

Hazards with hips in theatre

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Background

Hip fractures are common and place a significant burden on patients and the healthcare system.¹ According to the UK National Hip Fracture Database, the number of patients sustaining a hip fracture annually is predicted to increase from 77 000 cases in 2009 towards 100 000 cases in 2033 in line with the ageing demography of the population.² Approximately 60 per cent of surgical procedures are performed on patients more than 65 years of age.³ The poor medical condition of these patients is evident in the reported distribution of preoperative ASA physical status scores: approximately 50 per cent of patients are designated ASA class III, while another ten per cent are classified as ASA IV.⁴

The most common indication for total hip replacement (THR) is disabling arthritis. THR and hemiarthroplasty are also performed for fractures of the femoral neck or intertrochanteric fractures. Hip arthroplasties may be cemented, uncemented or hybrid. Although the proportion of uncemented procedures appears to have increased in recent years, cemented arthroplasty is unlikely to be completely surpassed by uncemented arthroplasty.^{5,6}

The 2011 NICE Guidelines⁷ for hip fracture management in adults suggests that cemented implants are preferable to uncemented implants in patients undergoing arthroplasty as it results in earlier postoperative pain-free mobility and increased long-term viability. The UK National Joint Registry 14th Annual Report⁶ also indicates a reduced risk of surgical revision for cemented arthroplasties.

However, the most recent registry-based analysis from Norway based on 11000 patients found cement use to be associated with a substantially higher mortality rate within the first day postoperatively: 1 additional death per 116 operations among cemented than uncemented arthroplasties.⁸

The incidence of Bone Cement Implantation Syndrome (BCIS) in relevant orthopaedic procedures is 25–30%⁹ and the incidence of a severe reaction resulting in cardiovascular collapse and mortality within this group is 0.5–2.7%.^{10,11} In more severe forms, BCIS confers a 16-fold increase in 30-day postoperative mortality.⁹

In a study by Rutter et al.¹², 89% of reports described an acute deterioration of patient physiology occurring during or within

a few minutes of cement insertion with up to 80% of deaths occurring on the operating table. Olsen et al.⁹ reported that 95% of the patients who died within 48 hours had BCIS grade 2 or 3 during surgery.

Interestingly, Costain et al.¹³ showed that at one year after operation, the mortality was reversed in favour of cemented hemiarthroplasties, suggesting that high-risk patients are more likely to succumb to BCIS in the early perioperative period if bone cement is used.

Furthermore, Rutter et al.¹² stated that the true incidence of BCIS is unknown due to serious under-reporting in the literature. Case reports generally identify fatalities, and lesser degrees of BCIS are probably under-reported in the literature. Importantly though, early mortality in BCIS grade 1 and 0 was 9.3% and 5.2% respectively.⁹

Although primarily a problem associated with hip replacement, BCIS has also been described during other cemented procedures including knee arthroplasty^{14,15} and vertebroplasty.^{16,17}

Thus the ability to predict, recognise and manage BCIS in the perioperative setting is important for every anaesthesia provider.

What is Bone Cement?^{18,19}

Polymethylmethacrylate (PMMA) bone cement is an essential component in many total joint arthroplasty procedures. The cement acts like a space-filling grout in order to hold the implant against the bone.

PMMA bone cements are usually supplied as two-component systems made up of a powder with copolymer beads of PMMA and a liquid methylmethacrylate (MMA) monomer. When they are mixed, an exothermic chemical reaction called polymerisation begins which forms the PMMA bone cement that eventually hardens within minutes.

The PMMA powder also contains:

- an initiator, such as benzoyl peroxide (BPO) - which encourages the polymer and monomer to polymerise at room temperature;
- contrast agents such as zirconium dioxide (ZrO₂) or barium sulphate (BaSO₄) - to make the bone cements radiopaque;
- and may contain antibiotics (e.g. gentamicin, tobramycin).

The MMA liquid also contains:

- an accelerator or activator (N,N-Dimethyl para-toluidine) (DMPT);
- stabilisers or inhibitors (hydroquinone) - to prevent premature polymerisation from exposure to light or high temperature during storage;
- and chlorophyll or artificial pigment - sometimes added to cements for easier visualisation in case of revision.

Complications of Antibiotics in Bone Cement²⁰

Complications of antibiotic impregnated in bone cement are the same as for systemic antibiotic use:

- Attenuation of the structural and mechanical properties of bone cement
- Antibiotic resistance
- Allergic reactions
- Systemic complications, such as acute renal failure²¹
- Cost implications.

Safety Issues Related to Bone Cement²²

The components of PMMA bone cement (powder and liquid MMA monomer) are toxic and highly flammable. Ignition of monomer vapours caused by the use of electrocautery devices in surgical sites near freshly implanted bone cement has been reported.²³ Excessive exposure to the concentrated vapours of the liquid MMA monomer may produce irritation of the respiratory tract, eyes, and possibly the liver. MMA fumes, which are emitted during preparation of PMMA bone cement, have been shown to have toxic side effects ranging from allergic reactions to neurological disorders. Although there is no evidence for potential carcinogenicity of the substance, all efforts should be made to reduce the exposure.

Methods of Cement Application¹⁸

- Digital – surgeon applies cement by hand.
- Syringe/Cement gun – applied retrograde using a bone/cement restrictor to prevent overflow and allow for pressurisation of the cement within the intramedullary canal in order to improve cement contact and penetration into the interstices of the bone.
- Vacuum mixing and delivery - reduces monomer evaporation and exposure in theatre.

Cementing Techniques¹⁸

The continuous advancement in cementing can be classified from first to third generation techniques, with the changes occurring in bone bed preparation, cement preparation and cement delivery.

Current third generation cementing techniques include:

- Vacuum-centrifugation used to prepare cement.
- Femoral canal irrigated with pulsatile lavage and packed with adrenaline soaked gauze.
- Prosthesis inserted using stabilisers.

BONE CEMENT IMPLANTATION SYNDROME

Definition

An exclusively intraoperative embolic phenomenon, BCIS is poorly understood and has no agreed upon definition. Donaldson et al.²⁴ proposed the following definition:

“BCIS is characterized by hypoxia, hypotension or both and/or unexpected loss of consciousness occurring around the time of cementation, prosthesis insertion, reduction of the joint or, occasionally, limb tourniquet deflation in a patient undergoing cemented bone surgery.”

It is commonly associated with, but not restricted to, hip arthroplasty and usually occurs at one of the six stages in the surgical procedure namely: femoral reaming; acetabular or femoral cement implantation; insertion of the prosthesis, joint reduction, or limb tourniquet deflation.²⁴⁻²⁶

Embolisation of femoral canal contents either through a patent foramen ovale or after transit through pulmonary vasculature has been suggested as a cause for postoperative delirium.²⁶

Clinical Features

BCIS has a wide spectrum of severity. Clinical features may include hypoxia, hypotension, cardiac arrhythmias, increased pulmonary vascular resistance (PVR) and cardiac arrest.²⁵⁻²⁷

Most patients develop non-fulminant BCIS characterised by a significant, transient reduction in arterial oxygen saturation and systemic blood pressure in the peri-cementation period.²⁵⁻²⁷ A smaller proportion of patients further develop fulminant BCIS resulting in profound intraoperative cardiovascular changes, which may progress to arrhythmias, shock or cardiac arrest.¹⁴

Cardiovascular changes²⁵⁻²⁷ are variable but include:

- Reductions in mean arterial pressure (MAP), stroke volume (SV) and cardiac output (CO);
- Systemic vascular resistance (SVR) may be reduced or increased.

Pulmonary vascular changes^{28,29} include:

- The pulmonary vascular resistance (PVR) and pulmonary artery pressure (PAP) may be increased; Right ventricular ejection fraction (RVEF) may be impaired; The compliant (RV) distends and causes the interventricular septum to bulge into the left ventricle (LV), further reducing LV filling and CO.

The effects on the pulmonary vasculature are usually transient³⁰ but may persist for up to 48 hours postoperatively.¹⁴

Classification

Donaldson et al.²⁴ further proposed the following classification:

- **Grade 1:** moderate hypoxia (saturation < 94%) or hypotension [fall in systolic blood pressure (SBP) > 20%];
- **Grade 2:** severe hypoxia (saturation < 88%) or hypotension (fall in SBP > 40%) or unexpected loss of consciousness;
- **Grade 3:** cardiovascular collapse requiring CPR.

Aetiology and Pathophysiology^{24,31}

The nature of the aetiology and pathophysiology is not fully understood. Three dominant theories have been postulated:

1. MONOMER-MEDIATED MODEL

- Circulating MMA monomers cause vasodilatation in vitro.³²
- This hypothesis is not supported in vivo in a number of animal studies that have shown that the plasma MMA concentration after cemented hip arthroplasty is considerably lower than the concentration required to cause pulmonary or cardiovascular effects.³³
- Thus it has been suggested that the haemodynamic changes observed in BCIS are the result of an increase in intramedullary pressure at cementation leading to embolisation, rather than a direct action of the monomer on the cardiovascular system.³⁴

2. EMBOLIC MODEL

- Embolic showers have been detected using echo in the RA, RV and PA during surgery.^{35,36}
- The physiological consequences of embolisation are the result of both a mechanical effect³⁴ and mediator release,²⁶ which provokes increased pulmonary vascular tone.
- This debris includes fat, marrow, cement particles, air, bone particles, thromboplastin and aggregates of platelets and fibrin.²⁵

Mechanism of emboli formation

- Embolisation occurs as a result of high intramedullary pressures that develop during cementation and prosthesis insertion.³⁴
- When a cemented prosthesis is being used, the cement is pressurised intentionally to force it into the interstices of the bone.
- This achieves improved bonding between the cement and bone by increasing the contact surface area.
- The cement undergoes an exothermic reaction and expands in the space between the prosthesis and bone, trapping and pushing air and medullary contents under pressure so that they are forced into the circulation.

The link between intramedullary pressure and embolization³⁴

- Cementation is achieved either with a cement gun or by manually packing the femoral canal.
- When cement is inserted into the femur using a cement gun, the pressures generated are almost double those seen when manual packing is used.
- Prosthesis insertion into the cemented femur is further associated with a considerable increase in pressure.
- The degree of embolisation may be related to the peak pressure generated in the femoral canal.
- High intramedullary pressure per se is thus an important factor in the genesis of BCIS.

The haemodynamic effects of embolisation

- The debris from the medulla can embolise to the lungs, heart or paradoxically to the cerebral and coronary circulations.²⁸
- Showers of pulmonary emboli may result in the characteristic hypoxia and RV dysfunction that leads to hypotension.²⁶

Problems with the embolic model

- Embolisation, however, does not explain all of the observed phenomena.
- Embolisation is not always associated with haemodynamic changes,³⁷ and the degree of embolism correlates poorly with the extent of hypotension or hypoxaemia.³⁶
- Hypotension, for example, has also been noted in patients where bone cement has been used during surgeries in which significant embolism is unlikely, such as percutaneous vertebroplasty.¹⁷
- Thus, although micro-embolism may be a contributing factor in BCIS, it is probable that other mechanisms co-exist.

3. MEDIATOR MODEL

Mediator release from emboli

- In addition to simple mechanical obstruction of the pulmonary circulation, there are several possible mechanisms by which emboli may result in an increase in PVR.
- First, mechanical stimulation or damage of endothelium may result in reflex vasoconstriction or release of endothelial mediators.
- Second, the embolic material may release vasoactive or pro-inflammatory substances that directly increase PVR, e.g. thrombin; or act indirectly by promoting release of further mediators which increase PVR.²⁵
- Medullary lavage before insertion of the cement significantly reduces the release of some of these mediators.²⁶
- Mediator-induced vasoconstriction, in combination with the mechanical obstruction from emboli, causes shunting of blood²⁷ that is the most likely cause of the hypoxaemia.

Histamine release and hypersensitivity

- Anaphylaxis and BCIS share many similar clinical features.
- A significant increase in plasma histamine concentration in hypotensive patients undergoing cementation has been demonstrated.³⁸ It is unclear whether the histamine release is d/2, a direct effect of the cement monomer, or through an IgE-mediated process.

Complement activation

- The anaphylatoxins C3a and C5a are potent mediators of vasoconstriction and bronchoconstriction.
- An increase in C3a and C5a levels, suggesting activation of the complement pathway, has been demonstrated in cemented hemiarthroplasty but not in uncemented hemiarthroplasty.³⁹

4. MULTI-MODAL MODEL²⁴

- It is likely that a combination of the above processes is present in any individual patient who develops BCIS.

- The extent to which each of these models contributes to the clinical features may depend upon the individual's physiological response and comorbidities.

Management of BCIS

The Association of Anaesthetists of Great Britain and Ireland (AAGBI)⁴⁰ published a 2015 guideline recommending a three-stage protocol for minimising the incidence and managing the occurrence of BCIS in cemented arthroplasty of hip fractures.

1. IDENTIFICATION OF PATIENTS AT HIGH RISK OF CARDIOPULMONARY COMPROMISE

Patient risk factors

The National Patient Safety Agency⁴¹ identified the following patient-specific risk factors for developing severe BCIS:

- Pre-existing disease;
- Pre-existing pulmonary hypertension;
- Significant cardiovascular disease;
- New York Heart Association (NYHA) class 3 or 4;
- Canadian Heart Association class 3 or 4.

In addition, Olsen et al.⁹ identified the following risk factors for developing severe BCIS Grade 2 or 3:

- ASA III or IV;
- Chronic Obstructive Pulmonary Disease;
- Diuretic use;^{*}
- Warfarin use;^{*}
- Pathological fracture (osteoporosis/bony metastases);^{27,42,43**}
- Inter-trochanteric fracture.^{27,42,43**}

*It is postulated that patients with congestive heart failure (CHF), and/or chronic atrial fibrillation, who require treatment with diuretics and warfarin may have pre-existing pulmonary venous hypertension due to increased left-sided filling pressures.

**These factors are associated with increased or abnormal vascular channels through which marrow contents can migrate into the circulation.

Patients with a patent foramen ovale or atrial-septal defect may further be at increased risk of paradoxical emboli and neurological sequelae.

Surgical risk factors

- Virgin femoral canal;^{42,43#}
- Long-stem femoral component.^{42,43##}

#Patients with a previously un-instrumented femoral canal may be at higher risk of developing BCIS than those undergoing revision surgery, because:

- There may be potentially more embolic material present in an un-instrumented femur; Previously instrumented and cemented femurs have smooth and sclerotic inner surfaces that may be less permeable to emboli.

##There is an increased risk of BCIS with a longer stem femoral component than a shorter stem because:

- More bone is reamed and cement used thereby increasing the amount of emboli;
- The longer stem penetrates and exerts more pressure deeper within the femoral canal and can thus dislodge more emboli.

2. PREPARATION OF TEAM(S) AND IDENTIFICATION OF ROLES IN CASE OF SEVERE REACTION

2.2 Preoperative multidisciplinary discussion when appropriate

The anaesthetic team should be fully involved in the preoperative assessment of patients scheduled for joint arthroplasty, allowing for full investigation of co-morbidity and pre-optimisation. In high risk cases, discussion should occur between the surgeon and anaesthetist regarding the most appropriate anaesthetic and surgical technique, including the potential risk-benefit of uncemented compared with cemented arthroplasty. The anaesthetic technique should be tailored to the individual patient and the type of prosthesis.

2.3 Pre-list briefing and World Health Organisation Safe Surgery checklist 'time-out'

Effective communication between anaesthetists and surgeons is intended to increase awareness of the potential for BCIS, enhance perioperative vigilance, reduce risk, and optimise responses should BCIS occur. It has been suggested that the step of cementation be discussed as part of the World Healthcare Organisation Surgical Safety Checklist when relevant.

A novel 'Cement Curfew'⁴⁴ protocol has been developed, and implemented at some institutions before every surgery for cemented hemiarthroplasty, which involves all members of the operating theatre team assuming specific roles and focusing around the time of prosthesis insertion.

Cement Curfew

When there is a cemented hip procedure on the operating list:

1. Identify cases requiring Cement Curfew (cemented hips) at Team Brief.
2. Discuss the need for increased monitoring.
3. Discuss appropriate cementing technique.
4. At the end of Time Out, assign roles to theatre team members.
5. Mark names against roles on Cement Curfew sheet.
6. When the cement is prepared for mixing, the scrub nurse informs the team that the Cement Curfew is about to start.
7. All members of the theatre team with assigned roles return to theatre.
8. Music is turned off for the duration of the Curfew.
9. Lead anaesthetist ensures that the patient has a good cardiac output before the cement is inserted and increases measurement of blood pressure to at least every 2.5 minutes, if not using invasive monitoring.
10. Lead surgeon informs the team when the cement is inserted.

11. The cement is inserted with a 3rd generation technique, usually without pressurisation.
12. Lead surgeon informs the team when the prosthesis is being inserted.
13. Lead surgeon informs the team when the hip is relocated.
14. Anaesthetist declares the end of the Cement Curfew.

If there is evidence of BCIS:

1. The lead anaesthetist ensures that the team is aware.
2. The lead anaesthetist decides if there is cardiovascular collapse requiring CPR and informs the team.
3. Team members perform their roles.
4. Once the critical event is over the patient is returned to the lateral position if at all possible and the hip is closed quickly, but formally.

5. SPECIFIC INTRAOPERATIVE ROLES

Anaesthetic team

Although there is no clear evidence regarding the impact of anaesthetic technique on the severity of BCIS, an animal study has suggested that volatile anaesthetic agents may be associated with a greater haemodynamic change for the same embolic load.⁴⁵

- Avoid N₂O in high risk patients to prevent exacerbating air embolism and pulmonary hypertension.²⁴
- Increasing the FiO₂ and ensuring an SBP within 20% of induction value should be considered in all patients at the time of cementation, especially in patients at increased risk of BCIS.⁴⁶
- Avoiding intravascular volume depletion may reduce the extent of the haemodynamic changes in BCIS.⁴⁷
- Prepare vasopressors/inotropes in case of cardiovascular collapse.
- Confirm awareness that cement is about to be prepared/applied.
- Maintain vigilance for cardiorespiratory compromise.

In addition to standard ASA monitoring, patients with one or more significant risk factors for developing BCIS should have a high level of perioperative vital signs monitoring. This should include invasive arterial blood pressure monitoring and a central venous catheter.²⁴

- CVP monitoring will aid volume optimisation and inotrope administration but changes in CVP may correlate poorly with changes in PAP in BCIS.³⁴
- Use of an intraoperative pulmonary artery catheter or TOE has been suggested in high risk patients.²⁸
- Hypotension in BCIS may be the result of decreased SVR, reduced CO, or a combination of the two, and CO monitoring with an assessment of cardiac filling, CO, and SVR should be given serious consideration in patients at high risk of BCIS. This would allow for management to be directed more appropriately should BCIS develop.²⁴

Surgical team

As anaesthetic management of BCIS is mainly supportive, once the decision has been made to proceed with the operation, surgical modifications are the only alterations which will affect occurrence of BCIS. Due consideration must be given to minimising the length of the prosthesis or using non-cemented prosthesis,⁴⁸ especially if using a long-stem implant.⁴²

- Inform the anaesthetist prior to cement application.
- Mixing bone cement in a specific cement-mixing set, which is in a vacuum, reduces the load of volatile vasoactive compounds.³¹
- Perform high volume, pulsatile medullary lavage and ensure good haemostasis and drying of the intramedullary canal before cement insertion.⁴⁹
- Apply cement retrograde,⁵⁰ using an intramedullary plug in the femoral shaft.
- Utilise a bone-vacuum cement application technique with a suction catheter.⁵¹
- Venting the bone permits the air to escape from the end of the cement plug and reduces the risk of an air embolus,⁵² but drilling a hole in the cortical bone to create a pressure-relieving vent can increase the risk of femoral fracture.
- Avoid excessive pressurisation by using a cement gun⁵³ results in more even pressure distribution in the medullary cavity,⁵⁴ and less reduction in oxygen saturation, however, intramedullary pressures are higher when cementation is performed with a cement gun rather than finger packing.⁵⁰

Treatment of BCIS

- Communication between the surgeon and the anaesthetist is important.
- In addition to the hazards of cement implantation and prosthesis insertion, reduction of the prosthetic femoral head is also a time of increased risk because previously occluded vessels are re-opened and accumulated debris may be allowed into the circulation.²⁹
- During knee arthroplasty, significant venous emboli are released at the time of tourniquet deflation and this may also be a high risk period.⁵⁵
- A fall in end-tidal carbon dioxide concentration may be the first indication of clinically significant BCIS in the anaesthetised patient and should alert the anaesthetist.
- Oesophageal Doppler measurements may detect impending BCIS at an earlier stage than standard haemodynamic monitoring.⁵⁶
- Early signs of BCIS in the awake patient undergoing regional anaesthesia include dyspnoea and altered sensorium.⁵⁷
- If BCIS is suspected, FiO₂ should be increased to 100% and supplementary oxygen should be continued into the postoperative period.
- It has been suggested that cardiovascular collapse in the context of BCIS be treated as RV failure.⁵²

- Aggressive resuscitation with intravenous fluids has been recommended.⁵²
- The choice of vasopressor is facilitated by the presence of noninvasive CO monitoring or a pulmonary artery catheter.
- Haemodynamic instability should be treated with the potential aetiology in mind.
- Sympathetic alpha-1 agonists should be first-line agent in the context of right heart dysfunction and vasodilatation.
- Fluid resuscitation should then be commenced if there is insufficient pre-load.

BCIS is a time-limited phenomenon; with human and animal studies strongly suggesting that PAP normalises within 24 hours.³⁰ Even with large embolic loads, healthy hearts may recover in seconds to minutes. The underlying mechanism - acute pulmonary hypertension and secondary RV failure - should be considered reversible. Aggressive stabilisation and supportive therapy are the cornerstones in managing BCIS. Patients who have not met the criteria for severe BCIS but who have a suspicious clinical picture should be monitored closely in a high-care unit for at least 24 hours postoperatively.

Conclusion

Total hip replacement and hemiarthroplasty procedures are on the increase globally as well as in South Africa. Due to improving living conditions, and better health practices, we are dealing with an increase in elderly patients with a myriad of comorbidities that we will have to manage in our daily practice as anaesthesiologists. By actively engaging our patients with a multidisciplinary approach to their healthcare, we may improve and reduce some of these negative outcomes associated with hip arthroplasty.

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