Minimally Invasive Stabilization Using Screws and Cement for Pelvic Metastases: Technical Considerations for the Pelvic "Screw and Glue" Technique

William B. Lea, MD[1] John C. Neilson, MD[2] David M. King, MD[2] Sean M. Tutton, MD, FSIR[1]

[1] Department of Radiology, Medical College of Wisconsin, Milwaukee, Wisconsin
[2] Department of Orthopaedic Surgery, Medical College of Wisconsin, Milwaukee, Wisconsin

Address for correspondence William B. Lea, MD, Division of Vascular and Interventional Radiology, Froedtert Memorial Lutheran Hospital, 9200 W. Wisconsin Avenue, Room 2803, Milwaukee, WI 53226 (e-mail: williamblea@gmail.com).

Semin Intervent Radiol 2019;36:229–240

Abstract

Metastatic disease involving the pelvis is common, often resulting in significant pain and disability. Several percutaneous interventions for unstable pelvic metastatic disease have been described, including osteoplasty, ablation, and screw fixation, that when used alone or in combination can significantly reduce pain and disability from metastatic bone disease. While it is possible to make a significant impact in patient care with basic principles and techniques, certain advanced techniques can extend the application of percutaneous interventions while minimizing morbidity.

Keywords
- interventional radiology
- fracture
- screw
- osteoplasty
- ablation
- pelvis
- metastases

Up to 100,000 new patients develop bone metastases each year. The lifetime incidence is estimated at up to 75% in patients with breast and prostate cancer, 60% in thyroid cancer, 40% in bladder and lung, and 25% in renal cell carcinoma.[1] The prevalence of metastatic disease involving the bones is increasing, in large part due to significant recent advances in systemic therapy that have led to more patients living longer with metastatic disease. As a result, long-standing osseous involvement can lead to significant complications affecting mobility and quality of life.

Metastatic involvement of the pelvis can be especially problematic, given the significant stresses present during weight bearing.[2] A frank protrusio fracture of the femoral head through a weakened acetabulum can be catastrophic, rendering patients essentially bedbound in severe pain. Surgical repair for these devastating fractures has traditionally required an extensive Harrington-type reconstruction to rebuild the acetabulum consisting of tumor curettage, extensive cementation of the pelvic defect, and placement of an antiprotrusio cage.[3,4] The complication rates of these extensive surgeries are high and physical recovery from such operations can be long, requiring extensive physical therapy to regain mobility.[5] Additionally, essential multimodality, systemic, and radiation therapies are often delayed or interrupted for weeks while surgical incisions heal.

Pathologic fractures of the sacrum may present as a similar clinical conundrum with limited therapeutic options for destructive metastases. Neither transsacral screws nor sacroplasty often provide adequate stabilization alone and true spinopelvic fixation can bring significant morbidity.

Therefore, patients presenting with pelvic metastases causing instability, especially when symptomatic, can greatly benefit from minimally invasive stabilization techniques that provide pain relief, maintain mobility, and essentially remove significant delays or interruptions in critical systemic therapies.[6–11]

Herein, we describe some of the clinical and technical considerations of our pelvic "screw and glue" technique developed in close collaboration between our interventional radiology and orthopaedic oncology services and performed in over 120 patients over the past decade.

Issue Theme Interventional Oncology: Management of Non-Liver Malignancies; Guest Editor, Thuong G. Van Ha, MD, FSIR

DOI https://doi.org/10.1055/s-0039-1693982.
ISSN 0739-9529.

Preprocedural Considerations

Patient Considerations

It is essential to consider certain individual patient factors when considering treatment options. These include, but are not limited to, the severity of pain, inadequacy or side effects of analgesic medications, degree of mobility limitations, life expectancy, quality of life, and oligometastatic versus widely metastatic disease.

In general, percutaneous stabilization is advantageous for painful or high fracture risk lesions in the following settings: poor open surgical candidates, concern for wound healing complications, extensive disease on presentation requiring prompt initiation of systemic and/or radiation therapy, and rapidly progressive disease requiring uninterrupted continuation of systemic and/or radiation therapy. Contraindications to percutaneous stabilization are generally relative, and even suboptimal stabilization through a percutaneous approach may be able to achieve acceptable short-term success in palliating pain and immobility, which may be adequate when considered within a patient's goals of care.

Open surgical fixation of the acetabulum can be considered in patients with oligometastatic disease, favorable tumor biology, and good performance status; however, in our practice it is only rarely performed initially, as we have found that previous percutaneous stabilization has generally facilitated rather than hindered subsequent surgical reconstruction.

Tumor Type

Tumor type is an important factor when considering whether percutaneous stabilization is necessary. In general, all tumor types will benefit from percutaneous stabilization if lesions are large and destructive, especially with associated pain or particularly aggressive growth. Small and moderate lesions of tumors considered responsive to systemic and radiation therapy such as breast, prostate, lung, myeloma, and lymphoma can usually be observed while theses therapies are pursued first, unless there is disability clearly related to an existing fracture.

Even patients without pain or disability may still carry a significant fracture risk following initiation of therapy as disease recedes and leaves less structural support. Although no clear guidelines exist at present, there may be clinical benefit to prophylactic stabilization in select asymptomatic patients, analogous to prophylactic femoral rodding in the setting of metastatic disease, to prevent a devastating fracture.

On the other hand, for moderate size tumors more resistant to systemic and radiation therapy such as renal cell and bladder carcinomas, early stabilization, combined with ablation when feasible, and often followed with standard radiation therapy, may be appropriate to prevent skeletal-related complications from progressive disease.

Myeloma is somewhat unique in that an initial favorable response to systemic and radiation therapy is often achievable but can leave the skeleton at significant risk of fracture if lytic lesions are moderately large and in weight-bearing portions of the pelvis. In these situations, stabilization with either cement alone or cement-augmented screws is helpful. Unique to myeloma, a standard cement, with its moderately exothermic reaction, generally fills the lytic defect completely, either "melting" the soft tumor or displacing it, and interestingly even in areas of apparent complete cortical dehiscence on imaging the periosteum often remains intact and a highly effective barrier for cement. As such, in our experience, myeloma lesions can often be completely treated locally with cementation alone without significant residual disease, thereby obviating the need for additional local therapy with radiation with the added benefits of avoiding radiation-induced osteoporosis of the already weakened pelvis, preserving bone marrow for transplant, and preserving radiation as a treatment option for recurrent disease.

Structural Assessment

While this discussion focuses on our combined use of orthopaedic screws with cement, in many instances, pelvic stabilization may be performed with cement alone.[12,13] Polymethylmethacrylate (PMMA) is exceptional in resisting compressive forces and works well on its own for small lesions within the cancellous bone, especially directly over the acetabular roof where forces are primarily compressive (►**Fig. 1**). But PMMA tends to fail with significant rotational, bending, sheer, or distracting forces, secondarily allowing persistent motion and resulting in inadequate stabilization. Therefore, in cases where these forces are present, the addition of screws should be considered to offer a more stable construct by resisting these forces, similar to rebar in concrete.[9] Specific examples where we have found benefit in adding screws include when there is a significant fracture already present, there is significant cortical destruction along the major buttresses of the pelvis (in addition to cancellous destruction) such as the ischial spine of the posterior column or superior ramus of the anterior column, there is anatomic concern for early cement leak leading to early osteoplasty termination and inadequate stabilization, or there is rapidly progressive disease where ongoing osseous destruction is likely. In practice, screw placement through an area of prior osteoplasty can be exceedingly difficult and less accurate; so, we have been aggressive with initial screw placement when, in our judgement, we feel osteoplasty alone is likely to fail.

Some specific lesion types can make adequate stabilization challenging. In severely comminuted fractures, it is often challenging to achieve adequate stabilization even with the addition of screws due to early and extensive cement extravasation. Sufficient long-term stabilization depends on adequate fracture reduction; however, this is difficult to achieve percutaneously for significantly displaced fractures. In these instances, we prefer open surgical techniques if possible and reserve percutaneous stabilization for pain palliation in poor surgical candidates with limited mobility where structural integrity is not as essential. Fractures through the acetabular rim can be more difficult to stabilize percutaneously, and, if significant, may warrant placement of a surgical cage to prevent progression. Moreover, extensive bone destruction along the screw paths, especially entry and exit cortices, may prevent adequate screw purchase and fixation, even if augmented with copious amounts of cement. While total stabilization is always preferred, it is true

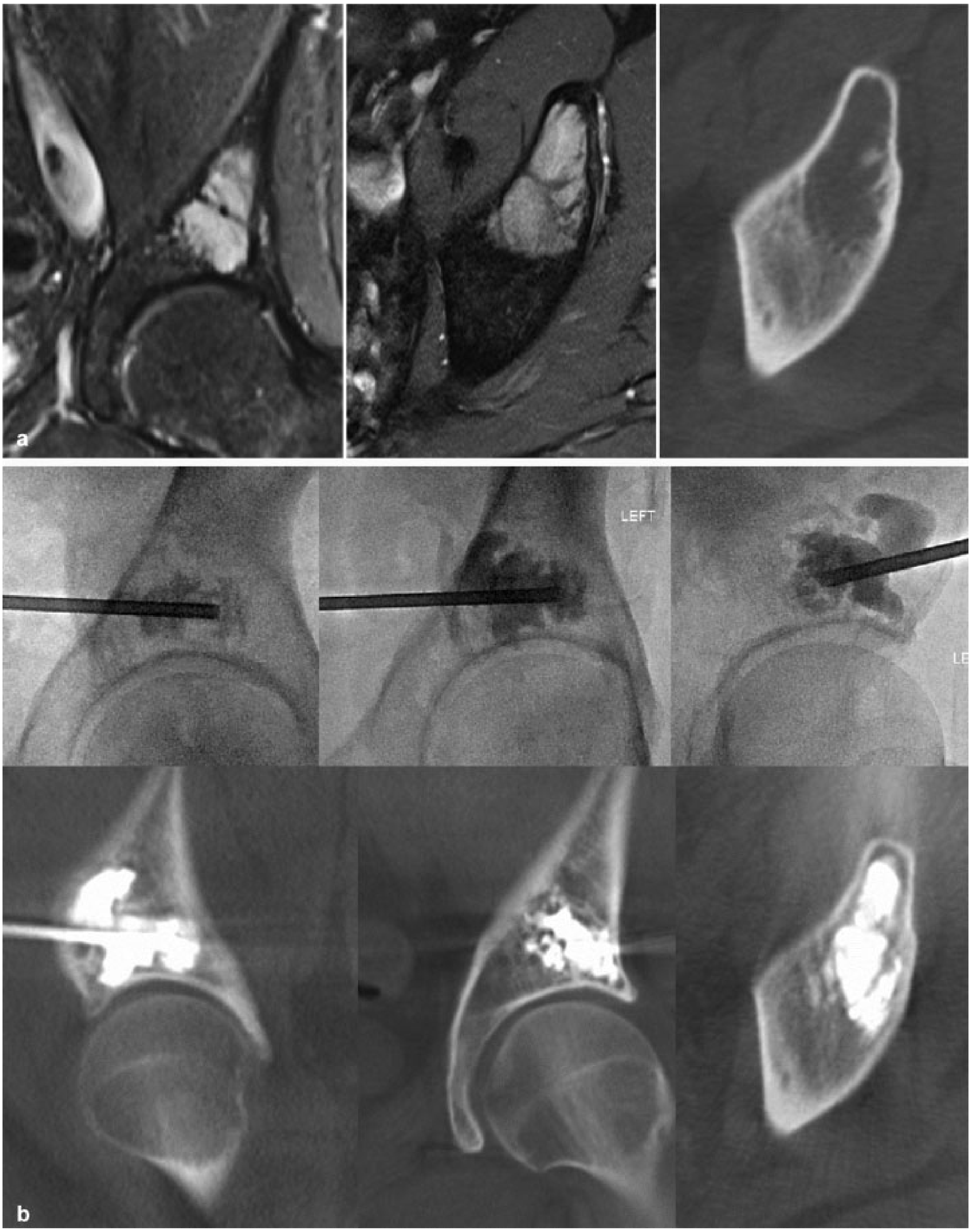

Fig. 1 A 48-year-old male with painful lytic myeloma lesion in the acetabulum (**a**), treated with polymethylmethacrylate osteoplasty alone (**b**).

that even suboptimal stabilization can often provide some degree of meaningful short-term benefit, which may be adequate for select patients without a better surgical option.[6]

Screw Planning

In our experience, there are three main screw corridors around the acetabulum that are achievable and can be combined to provide a base structure for adequate fixation, although from time to time additional screw orientations may be advantageous (►**Fig. 2**). The first screw is the ischial screw, buttressing the posterior column of the acetabulum, entering the ischium and travelling superiorly into the posterior ilium/iliac wing. The second screw is the superior ramus screw, buttressing the anterior column of the acetabulum. This screw can be placed in either a retrograde fashion entering near the pubic symphysis and travelling laterally over the acetabular roof to the lateral iliac cortex, or in the opposite antegrade fashion from a posterior approach. The

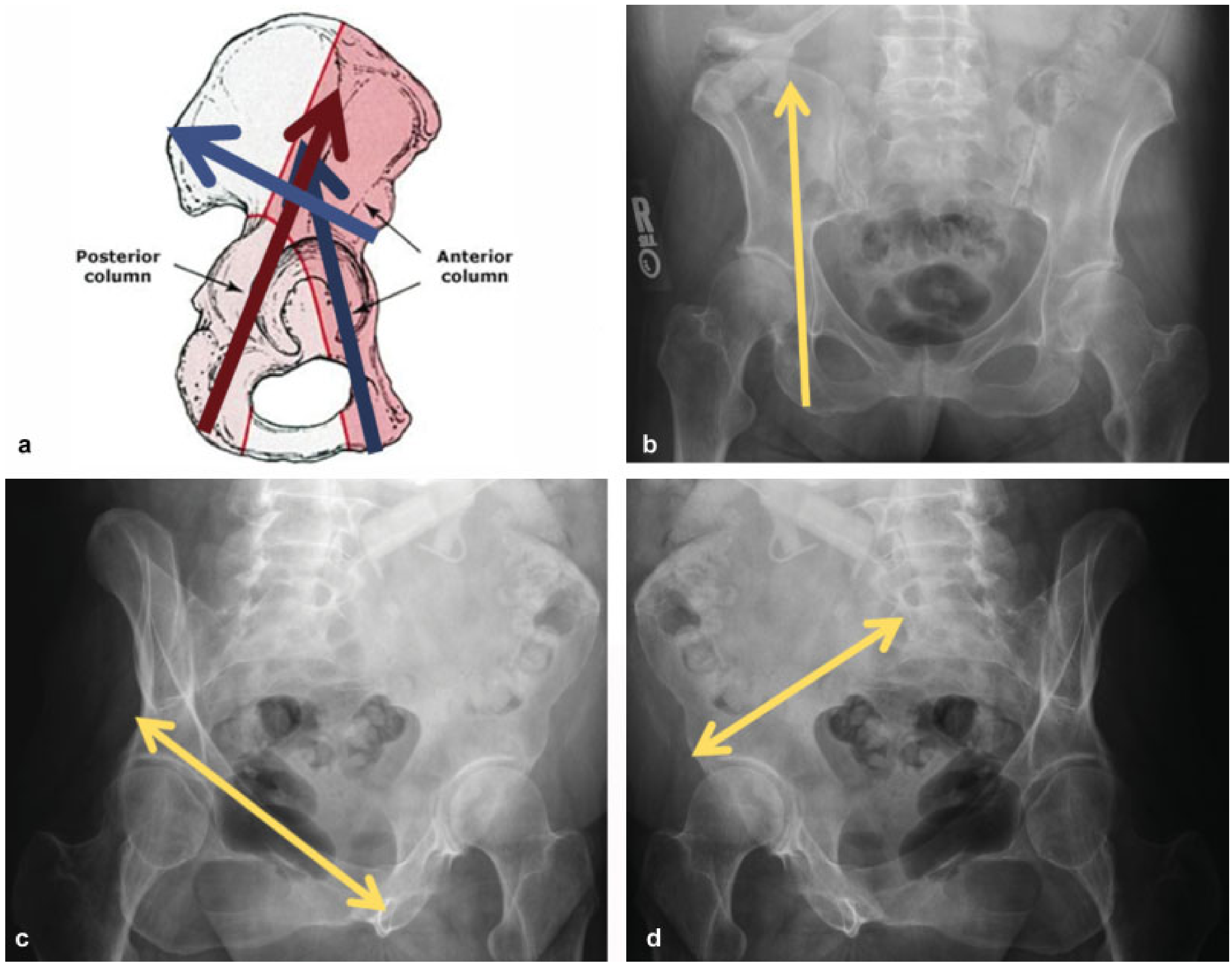

Fig. 2 (**a**) Schematic depicting the three main screw corridors around the acetabulum. (**b**) Ischial screw corridor from retrograde approach. (**c**) Ramus screw corridor from either antegrade or retrograde approach. (**d**) AP screw corridor from either antegrade or retrograde approach.

third screw is the anteroposterior or AP screw. This screw bridges the anterior and posterior columns together, beginning in the anterior inferior iliac spine (AIIS) and traveling just above the sciatic notch terminating in the posterior superior iliac spine (PSIS). This screw can also be placed in the opposite orientation from a posterior approach as a PA screw. Notably, we frequently place two parallel screws in this corridor stacked superiorly and inferiorly for additional support when appropriate.

The choice of which screws to place is patient specific and only rarely are all three corridors reinforced in the same patient. In general, these three primary screws are placed parallel to specific cortical buttresses that have been eroded or that are at high risk of destruction with rapidly progressive disease. In select cases, additional shorter screws can be placed tangential to specific fracture lines to reduce fracture distraction and further minimize torsional motion.

For severe sacral lesions with extensive bony destruction, severely comminuted fractures, or a high likelihood of progression, we have often decided that cement alone would provide inadequate stabilization. In these cases, we preferentially place two parallel transverse sacroiliac screws, through the S1 and S2 corridors (►**Fig. 3**). We avoid placing only one transsacral screw, as this often provides suboptimal stabilization and can lead to significant rotational forces around the single axis of the screw that will eventually lead to hardware loosening.

Of these five basic screws, only the ischial screw, AP screw, and S2 screw corridors are consistently achievable. The ramus screw and transverse S1 iliosacral screw corridors are usually achievable; however, some pelvic anatomies, especially in women with open pelvic anatomy, make these unachievable without passing outside the cortex for part of the screw path, and preprocedural multiplanar reformats along the proposed screw corridors can be extremely helpful when planning screw placement.

When necessary, the S1 iliosacral screw can be replaced by bilateral oblique iliosacral screws meeting in the S1 body, though this provides less stabilization. The ramus screw can usually be placed in an antegrade orientation at least over the acetabular roof and partially into the superior ramus, if not all the way to the pubic bone, whereas a retrograde ramus screw beginning at the pubic bone may not be able to clear the acetabular roof without violating the joint space.

In the vast majority of cases, we prefer using cannulated, fully threaded screws in all corridors. This provides maximal stabilization when augmented with adjacent cement in areas

Fig. 3 (**a**) Paired S1 and S2 screw corridors. (**b**) Example of inadequate S1 screw corridor addressed with bilateral iliosacral screws into the S1 body (**c**).

of extensive bony destruction and poor bone quality. Partially threaded screws (or lag screws) are generally avoided as they dynamically compress the traversed bone and can exacerbate compromise of fractured neuroforamina. However, these can be useful when attempting to reduce specific fracture lines or to mitigate sacral nerve irritation when there is a high probability of neuroforaminal encroachment by providing a smooth rather than threaded point of contact with the nerve. In our experience, currently available image guidance systems have made this relatively unlikely. We tend to use large cannulated screws between 7 and 8 mm but sometimes place smaller 6.5-mm screws for additional support or through particularly narrow ramus corridors. A screw with bicortical purchase is one that is positioned within cortex at both of its ends. This generally provides added stability and should be performed when feasible and safe.

Cannulated screw sets are available from Stryker (Kalamazoo, MI) and DePuy Synthes (West Chester, PA). While we use both, the Synthes screw set provides the greatest flexibility. In this set, fully threaded 7.3-mm screws are available up to 180 mm in length. While Stryker provides fully threaded screws up to 150 mm in 6.5 and 8 mm diameters, they do provide longer partially threaded screws up to 180 mm.

For acetabular metastases, the Harrington classification system is well known but may not be applicable when planning minimally invasive stabilization. A more meaningful assessment of pelvic lesions includes identifying which cortical buttresses are significantly weakened, the degree of cancellous bone destruction, and any fracture lines extending into the joint space or neuroforamina that would make aggressive cement deposition difficult due to the possibility of cement extravasation.

A multidisciplinary approach is essential to offer patients the best long-term plan. Interventional radiologists should collaborate deliberately with their orthopaedic surgery colleagues regarding a detailed procedural plan when possible so as to achieve the greatest structural reinforcement possible and avoid instrumentation that can make subsequent open surgical revision more difficult if necessary in the future. We found this collaboration to be professionally rewarding and greatly benefitting patients by combining the expertise of orthopaedic surgeons in fractures, bone healing, and structural principles and interventional radiologists in imaging, image guidance, and an ability to adapt minimally invasive techniques.

Osteoplasty

In general, aggressive osteoplasty is also performed during all screw fixation cases, with two specific stabilization goals. First, robust cement deposition provides resistance against compressive forces across large lytic defects, especially in the region of the acetabular roof where these compressive forces are significant. Second, cement serves to further stabilize the screws themselves within areas of osseous destruction and helps minimize screw motion that can lead to poor healing and/or hardware loosening. This additive stabilization advantage is likely increased by using fully threaded instead of partially threaded screws, maximizing the interdigitation between hardware and cement. And while the benefit of cement is primarily structural, tumor essentially does not grow through it, and strategic cement deposition can aid to some degree in preventing disease progression into augmented areas.

Ablation

Ablation can be helpful to provide pain relief as well as local tumor control.[14–19]

When focusing on pain relief, targeting of bone–tumor interfaces, areas of periosteal involvement, or when involved, the SI joint itself can maximize benefit.[19]

As for tumor control, ablation of large pelvic metastases is almost never intended to achieve complete tumor ablation, primarily because the adjacent nerves and hip joint frequently prevent achieving a complete ablation without unacceptable collateral damage. However, concurrent ablation can serve two primary roles: local tumor control and cavity creation to facilitate cement fill. The overall benefit for local tumor control has not been proven; however, targeted tumor control with ablation along the strategic margins can be helpful in preventing uninhibited disease progression locally in certain directions leading to hardware failure. Additionally, our experience suggests that local tumor debulking in certain radiation-resistant malignancies may be beneficial through some direct disease control, increasing the effectiveness of radiation on a smaller quantity of remaining disease. We usually do not perform ablation on malignancies that respond well to radiation and/or systemic therapy such as breast, lymphoma, or myeloma.

If ablation is to be utilized, the choice of which ablation technology to use is important, as each has strengths and weaknesses which have been detailed in the literature elsewhere.[20] Specific to pelvic reconstructions, cryoablation can be advantageous when ablation occurs near critical structures, often nerves, in which case discrete ice ball (ablation zone) visualization can reduce the risk of nontarget ablation. It is true that ice is poorly visualized within bone; however, the ice easily extends across cortex into the adjacent soft tissues, where it can usually be visualized with CT imaging, without significant asymmetry of the ablation zone. However, cementation immediately following cryoablation is challenging due to the residual ice and can result in inadequate augmentation. Several techniques can be used to minimize this including staging the ablation and cementation procedures a day apart, waiting at least 1 hour between, during which time screws can be placed, or utilizing a final extended or rapid thaw cycle to directly melt the ice ball. For this reason, we prefer to use heat-based ablation systems, both microwave and radiofrequency ablation, when performing ablation away from critical structures.

Nerve Review

A thorough documented preoperative neurologic exam is required, and all major pelvic nerves must be identified beforehand on cross-sectional imaging,[21] accounting for any significant displacement of nerves due to bulky soft-tissue disease. Various techniques have been described to mitigate nerve injury during ablation.[21–23] In general, unilateral injury to the S2 and S3 nerve roots is tolerated in the setting of normal contralateral innervation, as are injuries to cutaneous sensory nerves. The inferior gluteal nerve can often be sacrificed if needed resulting in a Trendelenburg gait that generally is tolerable. Injuries to the L4–S1 nerve roots, femoral nerve, and sciatic nerve are more significant, as these can significantly impact function and ambulation, and may necessitate long-term orthotic devices or the use of an assistive device. In our experience, the most significant postprocedural complications have all been related to significant nerve injury, manifesting as either severe pain or weakness, both of which significantly complicate the postprocedural goals of improved mobility and quality of life.

Technical Procedural Details

Patient Preparation

All cases are performed under general anesthesia with a ceiling mounted fluoroscopy unit capable of cone-beam CT. Supine patient positioning is easiest and preferred unless an ischial screw is needed through the posterior column—in which case patients are positioned prone with hips slightly flexed using appropriate bolstering and padding, often incorporating a radiolucent negative pressure beanbag to minimize patient movement. A Foley catheter is placed to facilitate bladder drainage, especially relevant if a ramus screw is planned, and a standard surgical preparation of the operative site including Ioban adhesive drape is performed.

Creation of 3D Objects for Use with Augmented Fluoroscopy

A fluoroscopy unit with advanced imaging features is essential to a successful outcome. These features include cone-beam CT and needle guidance software, or more generally augmented fluoroscopy, which consists of displaying in real time three-dimensional (3D) objects, registered to the patient's cross-sectional data and overlaid onto live fluoroscopic imaging (►**Fig. 4**). These objects include needle guidance lines used for placement of screws, bone trocars, ablation probes, and cement cannulae, as well as volumetric segmentation of targeted lesions or areas of bony destruction. These guides are exceedingly helpful when targeting soft-tissue disease or areas of severe bone loss where there are no good bony landmarks to reference on fluoroscopy alone and tactile feedback within the lesion is significantly diminished.

Ideally, all 3D objects to be utilized are created beforehand on a preprocedural cross-sectional CT or MR dataset that has been loaded into the workstation. This workflow saves intraprocedural time and allows for more precise object creation when contrast-enhanced datasets are available as well as preprocedural determination of screw lengths; however, it requires accurate fusion of preprocedural and intraprocedural imaging.

At the beginning of each case, a cone-beam CT is performed primarily to assess for interval changes such as fracture or disease progression but also for purposes of patient registration with preprocedural datasets and 3D objects using 3D/3D registration. Unfortunately, this process can be tedious and sometimes require manual alignment; however, this process can be streamlined significantly by first aligning either the sacral promontory or pubic symphysis in three orthogonal planes, then rotating one dataset around that point in each projection. In our experience, 2D/3D registration workflows designed to avoid an initial cone-beam CT are not sufficiently accurate for screw placement in narrow corridors. Alternatively, for more straightforward cases, 3D objects can be drawn directly on the initial intraprocedural cone-beam CT dataset, obviating the need for registration with preprocedural imaging.

It is critically important to continually check registration of the 3D objects with the patient during the procedure. If good registration between datasets is achieved initially, then any misregistration of 3D objects on live fluoroscopy is due to patient movement, which can occur with hammering and drilling; however, with a patient under general anesthesia, this movement really only occurs from side to side (i.e., no cranial–caudal or anterior–posterior translation). Therefore, a good rule of thumb is that when checking or correcting overlay registration, place the C-arm at 0 degrees and only adjust the overlay left to right until the cortices of the overlay are superimposed on the live fluoroscopic image (►**Fig. 5**). Realigning the overlay when the detector is at an oblique angle will give a false sense of security by appearing correct in that one projection; however, persistent misregistration will be obvious in any orthogonal view, at which point starting the registration process over is usually necessary.

Bone Access

Our most common procedural workflow is one of ablation, if indicated, followed by complete screw placement, followed by cementation. Every cortical defect is a potential area of cement

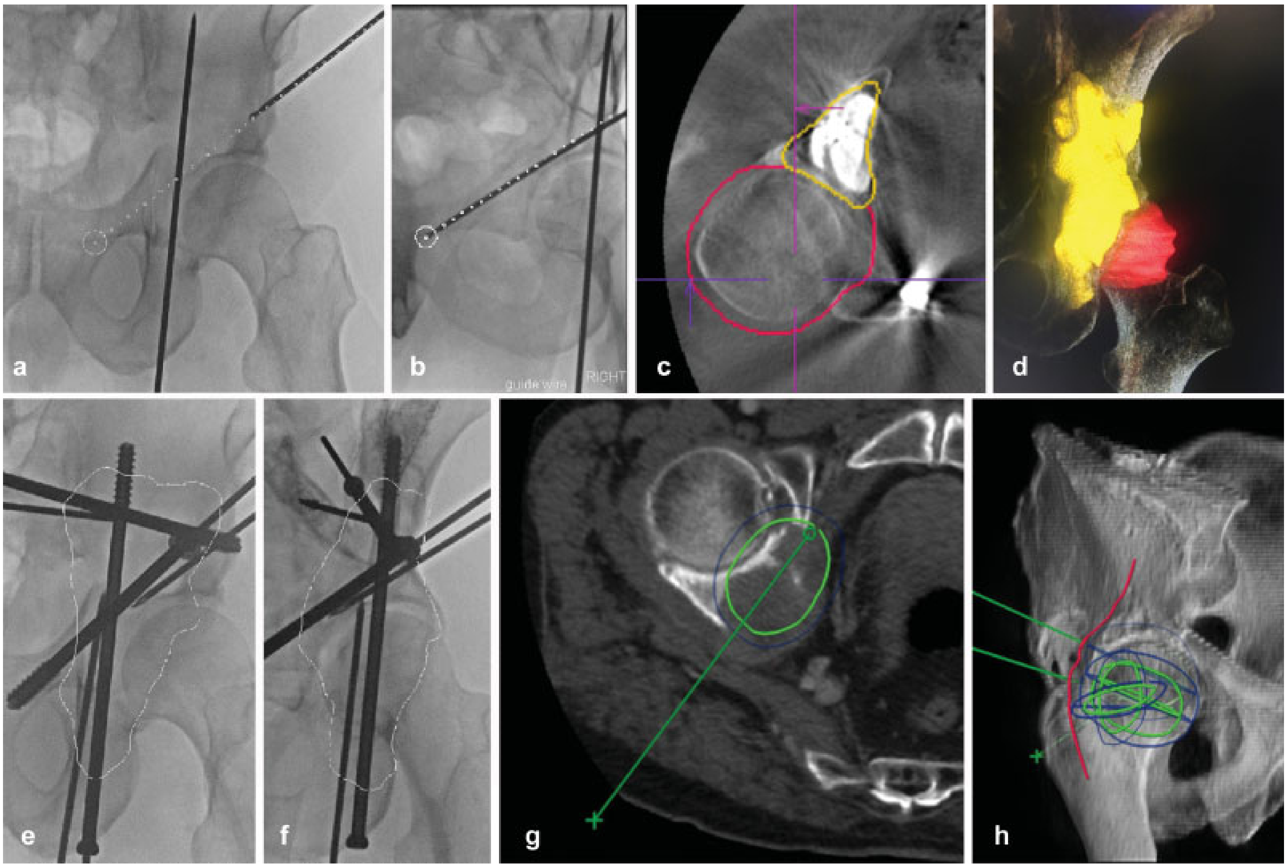

Fig. 4 Examples of augmented fluoroscopy (AF): Needle guidance during placement of Steinman guide pins (**a, b**) over which cannulated screws will be placed. (**c**) Volumetric segmentation of lytic defect (yellow, filled with cement) and joint capsule (red) on intraoperative cone-beam CT (**c**) with corresponding volume rendering (**d**) and orthogonal contour outline of the yellow volume from different fluoroscopic projections (**e, f**). 3D objects used to estimate ablation zone (**g**) and visualize ablation overlapping ablation zones in relation to sciatic nerve (red, **h**).

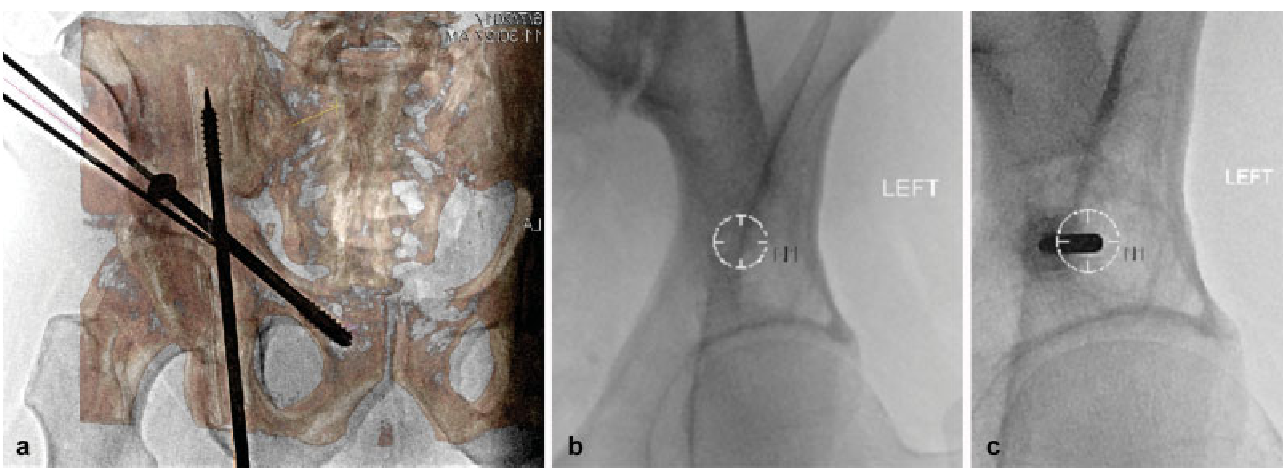

Fig. 5 Example of subtle misregistration when using augmented fluoroscopy between the volumetric 3D object overlay and actual fluoroscopic image, best seen by the misalignment of the bony cortices (**a**) resulting in inaccurate needle guidance targeting (**b**), improved after lateral realignment of the augmented fluoroscopy overlay while in the AP projection (**c**).

extravasation that can lead to early cement termination; therefore, bone access is planned carefully to avoid unnecessary access holes and used for multiple purposes (i.e., ablation accesses are repurposed for both screws and cementation).

Initial bone access is often performed with a 10-gauge bone trocar (Stryker). This size trocar accepts most ablation probes, including larger water-cooled microwave ablation probes. In general, we have performed bone ablation in a coaxial fashion using the base trocar to maintain bone access, prevent probe damage, and adjust probe position, taking care to use purposefully long ablation probe shafts to enable retraction of base trocars completely outside the ablation zone during energy delivery. Care should be taken not to damage ablation probes by advancing them through hard bone, especially when using cryoablation due to its use of highly pressurized gas. Damage can be minimized by advancing the base trocar fully through any bone before exchanging the stylet for the ablation probe and then retracting the trocar.

This size trocar also accepts 2.8-mm Steinmann guide pins (►**Fig. 6a**), over which the cannulated orthopaedic screws are placed in a coaxial fashion (►**Fig. 6b**). The diamond tip stylet facilitates precise bone entry which can sometimes be difficult to achieve when entering bone with only a Steinmann guide pin, especially when not tangential to the cortex (e.g., the lateral ilium when placing transsacral screws).

Screw Placement

Our workflow for placing screws generally starts with bone access using a 10-g trocar followed by placement of a 2.8-mm Steinmann guide pin through this trocar and along the entire planned screw path using a power drill (►**Fig. 6c**) and needle guidance. An oscillating, back-and-forth rotation of the guide pin can be advantageous during advancement through cancellous bone to minimize inadvertently exiting the bone cortex; however, a full forward drill rotation will be necessary when traversing intact cortex such as the sacroiliac joint. Once guide pins have been placed along all screw paths, a cone-beam CT is performed. Each guide pin is critically evaluated in bull's-eye and tangential multiplanar reformats to ensure proper position.

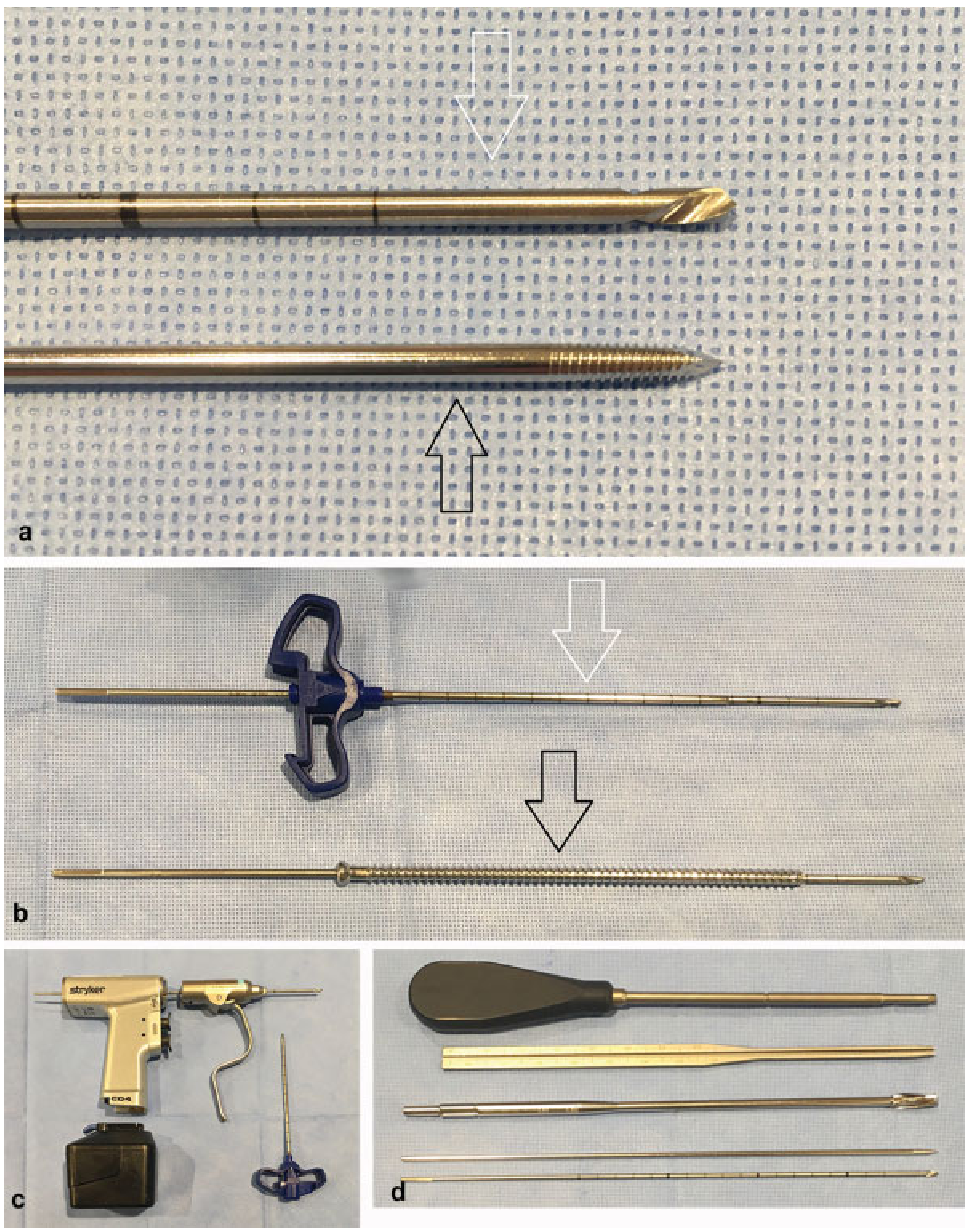

Fig. 6 (**a**) Steinmann guide pins with drill (white arrow) and screw (black arrow) tips for use with cannulated screw placement. (**b**) Coaxial configuration of 2.8 mm guide pins through both a 10-gauge bone trocar (white arrow) and cannulated, fully threaded screw (black arrow). (**c**) 10-gauge diamond tip bone trocar, power drill, battery pack (black), and collet chuck shown with guide pin. Separate chucks (not shown) are used when performing power screw driving or drilling. (**d**) Common tools include (top to bottom) a hand screwdriver, guide pin screw measuring device, drill bit used for overdrilling sclerotic bone, and Steinmann guide pins.

If malpositioning is present, the offending guide pins are repositioned, accepting that previous guide pin tracks can make repositioning challenging. Once the guide pins are in appropriate position, measurements to determine needed screw lengths are performed, either by making direct measurements on cone-beam CT reformats or utilizing mechanical measuring devices that fit over the guide pins. The bone trocar can then be removed, and the cannulated screw placed over the guide pin, similar to the Seldinger technique, and advanced using either a power or hand screwdriver. Rarely, analogous to creating a pilot hole, overdrilling the planned screw path with an appropriately sized drill bit may be necessary prior to screw insertion in especially sclerotic lesions (►**Fig. 6d**). Screws should be advanced such that the screw head is flush with the entering cortex, confirmed with an appropriate tangential fluoroscopic projection, without breaking the cortex. Washers are considered beneath the screw head in situations where there is extensive bony destruction or poor bone quality at the bone entry site.

Given the complexity of these procedures, operative times and the corresponding radiation doses can be high, and we routinely reduce fluoroscopic frame rates from the default of 15 frames per second to 2 to 4 frames per second along with aggressive radiation beam collimation without significant degradation of image quality.

Maximizing Needle Guidance

Software-based augmented fluoroscopic needle guidance can be extremely helpful in placing trocars, probes, and screws with a high degree of accuracy by automatically moving the C-arm to calculated positions, thus providing a bull's-eye or line-of-sight view as well as orthogonal views to needle paths created on cross-sectional datasets. However, some nuances of these systems can make accurate placement challenging.

When available, bull's-eye views are highly favored for initial trocar placement, as this allows for easy identification of the optimal skin entry site. However, the C-arm often cannot achieve a bull's-eye perspective for all trajectories, forcing the operator to rely on the calculated orthogonal views. This is most apparent for ischial access in the prone position. However, these orthogonal projections are often at oblique angles and not necessarily orthogonal to each other, making it extremely difficult to efficiently adjust the bone entry site and needle angulation, by even the most spatially adept operators.

An easy workaround for this limitation is to ignore the calculated projections for the needle pathway and instead force the C-arm into an AP projection. With the needle pathway still projected on live fluoroscopy, advance the needle along the path, taking care to optimize the horizontal displacement and horizontal angulation, until the needle tip is positioned at the bone entry site. Angulation of the C-arm in either tangential oblique projection (right anterior oblique or left anterior oblique for an ischial needle or craniocaudal for a transsacral needle) will likely display some degree of needle positioning error. While a full orthogonal projection will maximize the appearance of any malpositioning, it is not necessary for efficient readjustment so long as the needle position and angulation are adjusted only in the vertical plane (orthogonal to initial imaging). Restricting needle adjustments to only occur in the horizontal and vertical planes, even if needle paths are oblique, greatly facilitates accurate placement of almost any needle using augmented fluoroscopic needle guidance.

Maximizing Cement Fill

Adequate cementation is the most difficult aspect of percutaneous stabilization for large metastatic lesions but essential for maximal stabilization and long-term success. Robust cement deposition superior and medial to the acetabular roof is critical when there has been bony destruction in this high-stress area. Cement deposition at screw/screw interfaces and screw/bone interfaces can greatly enhance rotational and torsional stability and reduce postoperative motion and hardware loosening, which is why we prefer to use fully threaded screws whenever possible. In extreme cases, screws can be "potted" into cement alone when there is no good bone present for purchase. Additionally, adequate cementation at bone/tumor interfaces such that cement extends from the lytic cavity, interdigitating into normal bone, is highly preferred to simply filling the central portion of a lytic defect. In our experience, while not aesthetically pleasing, cement leakage in noncritical tissue planes is preferable to inadequate cementation.

For a small subset of straightforward cases, particularly single screw ramus fractures or very small lesions, distal cementation can technically be performed through a partially advanced screw, which can then be "potted" into the distal cement before it sets. We have found an 11-g bone trocar advanced through the cannulated Stryker screws to be ideal for this approach, as they are perfectly sized to prevent retrograde cement migration around the delivery cannula inside the cannulated screw. However, for larger or complex lesions, cement deposition through partially advanced screws usually leads to suboptimal results due to cement's finite working time, including inadequate cement deposition and incomplete advancement of the screw into the setting cement.

In these cases, it is almost universally preferable to place all screws completely before cementing through independent bone access trocars in a coaxial fashion. Generally, these cement trocars are placed parallel to our ischial and/or AP screws. A curved nitinol vertebroplasty needle can facilitate cementation over the acetabular roof and allow for multiple repositionings from the same access site as long as cement is kept flowing slowly. Cement is then injected under intermittent fluoroscopy, taking care to view complex geometries such as the acetabulum from all angles. At the conclusion of every procedure, a cone-beam CT is performed to assess the adequacy of cement deposition, and when necessary, additional trocars are placed to facilitate further cement deposition.

Sometimes, significant destruction or dehiscence of the cortex can obscure the intended margins of cementation on fluoroscopy alone. In such cases, if available, one can create or segment a 3D volumetric object encompassing the lytic defect or intended fill zone. In many fluoroscopy systems, the outline of this object can then be overlaid onto live

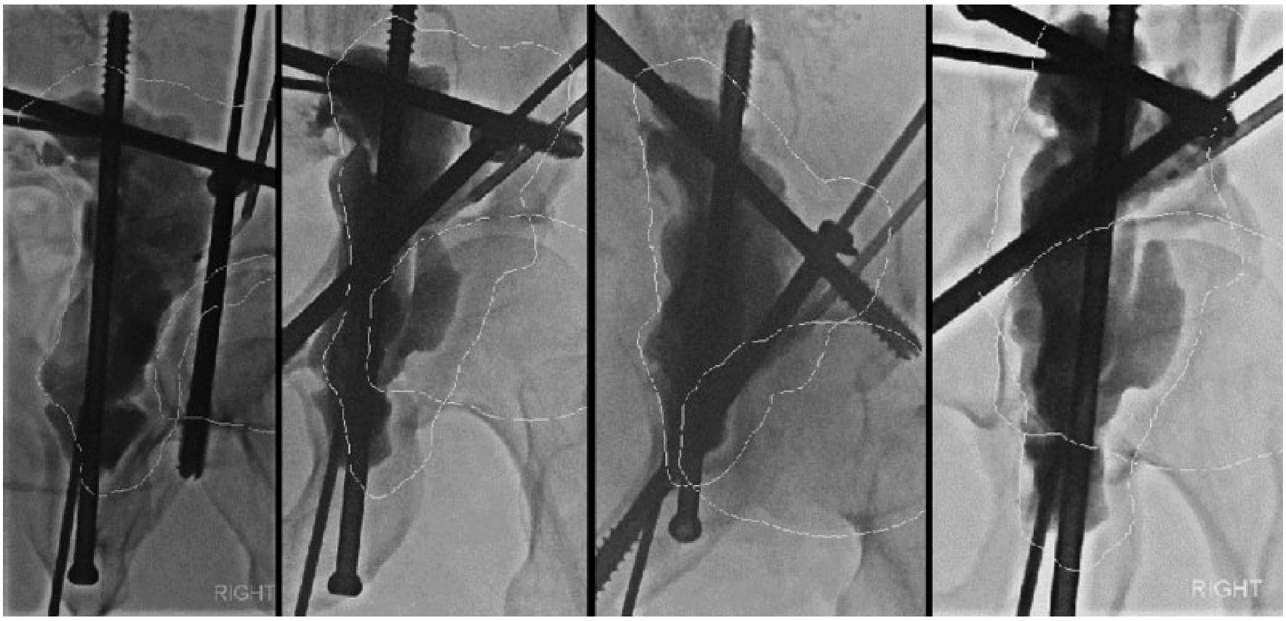

Fig. 7 3D volumetric object outline (white lines) of lytic defect can be helpful to confirm in real-time adequate cement deposition when lesion borders are difficult to visualize fluoroscopically.

fluoroscopy, providing real-time feedback as to the adequacy of cement fill (►**Fig. 7**).

In select cases, achieving maximal cement deposition safely can be uniquely challenging. This is especially true when the anatomy of interest is oriented such that it is superimposed in an AP fluoroscopic projection. Despite steep angulation of the fluoroscopy unit, the complex geometry of the pelvis can be challenging to interpret quickly. In these cases, most notably involving the posterior acetabulum and sacrum, intermittent cross-sectional imaging with a true CT scanner can provide increased confidence and prevent early cessation of cement deposition; however, the significant streak artifact associated with indwelling orthopaedic screws significantly degrades image quality, and in our practice, even with a combined fluoroscopy–CT imaging suite, CT imaging is reserved for only the most challenging cases.

Care must be taken to prevent cannulae from becoming stuck within hardening cement. This is most likely to occur during prolonged, high-risk cement deposition when using smaller gauge cement delivery needles such as a curved nitinol needle. In the event a needle becomes stuck within cement, most will come free with persistent traction, sometimes over several minutes; however, avoidance of this situation is advisable. For large base cannulae, a simple 360-degree rotation periodically with the stylet in place is very effective even if buried deep within cement for long periods of time.

Complication Management

Significant nerve injuries are usually the result of ablation and can result in significant functional limitation and pain. These symptoms may improve if the nerve injury is incomplete; however, this can still take several months if it occurs at all. The potential for recovery of nerve function is multifactorial; however, it is likely higher with cold-based ablation technologies than with heat-based ablation, as the neuronal architecture is generally preserved. Acute high-dose steroids may be considered if nerve compromise is felt due to extrinsic compression from postablation edema.

Functional motor deficits may require temporary or permanent orthoses, such as an ankle–foot orthosis in the case of sciatic nerve injury, extensive physical and occupational therapy rehabilitation, and utilization of ambulatory-assist devices to maximize function. Neuropathic analgesics should be considered for persistent pain in addition to traditional analgesics.

Cement will occasionally extravasate outside the bone, despite appropriate diligence. Small volumes of cement inside the hip joint are usually inconsequential but should be treated with full range of motion manipulation of the hip while on table to smooth out any cement within the joint before setting fully. In cases of a significant intra-articular extravasation, refractory hip pain and joint degeneration can result and arthroscopy may be considered for cement removal if total hip reconstruction is prohibitive.

From time to time, augmented screw construct failure does occur. One reason for this is failure to achieve adequate stabilization initially, in which case ongoing motion within the fixation construct will lead to the cycle of screw loosening, cement fractures, and progressive instability. For this reason, adequate cement deposition from the beginning is critical. However, the long-term structural integrity of even the most stable constructs depends in large part on a patient's capacity to form new bone across fracture lines and areas of destruction, as all constructs will eventually fail in the setting of either absent osseous healing or progressive disease leading to further skeletal erosion. In cases of failure, having maintained a close collaboration with orthopaedic surgery colleagues throughout the patient's care will facilitate a multidisciplinary discussion of appropriate treatment

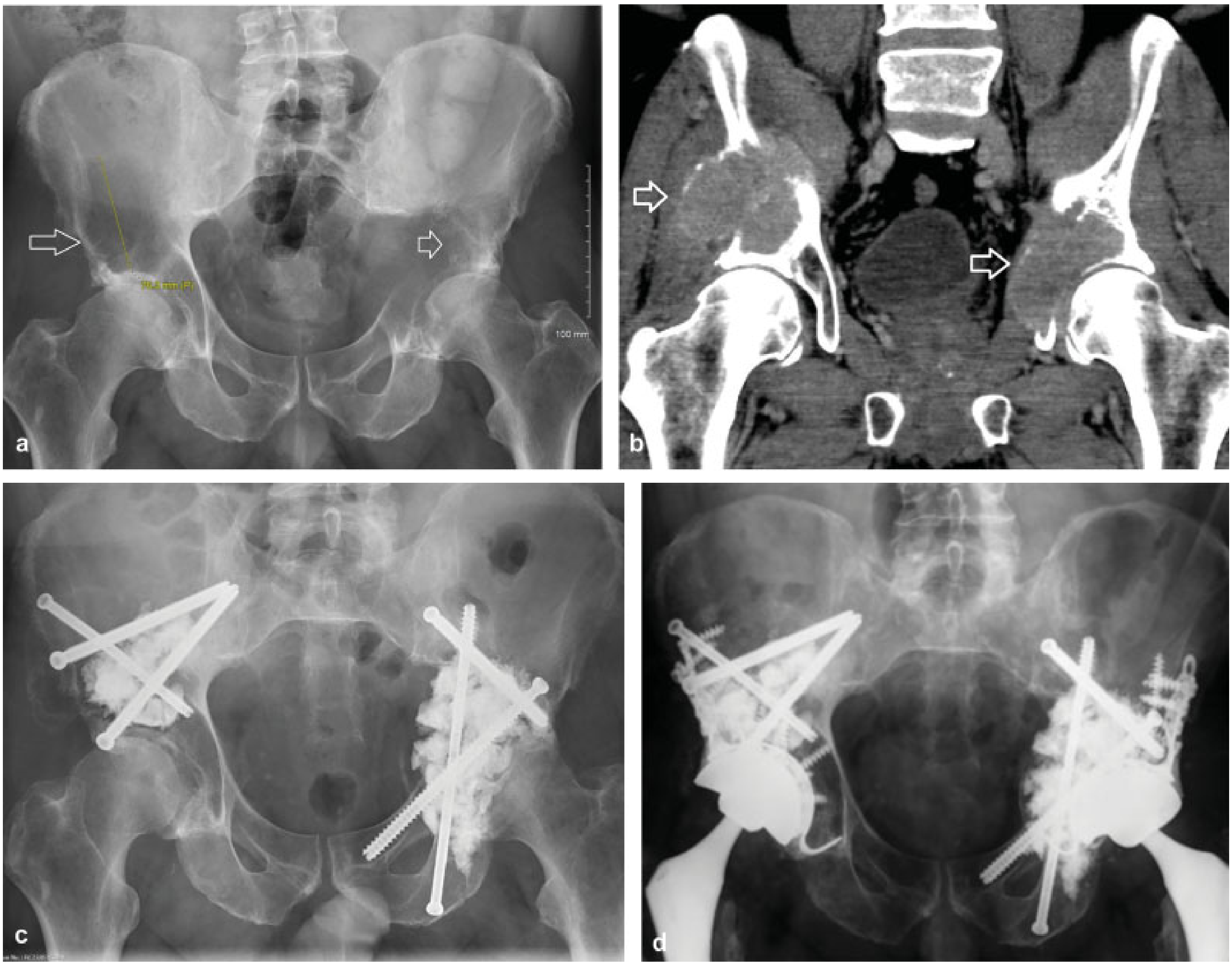

Fig. 8 A 63-year-old man with initial presentation of progressive left hip pain. Pelvic radiograph (**a**) and CT (**b**) showing bilateral destructive acetabular lesions (white arrows). (**c**) Status post bilateral acetabular percutaneous ablation and "screw and glue" fixation procedures. Each side was performed 7 days apart. Patient was ambulating with a walker on postoperative day 1. Adjuvant systemic and radiation therapy were both initiated within the week after stabilization. Unfortunately, despite initial pain relief, he developed bilateral hip pain 6 months after minimally invasive stabilization due to fragmentation of his acetabular rim and rapid joint degeneration bilaterally. He underwent sequential total hip arthroplasty with an end result similar to a Harrington type procedure (**d**), with good postoperative pain relief. The previous screws and cement were described at the time of surgery as facilitating rather than hindering surgical repair.

options going forward, as major surgical fixation or additional osteoplasty may be required (►**Fig. 8**).

Care should also be taken to minimize injury to the femoral head when performing ablation near the joint space. Microwave and cryoablation energy will easily transmit across the joint space and can lead to femoral head necrosis and collapse, which can be difficult to treat without surgical reconstruction. Radiofrequency ablation may be less injurious if the acetabular cortex is intact to provide some insulation of heat; however, this is not definitive. We have not tried more complicated adjunct techniques such as joint irrigation, as a complete ablation is usually not safely achievable and adjuvant therapy is already planned.

Postoperative Management

For the vast majority of pelvic augmented screw fixations, patients are weight bearing as tolerated after a couple of hour's bedrest. Patients typically receive nonsteroidal anti-inflammatory agents and steroids at the time of the procedure to facilitate postoperative pain control, although most patients will have significant pain relief just from stabilization. Physical therapy evaluation occurs the following morning primarily to optimize the use of necessary assist devices prior to discharge. Patients without complicating issues are often discharged on the first postoperative day.

The value of engaged multidisciplinary management in the postoperative period cannot be overstated. Nearly all patients will benefit from immediate adjuvant therapy as residual disease is almost always present. Patients can receive radiation therapy and systemic therapy generally within a couple of days after their procedure, as significant complications related to wound healing are extraordinarily low due to the minimal tissue disruption and small skin incisions. However, this is a significant deviation from current postoperative algorithms and the expeditious treatment of these patients often requires proactive education of the treating specialist preoperatively.

Long-term, periodic clinical follow-up is essential to identify any hardware loosening or local tumor progression and allow for early less invasive treatment before more significant complications occur. We typically see our patients in follow-up at 2 weeks, 3 months, 6 months, and yearly with radiographic imaging.

Additionally, the optimization of bone health and regeneration in the cancer patient is essential to long-term success especially as patients live longer with their disease. Engaging an oncologist or endocrinologist to aggressively prescribe metabolic medications such as zoledronic acid and denosumab when appropriate can significantly impact fracture healing and prevent construct failure.

Conclusions

Minimally invasive augmented screw fixation of the pelvis can provide significant clinical benefit with acceptable risk and minimal interruption to concurrent therapies and should be offered within a multidisciplinary approach to appropriately selected patients with unstable pelvic metastatic disease.

Interventional radiologists, with their unique, minimally invasive image-guided experience, are particularly well suited to perform these procedures; however, integrated preoperative planning between interventional radiology and orthopaedic surgery can synergize two complimentary and essential skill sets that are necessary to achieve optimal stabilization and the best outcomes for these patients within a long-term care plan.

Those interventional radiologists who become experts in these techniques will find a deeply rewarding practice and be well positioned to provide significant value to patients and referring clinicians alike.

Conflicts of Interest

W.B.L.: Consultant/Speaker for Siemens, IZI Medical, Galil Medical.

J.C.N.: None.

D.M.K.: None.

S.M.T.: Consultant/Speaker for BTG, IZI Medical, Galil, Merit, Stryker, Siemens, and Benvenue.

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