Chapter 7
Bone Tumor Navigation in the Pelvis

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Abstract Pelvic and sacrum bones are highly complex in shape that is why they are one of the most challenging surgeries to achieve in oncologic orthopedics. Traditional resection and reconstruction are done "freehand" that is highly inaccurate. Conventionally, surgeons rely on twodimensional images from the pelvis. In this kind of surgeries it is achieved negative but also wide resections margins to be removed with a surrounding margin of healthy tissue so as to ensure the complete resection of the tumor. The complexity of pelvic surgeries relies on the size of the tumors that use to be huge, the difficulty to access, close proximity to vital structures and multiplanar complexity. It makes impossible to design onedesignfitsall prosthesis that is why this kind of surgeries overturn to computer assisted surgery and navigated guideline because it has identifiable bony prominences to use as reference points for resection. Preoperative navigation enables physicians to explore the tumor area before the operation and learn about the possible way outs of the resection. Intraoperative navigation simplifies surgeries reducing the risk of damaging vital structures and measure depth of penetration of the instruments, guiding the surgeon within the anatomical structures during the whole procedure. Although computer navigation assisted surgery in the Pelvis is in its relative infancy it is a useful asset that results on decreasing revision rate, decreasing need of amputation and saving nerves roots.

Keywords Computed assisted surgery • Preoperative planning • Allograft reconstruction and musculoskeletal tumors

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Introduction

The pelvis and sacrum remain one of the most challenging locations for surgery in musculoskeletal oncology. The complex three-dimensional anatomy, proximity of vital structures, consistency of tumor and variable position of the patient during the procedure all contribute to the difficulty of surgical resection of pelvic and sacral tumors. Computer assisted sarcoma surgery has already improved surgical outcomes with regard to local recurrence, revision rates, amputations and nerve root damage despite being in its relative infancy within orthopedic tumor surgery [1, 2].

Osteogenic Pathology of the Pelvic Girdle

Pelvic and sacral tumors make up approximately 25 % of all chondrosarcomas and Ewings tumors but less than 8 % of osteosarcoma cases. The major tumor types seen that affect the pelvis are primary bone tumors but also locally invasive tumors from surrounding structures and metastases. Some less common tumors that have a predisposition to the pelvis and sacrum are chordomas, arising from remnant notochord, and benign tumors such as osteoblastomas, giant cell tumors and sacrococcygeal teratomas.

Primary Bone Tumors

Osteosarcoma, a malignant bone tissue tumor, is the most common primary bone tumor. It occurs most frequently in teens and young adults, and is the eighth most common form of childhood cancer, comprising 2.4 % of all malignancies in paediatric patients, and approximately 20 % of all primary bone cancers. Less than 8 % of osteosarcomas occur in the pelvis [3]. Ewing's sarcoma is a small round blue cell tumor, often located in the shaft of long bones and in the pelvic bones. It also occurs most frequently in children and young adults. Chondrosarcoma is a malignant growth of cartilage cells which often occurs as a secondary cancer by malignant degeneration of pre-existing benign tumors of cartilage cells such as enchondromas within bone and is primarily found among older adults. There is an average of 131, 96 and 55 new cases of osteosarcoma, chondrosarcoma and Ewing's sarcoma respectively diagnosed each year in England [4]. These malignancies tend to present late owing to their insidious growth and non-specific presentations and the ability of the pelvis to accommodate large tumors before they become noticeable to the patient. Though these tumors do not contribute a high volume of cases, the patients are typically young and therefore the loss of function is all the more devastating. The operations involved are also long, complex, may require personalised implants and have a mean inpatient stay of 28 days in our institution. Recurrence rates are high, as are rates of complications such as amputation, infection, prosthesis failure and nerve damage, all of which comes at great cost, both in terms of financial implications to the institution and morbidity for the patient.

Sacral Tumors

Tumors of the sacrum are rare. Primary benign and malignant tumors of the sacrum may arise from bone or neural elements. Six percent of all malignant bone tumors involve the sacrum, including chordomas (50 % of cases), lymphomas (9 %) and multiple myelomas (9 %), Ewing's sarcoma in children (8 %), chondrosarcomas in adults, and osteosarcomas [5]. Sacral tumors, like pelvic tumors, usually remain clinically silent for a long time. The most common initial symptom is local pain due to structural weakness, mass effect and compression [6]. Lateral extension of sacral tumors across the sacroiliac joints causes local joint pain and invasion into gluteus maximus and piriformis muscles leads to pain and decreased hip extension and external rotation power. Nerve root compression causes radicular pain radiating into buttocks, posterior thigh or leg, external genitalia, and perineum. At a later stage, motor deficit, and eventually, bladder/bowel and/or sexual dysfunction is noted [7]. Sacral tumors are especially difficult to resect and invariably neurological dysfunction results as nerve roots are disturbed. If the tumor is lateral, this may be avoided but there is a risk of damaging the sacroiliac joints and affecting the weight-bearing capacity of the pelvic girdle.

Metastases

Metastatic disease is the most common malignancy of bone; prostate, breast, lung, kidney, and thyroid cancer account for 80 % of skeletal metastases [8]. The pelvis is the second most common site of bone metastases after the spine [9]. The management of metastatic lesions may be curative or palliative and involves a wide array of treatment modalities including chemotherapy, radiotherapy and surgery. Not all metastatic lesions of the pelvis require surgical stabilization; lesions not directly involving the hip joint, pathological fractures not involving the acetabulum, and avulsion fractures of the anterior superior/inferior iliac spines, iliac crest, and pubic rami do not compromise pelvic stability [10]. In contrast, diffuse involvement of the pelvis, pelvic discontinuity and bony destruction of the periacetabular area warrant surgical treatment [11]. It may seem counter-intuitive to put palliative patients through high risk surgery, but the goal of palliation is to relieve the patient's suffering and improve quality of life. Therefore, according to the patient's condition, surgical treatment is recommended under the following conditions: (a) severe symptoms which are not alleviated by immobilization of the limb, analgesic drugs and anti-tumor therapy; (b) no pain relief or unsatisfactory recovery of function of the affected extremity after radiotherapy; and (c) pathologic fracture of the ipsilateral femur or adjacent site requiring simultaneous treatment [12].

Challenges Faced During Pelvic Surgery

The pelvis is a highly challenging area to operate upon which requires great skill and experience to achieve successful results. The reasons for this difficulty are explored in the following section.

Size

Pelvic tumors, particularly primary pelvic tumors, can grow very large before they are picked up. Figure 7.1 demonstrates a large pelvic tumor invading into local structures. Typical symptoms of bone tumors such as pain and stiffness may be attributed to more common pathologies such as hip osteoarthritis, swelling may be impalpable due to the considerable overlying muscle bulk and symptoms of nerve compression (such as sciatica or incontinence) are highly non-specific. Therefore pelvic tumors can be extensive at diagnosis.

Anatomy

The pelvic bones have a complex anatomy both in their three-dimensional structure and their relationship to one another. The pelvis forms a ring, therefore encompasses a full 360°. The pelvis is also relatively inaccessible, particularly when compared to the long bones, and it is large. Therefore pelvic surgery often involves moving the patient intraoperatively to gain access. This coupled with the complex multiplanar structure makes pelvic surgery very challenging.

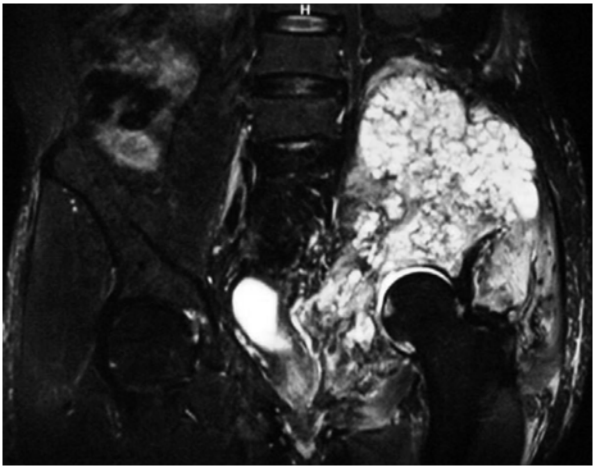


Fig. 7.1 Low grade chondrosarcoma of the pelvis

Consistency

Bone malignancies have variable consitencies, but often have cystic elements which may burst during the removal of the tumor. The tumor is also weaker than the surrounding healthy bone and may fracture upon removal. This makes it more difficult for the surgeon to remove the entire tumor en bloc and avoid tumor spill.

Margins

In order to reduce the risk of recurrence, it is accepted practice throughout oncology to achieve negative but also wide resection margins; that is, the tumor is removed with a surrounding margin of healthy tissue to ensure the entire tumor has been excised. This is very difficult to achieve during pelvic bone tumor surgery due to the size of the tumors being removed, difficulty of access, close proximity of vital structures and the multiplanar complexity of the structures involved. In addition, the late presentation of these tumors often allows the tumor to have invaded into local structures such as the pelvic veins or organs. Figure 7.2 demonstrates a pelvic chondrosarcoma in close proximity to the bladder, but with a clear plane for resection, Fig. 7.2a demonstrates a tumor invading into the bladder wall. Wide excision would be impossible in the case in Fig. 7.2a without a partial cystectomy. Additional difficulty occurs when a tumor has close anatomical relations to joints. It is common practice to preserve the joint architecture and articular surfaces during surgery to provide a better functional result, but often this is hampered by the desire to achieve a wide excision margin. Figure 7.3 shows intra-lesional, marginal, wide and radical resection margins. In patients with musculoskeletal malignancy the ultimate aim is to perform a wide-local resection and achieve adequate disease-free margins. Inadequate resection margins (intra-lesional or marginal) are frequently obtained [13]. The importance of achieving adequate surgical margins

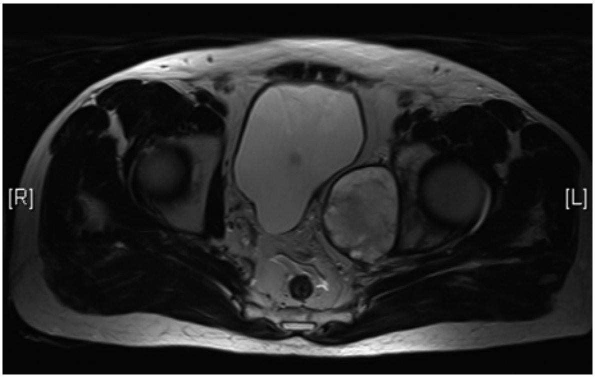
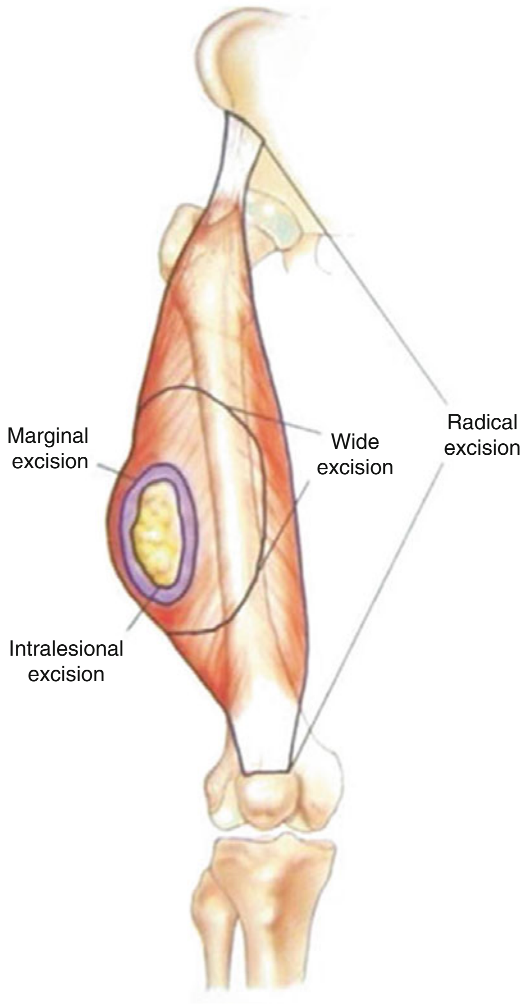


Fig. 7.2 Axial MRI scan of a pelvic chondrosarcoma with the cystic area and very thin soft tissue margin between the tumor and bladder

Fig. 7.3 Diagram depicting resection margins. In pelvic bone tumors, wide excisions are required to decrease recurrence rates



with these tumors is highlighted by the fact that local recurrence rates of up to 70 %and 92 % have been reported for pelvic tumors following marginal and intralesional resections respectively [13, 14].

Reconstruction

Unlike the long bones, it is impossible to design a one-design-fits-all prosthesis to implant following pelvic tumor resection. In order to achieve a successful reconstruction, the prosthesis must fit the resection margins exactly to preserve the mechanics of the pelvic girdle. Debate rages as to whether the pelvic ring needs closing by reconstruction with most surgeons favoring not to close the ring. The complexity of the pelvis makes designing and fitting functional reconstructions that are durable and allow patients maximum function incredibly challenging. Poorly fitting prostheses result in damage to existing healthy bone and revision surgery, which is all the more complex for the deranged anatomy caused by the original tumor and primary surgical procedure. The long term survival of the reconstruction by endoprostheses is 75 % [15] and 85 % for massive allograft reconstruction [16].

Complications

Patients with malignancies of the pelvis are at a higher risk of treatment failure than other patients with similar tumors located in a limb [17]. Treatment failure can include recurrence, prosthesis failure, amputation and nerve damage. All of these problems stem from the difficulty in achieving adequate resection margins, and difficulty with reconstruction and large dead space. All major series have reported complication rates of in excess of 50 % following reconstruction. The complication rates following resection without reconstruction are lower and may still produce good functional results.

Function

The primary aim of pelvic tumor surgery is to remove the tumor completely to prevent recurrence. However, a key secondary aim is the need to preserve the function of the patient as much as possible. The functions to keep in mind are; transfer of weight from the upper axial skeleton to the lower limbs, especially during movement; providing attachment for muscles and ligaments used in locomotion; protecting the abdominal and pelvic viscera.

Suitability of the Pelvis for Navigation

The pelvis particularly lends itself to computer-assisted surgery as it has multiple easily identifiable bony prominences to use as reference points. Accurate registration is important as it allows the computer to build up a picture of the patient's anatomy in space and therefore allows for direct correlation between the two-dimensional imaging studies and the three-dimensional surgical field by point to point and surface matching. This facilitates accurate orientation, tumor location and reconstruction thereby reducing the surgeon's margin for error. The anterior superior iliac spines (ASIS), anterior inferior iliac spines (AIIS), posterior superior iliac spines (PSIS), the top of the iliac notch or any other easily identifiable anatomical landmarks can be used for registration. The registration error should be <1 mm before proceeding with resection.

However, where the shape of the pelvis aids registration, it hinders the practicality of performing the surgery. Pelvic tumors are often very large and may require resection in multiple planes due to the unique geometry of the pelvis. There are also many critical structures that must be avoided during pelvic surgery, such as the sciatic nerve and the iliac vessels as they pass through the sciatic notch, the bladder and the peritoneum. The use of navigation can significantly reduce the risk of damage to vital structures by allowing the surgeon to know their location relative to the osteotome, as well of the depth of penetration of the instruments. This is particularly useful in the sacrum, where uninvolved sacral nerve routes can often be spared, improving the patient's neurological outcome after surgery.

Evolution of Surgical Techniques

All surgery requires extensive planning with knowledge of the patient's and the tumor's anatomy to enable a suitable implant to be designed. Since the advent of CT and MRI scanning, incredibly detailed three-dimensional representations of the tumor and surrounding anatomy can be isolated and explored before the operation. However, translating this information from view screen to intraoperative field can be difficult [17], resulting in inadequate resection margins or excessive removal of healthy tissue. Both of these scenarios result in unfavorable outcomes for patients. Inadequate resection margins (intra-lesional and marginal) frequently lead to local recurrence [14]. Excessive removal of bone causes difficulties to arise when trying to fit the implant or allograft. If this is not accurately done, there is a risk of non-union, disrupted biomechanics and implant failure.

Conventional techniques involve resection and reconstruction done 'freehand', with the scans available for reference. This has been shown to be highly inaccurate in a revealing study by Cartiaux et al. [18]. In this study, four experienced surgeons were asked to resect three different tumors on model pelvises under ideal conditions and the resection margins were measured. The probability of a surgeon obtaining a 10 mm surgical margin (5 mm tolerance above and below) was 52 %. This highlights the drawback of conventional surgical techniques within the pelvis.

Surgery using computer navigation has been used for a number of years to aid surgical precision in various branches of orthopedics, including spinal surgery, lower limb arthroplasty, and trauma [19–21]. In more recent years, there have been reports on the use of computer navigation assisted surgery for the resection of musculoskeletal tumors. Computer navigation assisted tumor surgery in the pelvis is in its relative infancy, therefore there have been huge improvements in a short time period. Initial attempts made use of spinal navigation software for intra-operative monitoring [22, 23]. These case reports demonstrated accurate excision and complete tumor clearance, however called for better CT and MRI imaging for the pre-planning stage to improve intraoperative precision.

Wong et al reported fusing CT and MRI images prior to tumor surgery, a technique used by neurosurgical and otorhinolaryngeal procedures. CT scans show intricate bony details well, whereas MRI is superior when examining intraosseous and extraosseous extensions of the tumor into the surrounding soft tissue. Therefore, integrating the two imaging modalities enables a more complete exploration of the tumor anatomy and better pre-operative planning [24]. They were also able to integrate functional imaging studies such as PET scans and angiography to further improve precision.

Cho et al. described improving intraoperative registration by preoperative implantation of four Kirschner wires—one in each of the two iliac crests and one in each of the two posterosuperior iliac spines—as fixed markers [25]. This is important when matching the patient's anatomy on the operating table with that on the scans, as subtle variations in orientation can affect accuracy of resection. It is also important to note that in patients with pelvic tumors, the normal anatomy and bony landmarks of the pelvis may be distorted or involved with the tumor. By implanting artificial landmarks at pre-defined sites and matching them with the scans, these difficulties can be overcome.

So et al. reported increased registration accuracy with CT-fluoro matching as opposed to point-to-point matching [26], and Cheong and Letson used both [17].

Although these studies have shown promising results, with more accurate resections and reconstructions being performed and improved implant positioning, it is recognized these conclusions are based on small case series and varied anatomical tumor sites [17, 22–26].

A study by Jeys et al. comprises the largest published series of the use of computer-assisted navigation in musculoskeletal tumors, and more specifically the largest series of primary pelvic and sacral bone tumors resected with navigation [1]. The results showed a significant reduction in intralesional excision rates from 29 % prior to the introduction of navigation to 8.7 % (n = 2) with clear bone resection margins achieved in all cases. At a mean follow-up of 13.1 months (3–34) three patients (13 %) had developed a local recurrence, whereas previous series had shown a local recurrence rate of 26 %. The conclusions from this and recent studies are that computer navigation is a safe technique with no complications specifically related to its use. To reduce the risk of errors, image-to-patient registration error should be less than 1 mm in all patients [1] to ensure accurate matching of the patients' intraoperative anatomy with the fused preoperative images. To minimize this registration error the time between imaging and surgical resection must be short [24].

How to Do It

Image Correlation

Accurate up to date MRI and CT scans are need to obtained prior to surgery. CT scans of the pelvis should <1 mm high resolution slices and the MRI should be 3–5 mm slices. Preferably the MRI and CT scan should include the whole pelvis and lower spine. The CT scan is used to delineate the bony anatomy and the MRI to identify the extent of the tumor and important soft tissue structures. Additional imaging techniques, such as CT angiography and PET-CT can also be incorporated into the pre-operative plan. The technique depends on whether intra-operative CT based navigation is being used or prior image correlation is being used; the rest of the description is for the latter. The pelvis lends itself to accurate image correlation given its complex 3D shape. Most of the systems will allow automatic correlation, but this can be time consuming and inaccurate; the authors therefore recommend manual correlation with automatic fine tuning. Generally using the acetabulae to match the anatomy on the CT and MRI scans is a useful starting point on the coronal scans, the Sacro-illiac joints in the axial plane and the spinal canal in the sagittal planes. At least 2 MRI sequences or planes should be used to correlate with the CT scan. Generally the author favours the use of axial and coronal STIR sequences for planning of the tumor, however, peritumoral oedema can be misleading and may result in greater bone resection than required. The STIR sequences should always be cross referenced to the T1 weighted images to allow accurate planning of the tumor location. Once the surgeon is happy that the image correlation is good, the automatic matching can be undertaken to check and improve accuracy.

Once the images have been correlated the tumor can be identified to the computer in a process known as segmentation. Again, automatic segmentation is possible with most software, but the author favours manual segmentation. The automatic segmentation works on differential signal intensity and will often segment peritumoral oedema, vessels and other non-tumor structures with similar signal intensity to the tumor. Therefore a 'slice by slice' manual segmentation on two planes is recommended. Once the images have been correlated and the tumor segmented, then the user will often remove the rest of the information from the MRI volume, leaving simply the bony anatomy and tumor segment visible at surgery. Image correlation and tumor planning generally will take approximately 15 min and is the most important step in pre-operative planning so great care should be taken.

Resection Plane Planning

It is vital that the surgeon realizes the goal of the surgery is to remove the tumor with an adequate margin of healthy tissue and that computer navigation simply allows the surgeon to execute the pre-operative plan. In some tumors it may be safe to resect the tumor with a narrow margin of less than 5 mm, however, the surgeon should remember that registration error may account for up to 1 mm of discrepancy at surgery and the thickness of the saw blade may cause discrepancies of 2 mm. Therefore, generally the authors recommend a resection margin of at least 10 mm of normal bone around the tumor. In the sacrum it is possible to plan resection planes into the sacral foramen, which will allow preservation of the nerve routes in that foramen. Some systems allow the planning for screw and implant trajectories, which can be extremely useful at surgery to achieve accurate joint line reconstruction with implants, ensure there is no cortical breach with stems and avoid damage to nerve routes with screws. In general, the author prefers multiplanar resections, especially with custom designed implants to preserve bone and ensure stable fixation.

Registration Points

The pelvis has a plethora of bony landmarks, which can be used for point to point registration. Typically the posterior superior iliac spine (PSIS), anterior superior iliac spine (ASIS) and anterior inferior iliac spine (AIIS) can be easily located at surgery. Even if these points are not being routinely exposed at surgery, stab incisions and percutaneous registration can be used as they are normally readily palpable. Other points can be used and vary with each case, but typically the iliac tubercle, pubic symphysis, sciatic notch, sacral foramen and acetabular tear drop can be used as readily identifiable points for point to point registration at surgery. The wider the spread of the registration points used in AP, lateral and sagittal planes will help to reduce the initial registration error and at least 4 points should used ideally. A registration error of 10–15 mm is acceptable initially, as this can be reduced to less than 1 mm with surface registration. The position of the patient at surgery, exposure and body habitus should all be taken into account when planning registration points (e.g. using the ASIS would be inappropriate if the patient is to be positioned prone for a sacral resection). Once point to point registration is completed then surface matching is used to reduce the registration error to <1 mm. This is done by taking 50–100 random points from the bone surface. Care should be taken to avoid areas where the tumor has spread outside the bone to avoid contamination, that the probe makes good contact with bone (and not soft tissue covering the bone) and that the points are spread out over as big an area of the bone as possible. The latter point can be sometimes difficult in a sacral resect from the posterior only approach, however, by exposing bilateral posterior superior sacro-illiac spines or making small percutaneous approaches remote from the operative field, this difficulty is easily overcome.

Design of Custom Made Implants

Given the detailed pre-operative planning that has been undertaken, the design of custom made implants is facilitated by navigation. The planned resection planes can be exported to engineers to design a custom made implant for the patient. If the software allows it, generally the engineers like to work with STL files or MIMICS software. If the programme does not allow exports, the authors generally measure the angles and distances of the resection planes from anatomical points to allow the engineer to reproduce the plan off exported screen shots.

The engineer will then create a virtual model of the desired custom implant on CAD-CAM software. The residual bone or implant can then be exported by the engineers and the STL file can be re-imported into the navigation software and compared for accuracy to the pre-operatively planned resection planes. The authors find that telephone/video conferencing is useful with the engineers to ensure the design of the implant is correct. The advantage of navigation is that it facilitates multiplanar tumor resection, and the engineers can then design an implant matching this interface, which is more inherently rotationally stable than the previous uniplanar design. The author has found that new manufacturing techniques including additive layer manufacturing (3D printing) has allowed very complex implants to be custom manufactured for the patient, which has improved implant design and delivery times.

Non custom implants such as the Coned hemipelvic replacement (Stanmore Implants Worldwide) or LUMiC (Implantcast) can more accurately be positioned using navigation as the trajectory and size of the stem can be determined pre-operatively. Providing the patient tracker is not resected with the tumor and the plane of the acetabulum is planned pre-operatively, at operation, after resection of the tumor, the implant can be accurately placed to reconstruct the joint line with appropriate inclination and anteversion, which can be very difficult without navigation.

Tracker and Camera Positioning

Most navigation systems use 'line of sight' infrared communication between three points to triangulate the position of the patient intra-operatively. If the camera on the navigation machine's view of the trackers is blocked by the surgeon, assistant or another object, then the navigation will not work and there will be a warning displayed to alert the surgeon which tracker cannot be seen by the camera. The three points used by navigation are:

(a) A patient tracker – this is a tracker, which must be placed on the bone, which is due to be partially, or wholly resected. It does not have to be fixed to the part of the bone which is resected and is generally best positioned on the part of the bone which remains. This because after the bone has been resected, navigation can still be used to gain further information (joint line, confirmation of accuracy of resection etc). Once the bone on which the tracker is placed has been osteotomised the navigation will no longer be accurate if used on the specimen bone, which is separated from the bone where the tracker is. As the computer will only see it as a whole bone, the order of the osteotomies during surgery is vital to ensure the final osteotomy is the one which separates the part of the specimen from the tracker bone. Patient tracker position is therefore vital; it must be securely fixed to the bone with a minimum of 2 pins but ideally 3 pins. If the patient tracker moves during the operation, the navigation will become less accurate and if this is noticed then the surgeon should check the stability of the patient tracker fixation and re-register the patient if it has moved. The navigation camera must be able to see the patient tracker throughout the entire procedure, therefore, using a mobile position of the patient (e.g. floppy lateral position) the patient tracker position must visible to the camera in the extremes of positioning and the sensors must be pointing towards the camera. Fortunately the sensors and camera have a wide angle of field of view, accommodating most positions, however, if the camera loses sight of the tracker during the procedure then the camera should be moved to 'see' the tracker, rather than the patient tracker.

(b) Navigation Camera – The camera is located on an arm of the navigation machine. On most systems this camera is mobile radially to the machine and also in the perpendicular axis allowing easy positioning and sight of the trackers. Intra-operatively if there is a poor view of the trackers the arm or machine can be moved into a better position without the need for re-registration of the patient.

(c) Instrument tracker/Pointer – The third point is made up of a pointer or tracker attached to an instrument, which has to be registered to the system either via a vector calibration device or by a registration point on the patient tracker. This can be done by scrub staff/assistant before the patient tracker is attached to the patient to save time intra-operatively. Intra-operatively the pointer can be used to identify the position of the tumor or set points required at surgery such as resection planes. The angle of the osteotomy or trajectory of a stem can be assessed using the pointer.

Navigated Instruments

The Stryker system allows calibration of any straight or angled instrument, to which a tracker can be attached and that will fit into the vector calibration device. Therefore osteotomes, burrs, saws and other instruments used during surgery can be recognized by the navigation, thus allowing precise knowledge of where the tip of a sharp instrument is in the bone or space. The authors have found this immensely useful when undertaking osteotomies of the sacrum from the posterior approach and will routinely undertake sacral osteotomies up to S1/2 from a posterior only approach rather than a combined approach prior to navigation. Knowledge of where the sharp end of the instrument is located increases the safety of the operation reducing the risk of inadvertent vascular injury.

Reduced Soft Tissue Exposure

An unanticipated advantage of the use of navigation in the pelvis is that if using navigated instruments less exploratory approaches are required, meaning that the retroperitoneum does not necessarily need exposing if undertaking a periacetabular osteotomy from the lateral ilium. As the tip of the osteotome can be accurately estimated (<1 mm) then routinely exposing and mobilizing the iliac vessels is not required providing the tumor is not intimately related to them. The author believes the reduction in the retroperitoneal dissection helps to prevent bleeding, reduces potential post-operative dead space and ultimately reduces the risk of infection. When using a planar (e.g. osteotome) or angled instrument care should be undertaken to ensure that the tracker can be seen by the navigation when being used in the orientation required. This sounds like an obvious point, but the author has frequently calibrated an instrument in the past, only to find the tracker is pointing 90° to the navigation and it cannot be 'seen' !!!

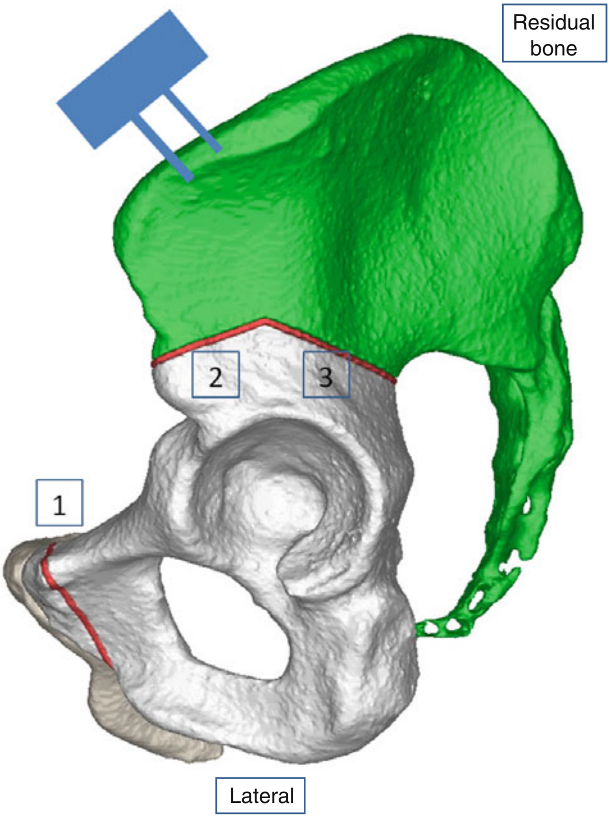


Fig. 7.4 If the green area is the residual bone anticipated after resection and the blue represents the patient tracker and the lower pelvis is to be resected in the midline, then the correct order of osteotomy would be (1) midline at the symphysis (2) superior illium and (3) inferior illium. This would reduce the risk of inaccuracy of the navigation. The author recommends marking the osteotomy planes with a diathermy prior to any osteotomy to give a reference line in case of navigation inaccuracy

Order of Osteotomy at Resection

As referred to earlier if an osteotomy either partially or wholly separates the resection specimen from the bone where the patient tracker is attached, then the navigation will be inaccurate and misleading. Therefore, careful consideration to the order of the osteotomy must be given. For most pelvic resections 3 osteotomies will be required (Fig. 7.4).

Sources of Error

It is vitally important that the surgeon appreciates the possible sources of error when undertaking navigated cases. The first source of error is in image correlation; the surgeon must ensure that the images are carefully correlated or else the basic plan of the operation is wrong from the outset.

The second source of error is poor planning of the tumor on the MRI scans. The surgeon must take into account the greatest possible extent of the tumor and determine whether peri-tumoral oedema represents tumor or not. If the surgeon fails to properly segment the tumor in planning intralesional margins may occur.

The third source of error is inaccurate planning of tumor resection planes. The surgeon must ensure that an oncologically safe margin is planned, normally 5–10 mm from the tumor. Just because navigation is accurate does not mean that narrow surgical margins are acceptable.

The fourth source of error is inaccurate registration. The surgeon should not proceed using navigation unless a registration error of <1 mm is possible. Large registration errors are typically due to poor exposure or recognition of the anatomical landmarks used for registration or landmarks which are too close together.

The fifth source of error is due to movement of the patient tracker during surgery. Occasionally the patient tracker will be knocked or hit, or if the pins are not securely fixed, it may move slightly during surgery. If this happens then the navigation will become inaccurate and re-registration is required.

The final source of error is interference with the infrared beams between the trackers. This has been reported with the use of plasma screen televisions in theatre or by having the navigation machine too close or far away from the trackers. An ideal distance is 6–10 feet from the machine. If inaccuracies are noticed or the camera is having difficulty 'seeing' the trackers, turning off any possible electrical sources of interference may be helpful.

The majority of errors when undertaking navigation are due to poor planning from the surgeon and are easily avoided.

Benefits of Bone Tumor Navigation in the Pelvis

There are many benefits to capitalizing on recent advances in technology. Bone tumor navigation has been shown to be a safe, effective technique that has promising early results in decreasing revision rate, decreasing the need for amputation and saving nerve roots [1]. In addition to these improved outcomes, bone tumor navigation allows for more complex resections by allowing intraoperative monitoring of patient position and improved cutting precision.

This increased accuracy also allows for better fitting implants with better biomechanics, as demonstrated in Fig. 7.5. This improves prosthesis function and decreases abnormal loading, thereby increasing prosthesis life-span and improving patient satisfaction.

Importantly, computer navigation achieves reduced intra-lesional resection rates [13, 14, 27]. However, it seems that recurrence is impossible to eradicate as even with clear margins Wong et al and Cho et al reported local recurrence rates of 25 % and 20 % respectively. High grade, thin soft tissue margins and large size denotes poor prognosis in pelvic and sacral tumors.

The extra time that it takes to plan a navigated case is rarely wasted as the surgeon gets a much better appreciation of the anatomy of the tumor and plans the case more carefully by spending extra time with 3D images of the tumor, being generally better informed about the pitfalls of the surgery pre-operatively.

Fig. 7.5 Resected acetabulum due to osteosarcoma using computer-assisted navigation. The resected specimen and implant match precisely

The downside of new technologies is that they are costly and time consuming. It is generally agreed amongst surgeons that the time component will improve as surgeons become more practiced. Also, the use of computer navigation systems negates the need to establish resection margins intra-operatively, which could eventually result in reduced operation times. It is still early days, therefore cost-effectiveness remains to be evaluated, however, if it proves to reduce complications and locally recurrent disease this will undoubtedly prove worth the cost, particularly as techniques develop and materials decrease in price.

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