. *Curr Orthop Pract* 2014;25:352-355.

7. **Balakumar B, Madan S.** Late correction of neck deformity in healed severe slipped capital femoral epiphysis: short-term clinical outcomes. *Hip Int* 2016;26:344-349.

8. **Huber H, Dora C, Ramseier LE, Buck F, Dierauer S.** Adolescent slipped capital femoral epiphysis treated by a modified Dunn osteotomy with surgical hip dislocation. *J Bone Joint Surg [Br]* 2011;93-B:833-838.

9. **Lawane M, Belouadah M, Lefort G.** Severe slipped capital femoral epiphysis: the Dunn's operation. *Orthop Traumatol Surg Res* 2009;95:588-591.

10. **Madan SS, Cooper AP, Davies AG, Fernandes JA.** The treatment of severe slipped capital femoral epiphysis via the Ganz surgical dislocation and anatomical reduction: a prospective study. *J Bone Joint Surg [Br]* 2013;95-B:424-429.

11. **Massè A, Aprato A, Grappiolo G, et al.** Surgical hip dislocation for anatomic reorientation of slipped capital femoral epiphysis: preliminary results. *Hip Int* 2012;22:137-144.

12. **Niane MM, Kinkpé CV, Daffé M, et al.** Modified Dunn osteotomy using an anterior approach used to treat 26 cases of SCFE. *Orthop Traumatol Surg Res* 2016;102:81-85.

13. **Novais EN, Hill MK, Carry PM, Heare TC, Sink EL.** Modified Dunn procedure is superior to in situ pinning for short-term clinical and radiographic improvement in severe stable SCFE. *Clin Orthop Relat Res* 2015;473:2108-2117.

14. **Sankar WN, Vanderhave KL, Matheney T, Herrera-Soto JA, Karlen JW.** The modified Dunn procedure for unstable slipped capital femoral epiphysis: a multicenter perspective. *J Bone Joint Surg [Am]* 2013;95-A:585-591.

15. Slongo T, Kakaty D, Krause F, Ziebarth K. Treatment of slipped capital femoral epiphysis with a modified Dunn procedure. *J Bone Joint Surg [Am]* 2010;92-A:2898-2908.

16. Souder CD, Bomar JD, Wenger DR. The role of capital realignment versus in situ stabilization for the treatment of slipped capital femoral epiphysis. *J Pediatr Orthop* 2014;34:791-798.

17. Upasani VV, Matheney TH, Spencer SA, et al. Complications after modified Dunn osteotomy for the treatment of adolescent slipped capital femoral epiphysis. *J Pediatr Orthop* 2014;34:661-667.

18. Rebello G, Spencer S, Millis MB, Kim YJ. Surgical dislocation in the management of pediatric and adolescent hip deformity. *Clin Orthop Relat Res* 2009;467:724-731.

19. Davis RL II, Samora WP III, Persinger F, Klingele KE. Treatment of unstable versus stable slipped capital femoral epiphysis using the modified Dunn procedure. *J Pediatr Orthop* 2019;39:411-415.

20. Sikora-Klak J, Bomar JD, Paik CN, Wenger DR, Upasani V. Comparison of surgical outcomes between a triplane proximal femoral osteotomy and the modified Dunn procedure for stable, moderate to severe slipped capital femoral epiphysis. *J Pediatr Orthop* 2019;39:339-346.

21. Masquijo JJ, Allende V, D'Elia M, Miranda G, Fernández CA. Treatment of slipped capital femoral epiphysis with the modified Dunn procedure: a multicenter study. *J Pediatr Orthop* 2019;39:71-75.

22. Alves C, Steele M, Narayanan U, et al. Open reduction and internal fixation of unstable slipped capital femoral epiphysis by means of surgical dislocation does not decrease the rate of avascular necrosis: a preliminary study. *J Child Orthop* 2012;6:277-283.

23. Nötzli HP, Siebenrock KA, Hempfing A, Ramseier LE, Ganz R. Perfusion of the femoral head during surgical dislocation of the hip. Monitoring by laser Doppler flowmetry. *J Bone Joint Surg [Br]* 2002;84-B:300-304.

24. Jackson JB III, Frick SL, Brighton BK, et al. Restoration of blood flow to the proximal femoral epiphysis in unstable slipped capital femoral epiphysis by modified Dunn procedure: a preliminary angiographic and intracranial pressure monitoring study. *J Pediatr Orthop* 2018;38:94-99.

25. Ziebarth K, Leunig M, Slongo T, Kim YJ, Ganz R. Slipped capital femoral epiphysis: relevant pathophysiological findings with open surgery. *Clin Orthop Relat Res* 2013;471:2156-2162.

26. Barrios C, Blasco MA, Blasco MC, Gascó J. Posterior sloping angle of the capital femoral physis: a predictor of bilaterality in slipped capital femoral epiphysis. *J Pediatr Orthop* 2005;25:445-449.

27. Loder RT, Richards BS, Shapiro PS, Reznick LR, Aronson DD. Acute slipped capital femoral epiphysis: the importance of physeal stability. *J Bone Joint Surg [Am]* 1993;75-A:1134-1140.

28. Kohno Y, Nakashima Y, Kitano T, et al. Is the timing of surgery associated with avascular necrosis after unstable slipped capital femoral epiphysis? A multicenter study. *J Orthop Sci* 2017;22:112-115.

29. Upasani VV, Birke O, Klingele KE, et al. Iatrogenic hip instability is a devastating complication after the modified Dunn procedure for severe slipped capital femoral epiphysis. *Clin Orthop Relat Res* 2017;475:1229-1235.

30. Loder RT. What is the cause of avascular necrosis in unstable slipped capital femoral epiphysis and what can be done to lower the rate? *J Pediatr Orthop* 2013;33:S88-S91.

31. Persinger F, Davis RL II, Samora WP, Klingele KE. Treatment of unstable slipped capital epiphysis via the modified Dunn procedure. *J Pediatr Orthop* 2018;38:3-8.

32. Vanhegan IS, Cashman JP, Buddhdev P, Hashemi-Nejad A. Outcomes following subcapital osteotomy for severe slipped upper femoral epiphysis. *J Bone Joint Surg [Br]* 2015;97-B:1718-1725.

33. Ziebarth K, Domayer S, Slongo T, Kim YJ, Ganz R. Clinical stability of slipped capital femoral epiphysis does not correlate with intraoperative stability. *Clin Orthop Relat Res* 2012;470:2274-2279.

34. Aprato A, Leunig M, Massé A, Slongo T, Ganz R. Instability of the hip after anatomical re-alignment in patients with a slipped capital femoral epiphysis. *J Bone Joint Surg [Br]* 2017;99-B:16-21.