Surgery of Pelvic Bone Tumors

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Editors

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Surgical Approaches in Pelvic Bone Tumors

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Andrea Angelini, Alberto Crimì, Elisa Pala, and Pietro Ruggieri

1.1 Introduction

Surgical approaches to the pelvis in musculoskeletal oncology are employed primarily for tumor removal and, in recent years for pelvic reconstructions. Because of the constraints posed by pelvic anatomy and tumor volume, standard "traumatological" exposures are often inadequate. Moreover, preoperative biopsy is frequently performed to reach the definitive diagnosis before surgical treatment and biopsy tract must be included with the specimen to avoid local tumor cell seeding [1]. This aspect underlines that also the trocar-needle biopsy should be performed by a surgeon with experience in pelvic resection [2]. The surgical approach for pelvic resections was first described by Enneking in 1978 [3] to achieve the desired surgical objective: the utilitarian pelvic incision. This extended ilioinguinal approach has been described and used for all the primary (benign and malignant) and secondary tumors of the pelvic girdle. It can be exploited partially or completely depending on the tumor malignancy and site as well as it can be extended for wider pelvic resections [4–6]. Since the initial description, various modifications have been proposed by Campanacci, Karakousis, and other authors [7–11]. The main ones are the T-incision, the question mark incision, the vertical posterior extension to the vertebral midline, and the ilioinguinal approach extended to the contralateral pubic ramus. These approaches require an appropriate preoperative planning and surgeon' familiarity with the anatomic relationships of pelvic region [12]. In some cases, a multidisciplinary approach with two different team for resection and reconstructive procedures could be useful under oncologic point of view.

1.2 Preoperative Evaluation

1.2.1 Relative Indications

Several preoperative considerations must be considered before proceeding with internal/external hemipelvectomy. There are some precautions that should be taken into account to avoid intra/postoperative complications.

1. As is true for all areas of medicine, a complete history is crucial to estimate patient's suitability for surgery, estimation of comorbidities, and definition of surgical-related risks. In particular, in oncologic patients, aspects resulting from prior surgery, biopsy tract, radiation therapy, history of infection may significantly influence the choice of surgical procedure and approach. Moreover, depending on the size

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and site of the tumor, all pertinent imaging and pathologic studies should be completed before the final decision to proceed is made.
2. We strongly suggest the use of rectal probe placed into the rectum and fixed to the perineal region. Not only does it allow the surgeon ability to demarcate the rectum during surgery, but also it reduces the risk of wound contamination by fecal material in the immediate postoperative management.
3. Localizing the ureters during a surgical procedure can be a challenging task in patients undergoing pelvic resection. The ureter lies in the interval between the peritoneum and the psoas fascia and may be displaced by large tumors extending medially into the pelvis. A prophylactic Double-J ureteral stent placement few days before surgery may reduce the chance of injury to the ureter or increase the chance that an injury will be recognized immediately [4, 9, 13, 14]. Moreover, a Foley catheter should always be inserted into the bladder.
4. A general anesthetic is usually administered. An arterial catheter is inserted for continuous hemodynamic monitoring, and a central venous catheter is advisable. One or more large-bore peripheral venous catheters are secured in place.
5. Infectious complications following major surgical procedures are a significant source of morbidity and potential mortality [15–18]. Antibiotic prophylaxis is intended for elective procedures in which the incision will be closed in the operating room. Numerous protocols have been designed for pelvic surgery, but usually must be adapted to specific resistance patterns of each hospital environment [18]. Prophylactic antibiotics should be administered shortly before or at bacterial inoculation. This should be done 15–60 min before skin incision. The majority of studies suggest that a single dose is effective but that for lengthy procedures (>3 h) the dose should be repeated at intervals one or two times the half-life of the drug. It has also been suggested that with large blood loss (>1500 mL), a second dose should be given.
6. In addiction to optimization of the patient's cardiopulmonary and general medical health before such massive surgical procedures are undertaken, the strict collaboration with anesthesiologist to alleviate the burden of local disease certainly plays a significant role. As a large amount of blood loss is sometimes encountered in limb salvage procedures for pelvic tumors, it is essential to identify risk factors predicting the possibility of extensive hemorrhage. The differences in patients' general condition, blood clotting ability, surgical team experience as well as speed and volume of blood transfusion may influence brisk hemorrhage. Tang et al. focused a study on this topic, finding that acetabulum or sacrum involvement, a tumor volume greater than 400 cm- and an anticipated operation time of more than 200 min are likely to have a large amount of blood loss [19]. We usually suggest large amounts of transfused blood and platelets should be prepared in such cases. Moreover, anesthesiologist should be intraoperatively updated on the current blood loss to avoid chasing progressively low hemoglobin levels. We usually avoid the use of the Esmarch bandage in patients with oncologic disease, even in case of external hemipelvectomy.

1.2.2 Patient Positioning

Patient positioning and surgical incision depend on the portion of the pelvis and soft tissue to be resected, surgeon taste, and experience. All these positions have pros and cons. The patient can be positioned in supine position (with a bumper on the contralateral side), so when required the table can be tilted. A sandbag beneath the lower thoracic spine of the affected site is useful to roll the patient approximately 45° anteriorly during posterior dissection. In this anterior "floppy-lateral" position, the skin should be prepared from the great toe on the involved site to the level of the xiphoid proximally (including the entire abdomen above the pubic symphysis), and beyond the midline posteriorly.

Lateral decubitus position allows simultaneous unilateral ventral and dorsal exposure of the hemipelvis, with the abdominal organs shifting downward far from the deep surgical plan. The patient is placed with the affected side up and the contralateral iliac crest centered over the point of flexion of the operating room table. Obviously, all bony prominences should be protected as well as the contralateral axilla and upper extremities.

Combined approaches may be performed simultaneously or staged as separate procedures depending on tumor site, type of reconstruction, and patient's comorbidities. When a custom-made prosthesis with spinal fixation is considered for pelvic reconstruction, a consecutive procedure which would allow a change in the patient's position under the same anesthesia is possible. In this case, we prefer a first surgical time in prone position before the second surgical time in supine (with the possibility of tilting the patient 45°) or lateral position. Regardless of the variation chosen, a third surgical time for complete spinopelvic fixation could be required.

1.3 Utilitarian Pelvic Incision

The utilitarian incision provides access to the inner and outer aspects of the innominate bone, the lower part of the abdomen, and the proximal femur. The starting point is the posterior inferior iliac spine, the incision then follows the iliac crest reaching the anterior superior iliac spine (Fig. 1.1a). At this point, it divides in two branches (Fig. 1.1b): the first branch of the incision extends along the inguinal ligament ending at the symphysis pubis, the second branch extends caudally with a gentle curve on the anterior aspect of the thigh for 5–7.6 cm and then bends laterally crossing the femoral shaft just below the greater trochanter following the posterior aspect of the femur and the insertion of the gluteus maximus muscle. In the modified T-shaped approach, the surgical incision is much more laterally in the turning point compared to the utilitarian incision; the distal branch runs straight on the lateral aspect of the thigh and does not turn posteriorly like in the Enneking approach. It was described for the first time by Karakousis in 1989 [20].

Some adjustments are necessary based on the size and position of the tumor: in periacetabular resections the incision is extended on the lateral thigh, in posterior resections the posterior part of the incision can be extended to the spine (with an added vertical incision), in anterior resection (pubic rami resections), the ilioinguinal incision can be extended to the contralateral side or downward facilitating the femoral vessels identification [9, 13, 14, 20, 21].

The preoperative planning of the resection and a correct biopsy technique are pivotal in order to

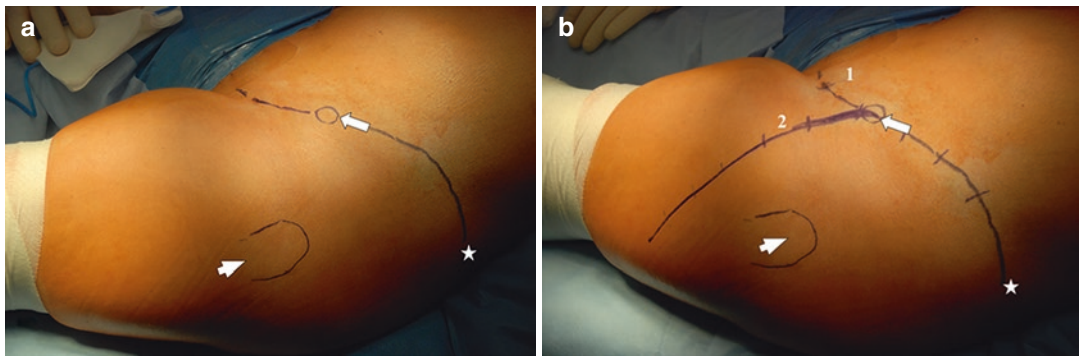


Fig. 1.1 Utilitarian pelvic incision. (**a**) The landmarks are the great trochanter (arrow head), anterior superior iliac spine (white arrow), and symphysis pubic. The starting point is the posterior inferior iliac spine (white star) and the incision follows the iliac crest reaching the anterior superior iliac spine. (**b**) Then it divides in two branches: the first branch extends along the inguinal ligament ending at the symphysis pubis (n. 1) and the second branch extends caudally on the anterior aspect of the thigh and then laterally just below the greater trochanter (n. 2)

avoid the jeopardizing effect on the soft tissue survival and reconstruction. The biopsy has to be performed along the utilitarian pelvic incision because the excision of the biopsy tract to avoid seeding of the tumor cells can bring to an extensive soft tissue damage [14].

1.4 Indications Related to Types of Pelvic Resections

Pelvic resections are classified according to the Musculoskeletal Tumor Society into four types: (1) Type I—iliac resection, (2) Type II—periacetabular resection, (3) Type III—obturator resection, (4) Type IV—resections involving sacrum [13]. Resections combining different portions can be classified and represented with the relative roman numbers, such a resection involving iliac and acetabular areas is called Type I/II resection. When all the three parts of the innominate bone are resected preserving the limb, the procedure is called internal hemipelvectomy (Type I/II/III) [22].

If the resection includes the proximal femur it is defined a Type H resection, divided in: Type H1—resection involving the femoral head, Type H2—resection involving the trochanteric area, Type H3—resection involving the subtrochanteric area [13, 21].

When resection includes the sacrum, the subclassification is categorized in four types: Type 1—resection involving a total sacrectomy, Type 2—resection involving a emisacrectomy, Type 3—resection involving a partial sacrectomy associated with an external hemipelvectomy, Type 4—resection involving a total sacrectomy associated with an external hemipelvectomy [4, 20].

1.4.1 Type I Resection

In order to obtain a Type I resection, only the first portion (most posterior part) of the utilitarian pelvic incision is usually needed. Anteriorly, the lateral attachment of the inguinal ligament is resected together with the external oblique aponeurosis, internal oblique, and transversus abdominis muscles. The anterior osteotomy is performed through the greater sciatic notch or just over the acetabulum (preserving the hip joint), under direct visualization to prevent injuries to the superior gluteal nerve and vessels. The posterior osteotomy is through or near the sacroiliac joint using an osteotome directed from posterior to anterior, with a protection of lumbosacral trunk and sacral roots. The exposure can be implemented by the release of the iliolumbar ligament at the posterior part of the iliac crest. The L5 nerve root should be visualized and preserved because it runs inferior and medial to the ligament [9, 13, 14, 20, 21].

1.4.2 Type II Resection

If the tumor involves the acetabulum (a tumor arising from the acetabulum itself or from the proximal femur and involving the hip joint in the acetabular component), a periacetabular Type II resection is indicated. In contrast to the iliac resection, the internal hemipelvectomy could be performed if an adequate wide resection procedure could be performed sparing the major nerves and preserving a functional limb [3, 21]. The lateral arm of the incision to the thigh is developed through the skin and the subcutaneous tissue, releasing the tensor fascia lata, sartorius muscle, and the straight head of the rectus femoris from their insertions on the iliac crest and anterosuperior iliac spine, respectively. The anterior osteotomy is performed through the anterior column of the acetabulum, the base of the superior pubic ramus. The posterior osteotomy is in the posterior acetabular column or in the ischium. The superior osteotomy is through the greater sciatic notch. If the posterior column is involved, some authors suggest en-bloc removal of the acetabulum and ischium [9, 20].

1.4.3 Type III Resection

Type III pelvic resection requires a medial osteotomy (through the pubic symphysis) and it is the

case where the utilitarian incision should be extended to the contralateral pubic ramus. Another osteotomy should be performed just medial to the acetabulum, avoiding the hip dislocation [21]. In this kind of resection, due to their proximity to the pelvic sidewall, obturator artery, vein, and nerve are usually sacrificed with part of the obturator internus muscle [13, 20, 21]. In order to avoid hernias of the peritoneum, a careful reconstruction of the inguinal floor is required all along the excised part of the pubic ramus. After the excision of the bony part, femoral vessels and spermatic cord should be repositioned deep to the abdominal wall reconstruction [23].

1.4.4 Type IV Resections and Sacrectomies

Type IV resections involve the sacrum. Sacrectomy can be partial or total, combined usually with iliac resections and lower lumbar spine resections [4, 21, 24, 25]. The S2 level is pivotal to define the outcome and surgical approaches to obtain a resection with wide margins. A tumor extending below the S2 level can be treated with a partial sacrectomy (transverse, sagittal, combined) without spino-pelvic reconstruction, with good expected neurologic results related to bladder and bowel function [24–27]. Moreover, a posterior-only approach could be used in selected cases [28]. If the sacroiliac joint is not involved by a sacral tumor (lateral sacral tumor), a sagittal partial sacrectomy is indicated, whereas in case of sacroiliac joint involvement a partial sacrectomy and resection of the posterior part of the ileum (type I, IV resection) should be considered [29]. Sacral midline tumors not involving the sacroiliac joint are treated with a transverse sacrectomy [30, 31]. A total sacrectomy is indicated when an aggressive lesion involves the proximal sacrum with anterior extension (rarely tumor can penetrate the anterior pelvic fascia extending to the rectum and other pelvic organs) [32–36]. In this case, sacral roots are necessarily sacrificed to obtain wide surgical margins and local tumor control [24, 37]. Despite major complications and implicit neurological deficits of this resection technique, patients' survival and tumor control can be achieved with a total sacrectomy [24–27]. If the tumor invades S1, lumbar spine, and pelvis, the proposed surgical approach is a combined staged posterior and anterior approach. The combined approach finds indication in tumors with high vascularization, primary sacral tumors involving S1 or invading the lumbosacral junction [9, 38].

1.5 Deep Surgical Dissection

A large flap of the gluteus maximus is reflected posteriorly in order to give exposure to the greater and lesser sciatic notches, the ischium, and the proximal third of the femur. The flap is based on a line that extends from the most medial portion of the posterior part of the iliac wing to the posterolateral aspect of the thigh [3]. The sciatic nerve is close to the pelvis at the sciatic notch; it is usually not infiltrated and can be isolated and easily separated from the tumor. Iliac muscle, gluteus medius, and gluteus minimus muscles are usually excised in order to obtain wide margins and good coverage of the pelvic tumor (more gluteus medius is not excised more abductor function will be preserved). The superior gluteal artery and vein are sacrificed because the gluteus medius and gluteus minimus are resected with the tumor.

In the anterior branch of the approach (Fig. 1.2a), the inguinal ligament has to be detached from the anterior superior iliac spine and, as well as in ilioinguinal approach, the aponeurosis of the external oblique muscle has to be incised from the superficial inguinal ring to the anterior superior iliac spine (Fig. 1.2b). Spermatic cord in male or the round ligament in female patients should be protected and retracted medially, then the section of the posterior wall of the ilioinguinal canal (fibers of internal oblique and transverse abdominis muscles) is performed under tension. The femoral bundle should be identified between the pubic tubercle and iliac crest, just anterior to the superior pubic ramus (Fig. 1.2c). Inferior epigastric artery and vein should be ligated. The multidisciplinary team

should include the plastic surgeon considering that, if ipsilateral vertical abdominis musculocutaneous flap should be used, the deep inferior epigastric artery should be preserved and protected. The important structures in the area should be identified and protected: the spermatic cord (while round ligament in women can be sacrificed), the femoral vessels (section of the iliopectineal fascia in order to mobilize the vascular bundle), and iliopsoas muscle with the femoral nerve that lies deep inside the muscle [13, 14, 20, 39]. A large vessel loop is placed around the common iliac vessels to assist with their mobilization (Fig. 1.2d). Arising from the medial and lateral aspects of the common femoral artery are the external pudendal and superficial circumflex iliac arteries that could be ligated to allow mobilization of the femoral vessels. Protection of the bladder is required, if pubis ramus osteotomy has to be performed. The pubic symphysis is exposed by detaching the anterior rectus abdominis and pyramidalis muscles from their insertion onto the ipsilateral pubic crest (Fig. 1.2e). The urethra that lies just inferior to the pubic symphysis and separated only by the arcuate ligament, should be protected during osteotomy. These structures are better identified with a Foley catheter inserted. In the following step, the help of a general surgeon is needed at this time to gentle separate the abdominal organs from the pelvic tumor assessing that wide margins are granted.

In the posterior pelvis after anterior part of the sacroiliac joint is identified and going further medially, common iliac vessels should be identified and followed into the pelvis (the same for the inferior vena cava in a right internal hemipelvectomy). A Double-J ureteral stent inserted before surgery in the ureter facilitates its identification as it crosses the common iliac artery, it must be identified and should be retracted medially. The posterior part of the sacroiliac joint should be visualized; the L5 nerve roots come out just below the L5 vertebra's transverse process, where the iliolumbar ligament attaches to the posterior ilium. In pelvic resection type 4, a posterior approach is usually needed for vertebral instrumentation.

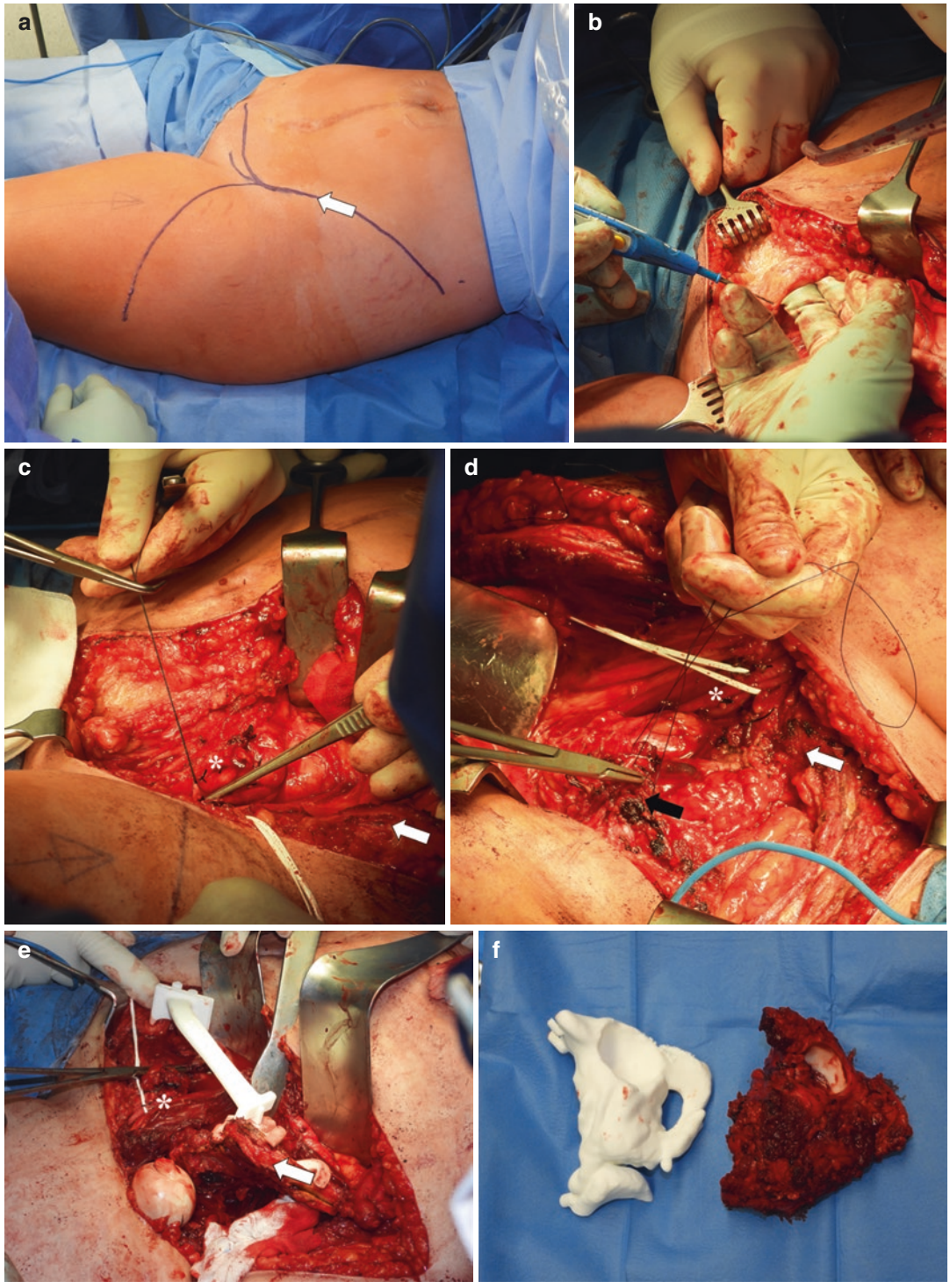
Once the bone cuts have been completed, the pelvis will open, but the sacrospinal and sacropubic ligaments must be resected to release the hemipelvis and make it loose still [13, 14, 20, 39]. The specimen should be compared with preoperative resection planes and margins macroscopically evaluated (Fig. 1.2f). After that, the reconstructive phase can be carried out (Fig. 1.2g–j).

The "reverse question mark" approach is characterized by the absence of the anterior branch of the utilitarian pelvic incision (Fig. 1.3a) and could be used when pubic osteotomy is planned close to the acetabulum. The deep surgical dissection includes the same previously described steps starting from neurovascular identification (Fig. 1.3b). One of the advantages of the supine position is the intra- and inter-observer reproducibility of radiographic measurements, especially when a custom-made resection (Fig. 1.3c) and prosthetic reconstruction are planned (Fig. 1.3d, e).

1.6 Pelvic and Soft Tissue Reconstruction

At today, there are few instances in which a staged approach may be preferable. In most of the cases, a consecutive procedure allows the possibility of

Fig. 1.2 Young patient (12 years-old) with Ewing's sarcoma of the left hemipelvis. (**a**) The skin incision was first drawn follows the utilitarian approach in supine position. (**b**) The inguinal ligament is incised from the anterior superior iliac spine (white arrow), as well as the aponeurosis of the external oblique muscle. (**c**) The femoral bundle has been identified (asterisk) and (**d**) protected with a large vessel loop. The tensor fascia lata, sartorius muscle, and the straight head of the rectus femoris have been released from their insertions on the iliac crest and anterosuperior iliac spine, respectively (black arrow). (**e**) A cutting jig has been positioned on the exposed iliac bone and pubic symphysis to perform correct osteotomies. (**f**) The model of the tumor and the specimen is shown to emphasize the similarity between resection plan and actual margins. (**g**) After tumor removal, it is possible to evaluate bone defect, osteotomy surface of the iliac bone (dashed line), and neurovascular bundle (asterisk). (**h**) In this case, reconstruction has been performed with an iliofemoral coarctation stabilized with a mesh tube (Trevira; Implantcast, Buxtehude, Germany). (**i**) Soft tissue reconstruction and (**j**) reinforcement of the abdominal wall with fascia lata graft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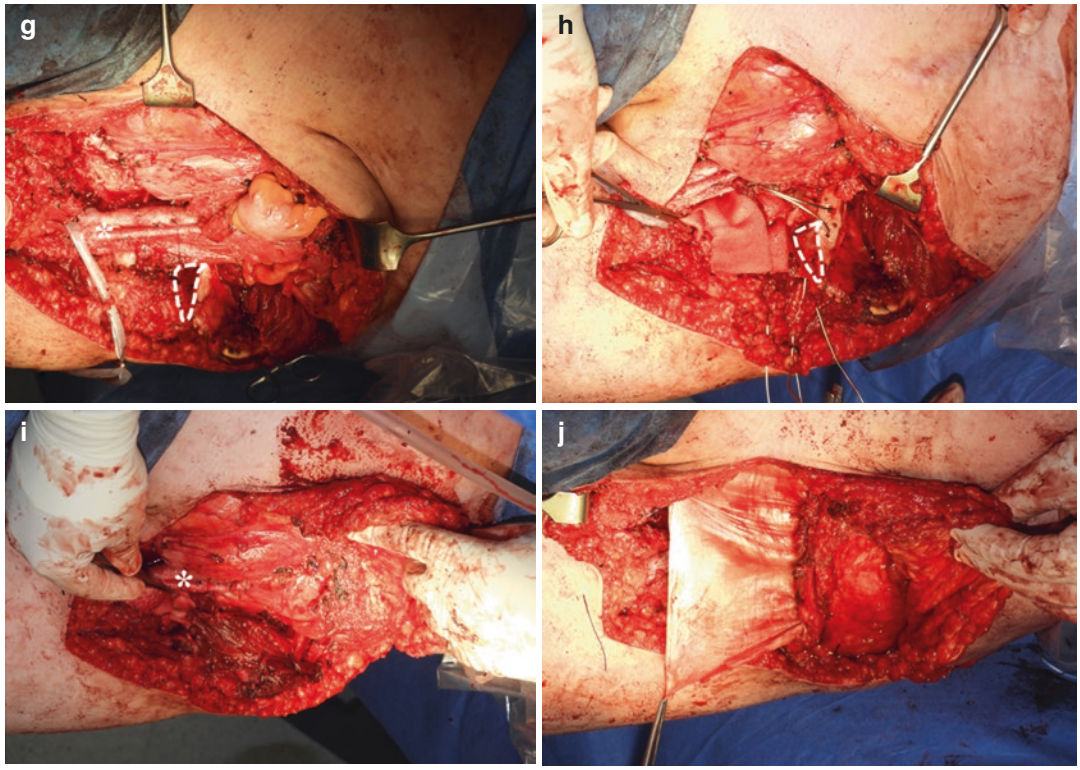

Fig. 1.2 (continued)

an immediate reconstruction, with a better reattachment of the soft tissue. In wide pelvic resections (mainly in combined type including a type II), the reconstruction of soft tissue defect and adequate implant coverage is crucial [40, 41]. Modular prostheses, custom-made 3D-printing prostheses, massive allografts, and other techniques are used for these challenging reconstructions [42–50] and infection remains the main complication [15–18]. In literature, it is widely reported that good soft tissue coverage of the prosthesis is considered one of the most relevant factors associated with implant survival [16, 18, 46].

The intersection point of the cutaneous incisions is at risk of delayed healing and wound necrosis (with finally high risk of periprosthetic), significantly higher if the soft tissue reconstruction of the deep tissues is not adequate. Enneking suggested, if there was not enough tissue to close the wound primarily, to cover important structures with flaps of omentum, it dressed with pigskin and then by skin grafts [3].

Different flap techniques are in use and are available considering the extension and the soft tissue damage during tumor excision [51, 52]. Preoperative CT with contrast study is always mandatory to properly plan the flap.

1.6.1 Rectus Abdominis Musculocutaneous Flap

Local flaps (advancement, rotation, propeller, and transposition flaps) are mainly based on a perforator as a pedicle. The rectus abdominis musculocutaneous (RAM) flap could be used as a muscular or a musculocutaneous flap, and could be realized with a transverse RAM (TRAM) or a vertical RAM (VRAM) based on the orientation of the skin paddle, to fill small defects with exposed vital structures. The VRAM flap is a solution in periacetabular and sacral reconstructions [41, 53–57]. In some cases, if there is a large fascial defect, it can be associated with a

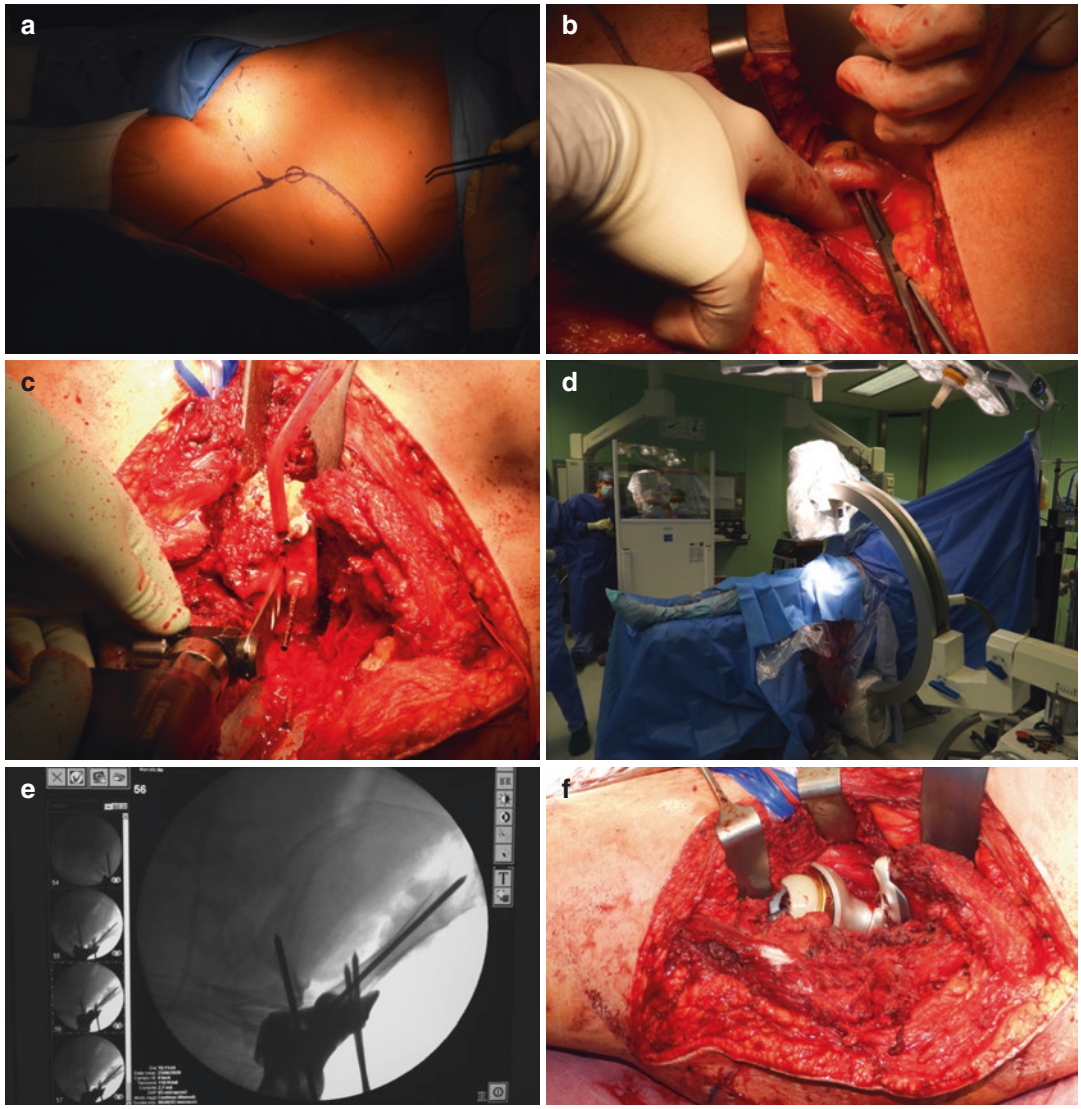

Fig. 1.3 Adult patient (52 years-old male) with an osteosarcoma of the left hemipelvis. (**a**) The "reverse question mark" approach has been drawn on the skin. The classic anterior branch of the utilitarian pelvic incision is dashed medially to the pubic symphysis. (**b**) Identification of the femoral bundle. (**c**) The iliac wing should be accurately prepared to fit with the cutting guide jig. (**d**) The picture shows the classic use of C-arm fluoroscopy in intraoperative orthopedic procedures. (**e**) Image intensification is very useful in the evaluation of bone resection and reconstructive aspects, and it allows greater flexibility with standard radiographic projections. (**f**) Definitive custom-made 3D printed prosthesis implanted before soft tissue reconstruction

synthetic mesh or an acellular dermal matrix. These solutions can be used to repair anterior defects of the donor site, posterior defects or both. The patient is positioned supine, the rectus abdominis muscle is palpated and outlined with a marker, and the flap is designed around the needed skin island (Fig. 1.4a). A midline incision extending from the pubic symphysis to just above the umbilicus is performed. The rectus abdominis muscle is then dissected maintaining intact the anterior portion of the sheath to avoid damaging the vascular perforators (Fig. 1.4b). The harvested rectus flap could be rotated on its pedicle (Fig. 1.4c, d) and tunneled via an intraperitoneal

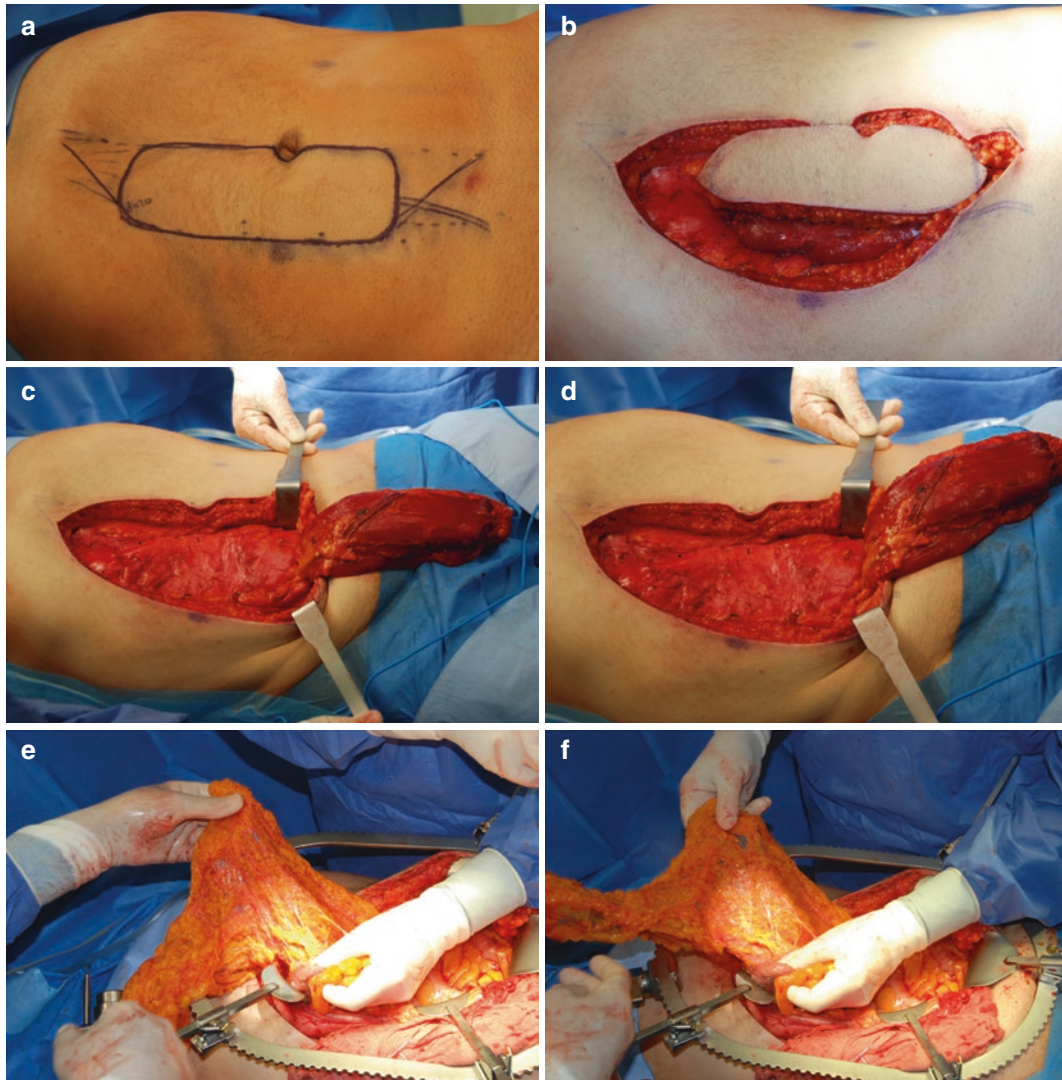

Fig. 1.4 Adult patient (54 years-old) with sacral chordoma. (**a**) Patient in supine position. The skin island is drawn based on the shape of the rectus abdominis muscle and the planned plastic reconstruction. (**b**) The rectus abdominis muscle is then dissected maintaining intact the anterior portion of the sheath to avoid damaging the vascular perforators. (**c**, **d**) The harvested rectus flap can be rotated on its pedicle and temporarily placed intraperitoneally. (**e**, **f**) During the anterior approach for proximal sacral resection, an omental-pedicled flap based on the right gastroepiploic artery is fashioned and used to fill the dead space

route into the pelvis or via an extrapelvic subcutaneous route to support wound closure [56, 57].

1.6.2 Other Flaps

Superior gluteal artery perforator (SGAP) or inferior gluteal artery perforator (IGAP) flaps are fascio-cutaneous flaps usually considered for partial sacral or total sacrectomies [58]. They may eventually include the underneath muscle, even if this myocutaneous technique should be generally avoided because it can lead to severe walking impairment. The use of a pedicled omental flap has been described as a tool of decreasing wound complications reducing the

dead space with a vascularized tissue (Fig. 1.4e, f) [53, 59]. Anterolateral thigh (ALT) flap is a reliable flap that can be used in periacetabular and sacral soft tissue reconstruction in some rare situations, usually to cover perineal or groin soft tissue defects. Tensor fascia latae (TFL) flap is a good flap for the coverage of the trochanteric, periacetabular, perineum, and abdominal wall soft tissue defects. It can be both a muscular or musculocutaneous flap.

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2 The History of Pelvic Tumor Surgery

Peter S. Rose and Franklin H. Sim

2.1 Introduction

The field of pelvic tumor surgery has advanced over the last 125+ years; this progress has been based on advances in several related areas of medicine:

- Improved anesthesia and perioperative care capabilities.
- Greater understanding of sarcomatous disease processes and margins.
- Improved imaging capabilities, particularly the use of computed tomography and magnetic resonance imaging.
- The development of adjuvant chemo- and radio-therapy.
- Expansion of orthopedic resections to locally advanced visceral disease processes.
- Critical examination of patient results and outcomes.

At present, most patients with localized pelvic sarcomas are candidates for curative resection, although high immediate and long-term morbidity remains inherent to these procedures. As well, the majority of patients are candidates for limb salvage operations. Several controversies remain in the selection and management of patients for these aggressive surgeries.

2.2 Early History

The first known attempted hemipelvectomy was by Bilroth in 1891 with a fatal outcome from hemorrhagic shock [1]. A subsequent successful operation (for advanced tuberculosis of the hip) was performed in 1900 by Hogarth-Pringle and is the first reported in the English literature [2]. Kocher described the first limb sparing pelvic excision in the late nineteenth century [3], but Putti provides the first well-documented case of internal hemipelvectomy in 1914 with successful outcome [4].

Speed popularized the term "hemipelvectomy" to describe radical amputation through the pelvis and replace the cumbersome "inter-ilio-abdominal amputation," while Gordon-Taylor referenced the procedure as a "hindquarter amputation" [5, 6]. The modern term "internal hemipelvectomy" to describe limb sparing approaches was first reported by Eilber in 1979 [7], and by analogy amputative resections are often referred to as "external hemipelvectomies" in contemporary practice.

The early twentieth century publications were primarily case reports or small case series which emphasized the surgical anatomy of approaches with relatively little data on patient outcome

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beyond mortality [6, 8]. Initially, operative mortality remained prohibitively high during the first half of the twentieth century. Gordon-Taylor reported operative mortality in 31 of 55 patients (56%) treated with hemipelvectomy for sarcoma or tuberculosis in 1934 and described the procedure as "one of the most colossal mutilations practiced on the human frame" [5, 9]. This operative mortality decreased to 22% in a later report as their team gained experience [10]. The decrease is likely due to a combination of team experience and improved perioperative care.

2.3 Advances in Disease Understanding

The mid-twentieth century brought significant advances in the scientific understanding of sarcomatous disease processes and the treatment of tuberculosis (an early indication for major pelvic resection). This included the establishment of sarcoma diagnostic categories and a tabulation of the natural history of conditions. For example, Dahlin and Henderson enumerated the basic treatment principles of chondrosarcoma in 1956 which remain true for the treatment of pelvic chondrosarcomas to this day [11]:

1. An adequate biopsy specimen for diagnosis should be obtained.
2. The definitive operation that is carried out is performed in such a manner that the biopsy wound will be excluded from the incision and will be removed with the specimen or limb, or both, without being opened again.
3. The tumor itself should be completely excised with a zone of surrounding tissue so that the surgeon does not break into or see the tumor at any time.

Dahlin and Henderson documented the difficult and morbid course of tumor recurrence as justification for aggressive initial treatment. They noted that only 3.4% of patients with inadequate surgical treatment survived or remained disease-free at 10 years, while 41% of patients treated according to these principles remained disease-free, a decade or more after surgery. This work remains one of the first and clearest tabulation of the principles of bone sarcoma resection and the greater than tenfold increase in survival seen with proper treatment.

Similar results accrued in other bone sarcomas and in soft tissue sarcomas to define the strong importance of proper biopsy and en bloc resection techniques in the treatment of sarcomas [12, 13]. Enneking, a pioneering pelvic sarcoma surgeon who helped usher in the modern era of treatment, tabulated and popularized these principles to guide sarcoma surgery in general [14]. The accumulating experience which helped to define disease processes and these principles and the dissemination of them to surgeons helped propel the role of surgery as a part of curative treatment protocols for pelvic neoplasms.

2.4 Imaging Advances

The imaging of pelvic sarcomas remains complex today, even with the variety of advanced imaging modalities available. The first pelvic tumor surgeries were based on plain film radiographs, physical examination, and surgical exploration. Later surgeons used plain film tomograms to better image the bone in combination with catheter angiograms and barium enemas to infer soft tissue extension [15]. Bone scans were incorporated as well but lacked spatial resolution.

The lack of imaging frequently lead to poorly placed biopsies, inadequate margins, and poor outcomes. Enneking's large series published in 1978 (patients operated between 1957 and 1977) revealed that one-third of patients treated with pelvic resections had oncologically inadequate surgeries for these reasons [16]. Tumor recurrence was seen in 100% of patients with inadequate surgeries. The certain morbidity of these procedures and far from certain surgical outcomes naturally tempered the enthusiasm of physicians and patients alike in selecting aggressive management of pelvic sarcomas.

The advent of computed tomography in the 1970s significantly improved the ability to image patients with pelvic tumors [17, 18]. CT imaging

provided surgeons with two primary benefits. First, it allowed much improved anatomic definition of the extent of pelvic sarcomas to define their osseous and soft tissue extension as well as visceral relationships. Second, CT scans of the chest provided improved sensitivity to detect pulmonary metastases compared to chest radiographs or lung tomograms. This second benefit allowed teams to more reliably exclude from surgery patients with established metastatic disease. CT became widely available at regional tumor centers in the early 1980s. In a similar fashion, magnetic resonance imaging provided additional anatomic discrimination of tumor extent and became widely available by 1990 [19]. In the recent two decades, positron emission tomography has similarly increased the ability of physicians to properly stage sarcoma patients [20].

These imaging advances improved the ability of surgeons to assess patients for resectability, decrease inadvertent positive margins, and to avoid morbid surgery on patients with metastatic disease. The current imaging of pelvic sarcomas is center-specific but typically combines CT and MR imaging of the local disease with CT of the chest and bone scan (or potentially PET) for staging.

2.5 Adjuvant Treatments

The three most common bone sarcomas encountered in the pelvic region include chondrosarcoma, osteosarcoma, and Ewing's sarcoma. Chondrosarcoma remains stubbornly resistant to any known adjuvant treatment, with prognosis heavily influenced by grade and surgical margin for patients with localized pelvic tumors [21]. However, dramatic advancements in chemotherapy have improved the prognosis for patients with osteosarcoma and Ewing's sarcoma.

Prior to adjuvant chemotherapy, the survival of clinically localized osteosarcoma was <15% [12]. While specific survival rates for pelvic osteosarcoma in the prechemotherapy era are not reliably recorded, these tumors are known to carry an even worse prognosis than extremity tumors, and it is reasonable to infer that long-term disease-free survival was rarely achieved in these patients.

The advent of doxorubicin-based chemotherapy immediately and dramatically improved the survival of patients with osteosarcoma [22]. These advances provided a meaningful potential for survival for patients with high-grade axial sarcomas and opened the door to consideration of aggressive surgical treatment for what had generally been considered a fatal disease. Parallel advances were made in the treatment of Ewing's sarcoma during this era as well [23].

Simultaneous advances were made in the understanding of the use of radiotherapy for pelvic Ewing's sarcoma [24]. Because of the uncertainties of imaging, margin, and prognosis, the majority of patients with Ewing's sarcoma of the pelvis were treated with radiation therapy for local control. Greater enthusiasm grew for surgical management of pelvic Ewing's tumors (with or without radiation) in the 1980s and 1990s with improved imaging, although this remains a controversial aspect of pelvic sarcoma treatment [25, 26].

2.6 Application to Visceral Diseases

While initially associated with high morbidity, the same conditions which led to advances in pelvic sarcoma surgery provided parallel advances in surgery for pelvic visceral diseases [27]. This allowed for the identification of a subset of patients with locally advanced visceral malignancies and musculoskeletal involvement and no distant metastases; typical examples would be locally advanced primary or recurrent colorectal cancer invading the sacrum or gynecologic malignancy invading the pelvic sidewall or ilium with no distant tumor spread.

Musculoskeletal involvement of visceral malignancies had traditionally been considered a marker of unresectability. However, by combining the advancing understanding of tumor biology and pelvic resection techniques, extended en bloc resections of visceral disease and involved musculoskeletal structures began in the

mid-1980s to provide curative treatment for select patients [28, 29]. While initially limited to patients with modest osseous involvement, expanding experience showed that reasonable oncologic results and survival could be obtained even with extensive resections [30]. At present, extended pelvic exenterations (en bloc resection of the visceral malignancy and associated musculoskeletal structures) are now offered at select cancer centers with reasonable patient morbidity and oncologic outcome. As is seen in virtually all pelvic tumors, margin status is a key determinant of outcome, highlighting the role of aggressive resections in curative intent procedures.

2.7 Collaboration and Examination of Results

A key aspect of surgical and scientific advancement is the collaborative sharing and critical examination of results. In parallel with the development of the field of pelvic sarcoma surgery, several professional organizations formed to improve progress and better evaluate the outcomes of patients with musculoskeletal malignancies. Notable organizations in this field include:

- The Musculoskeletal Tumor Society (MSTS, est. 1977)
- The International Society of Limb Salvage (ISOLS, est. 1981)
- The European Musculoskeletal Oncology Society (EMSOS, est. 1987)
- The Connective Tissue Oncology Society (CTOS, est. 1995)

These multidisciplinary professional organizations have (and continue) to actively advance the practice and understanding of pelvic tumor surgery. A prime example of this is the evaluation system for the systematic evaluation of patient outcomes initiated at the inception of ISOLS in the 1981 meeting. This culminated in the standard MSTS outcome instrument for evaluating the results of musculoskeletal tumor surgery [31] which remains in use to this day.

2.8 Current Practice in Pelvic Tumor Surgery

Modern imaging now allows reliable determination of tumor extent and the overt metastatic status of patients presenting with pelvic malignancies. As well, current practice provides for limb sparing resections in the majority of patients. The common nomenclature for amputative resections is either "external hemipelvectomy" or "hindquarter amputation." Limb sparing resections are termed "internal hemipelvectomies" and classified as outlined by Enneking and Dunham as to involvement of the iliac bone, acetabulum, or pubic region [16]. Clinical outcome assessment is still most commonly performed using the Musculoskeletal Tumor Society rating scale [31], although more generalizable patient reported outcomes are becoming more common.

Time and institutional practice patterns have seen different approaches and shifts in the management of pelvic sarcoma patients. The initial management of these patients focused on tumor removal alone; reconstruction was rarely used and difficult with the techniques available [7]. Recent reports have demonstrated the enduring value of this technique, and it remains a viable surgical option in contemporary practice [32].

However, other centers have demonstrated improved functional results with restoration of femorosacral continuity (anatomic reconstruction or substitution) following limb sparing resection in the pelvis [33]; this is most difficult in resections which remove the acetabulum.

A number of different approaches have (and continue) to be used in these patients. While cemented and reinforced conventional arthroplasty constructs have been reported (commonly referred to as the Harrington technique), they are most commonly used after surgery for periacetabular metastases which typically remove less bone than a primary tumor excision with oncologic margins [34]. Iliofemoral arthrodesis was initially performed for these patients but remained technically challenging with pseudarthroses and modest functional outcomes [35].

Early anatomic reconstruction experience utilized massive pelvic allografts or processed

autograft for reconstruction [36]. These reconstructions were technically demanding and suffered high complication rates. The saddle prosthesis, an adaptation of an implant for massive bone loss after failed or infected hip arthroplasty, was utilized in tumor resections in an attempt to provide a reconstructive option utilizing a modular endoprosthesis [37]. However, greater experience and follow-up have highlighted the limitations of this method, and its use in current practice is rare [38].

Modern techniques of periacetabular reconstruction include modular endoprostheses, custom prostheses, and porous tantalum implants [39, 40]. Each of these techniques has relative advantages and disadvantages based on resection and remaining bone stock as well as center experience and preferences. The use of intraoperative navigation or preprinted custom cutting guides allows precise resections to be made to match prefabricated implants.

Not all pelvic resections are commonly considered for reconstruction. While reconstructions have been reported following pubic resections [41], most centers provide soft tissue reconstructions only for these resections. Controversy exists as to whether resections of the supra-acetabular ilium require reconstruction or not. Some centers advocate for no reconstruction to minimize complications and allow medialization of the hip center to decrease Trendelenberg gait (at the expense of leg length discrepancy) [42]. Other centers have shown good results with reconstruction of these defects [43].

Despite advances on many fronts, there remains a role for external hemipelvectomy/hindquarter amputation in current clinical practice [44]. Patients are currently considered for hemipelvectomy in three primary scenarios:

1. En bloc resection of a tumor would leave a limb with such little function as to make amputation preferable. This primarily occurs when tumor extent would require removal of two or three of the critical elements of limb function (the sciatic nerve, the femoral neurovascular bundle, and the acetabulum).
2. Patients in whom resection will result in a soft tissue defect so large that the wound cannot be closed without the benefit of an amputation flap. With increasing experience with free flap coverage and the use of omentum for closure, this scenario is becoming less common.
3. For salvage of patients who experience tumor recurrence following internal hemipelvectomy.

While many teams have been pessimistic about patient function following external hemipelvectomy, modern prosthetic management can allow single hand-free ambulation for many individuals [45].

2.9 Contemporary Issues in Pelvic Tumor Surgery

Despite the large number of advances made since the first reported attempt at hemipelvectomy in 1890, a number of areas of pelvic tumor surgery remain unresolved. The need for (and if performed method of) bony reconstruction after major pelvic bone resection remains unclear. Reconstruction appears to offer better function at the price of higher complications, but selection and center treatment bias clearly influence these results. True long-term follow-up studies of patients are rare and show an expected decline in function in long-term survivors of their malignancies [46].

The uncertainties of the role and method of reconstruction are magnified in pediatric patients in whom little published literature exists to guide surgeons [47]. Most children undergoing major pelvic surgery have consideration of reconstruction for iliac defects. If the acetabulum is resected, consideration for reconstruction is given in older adolescents; young patients are generally treated with resection arthroplasty. While not strictly tabulated, the authors' clinical experience of this in young patients is generally favorable.

The role of amputation or limb salvage remains controversial. The criteria outlined above represent the classic criteria for hindquarter amputation, but some centers strive to avoid the morbidity of this by offering limb salvage to "borderline" cases. It is not clear which path provides better functional and oncologic outcomes.

Because of the morbidity of surgical resection, many centers try to employ radiotherapy when possible. This is most common in patients with Ewing's sarcoma in whom local control may be achieved with surgery, radiotherapy, or both. The combination of surgery and radiotherapy appears to decrease the risk of local failure [48]. Some studies have suggested improved survival with surgical treatment [25, 26, 49]. However, others have not shown a clear benefit [50]. No studies randomize patients between treatment arms. In addition to Ewing's sarcoma, some groups have attempted to employ high-dose proton-based radiotherapy to achieve local control of otherwise adversely presenting pelvic sarcomas with some success [51]. To date, the authors' personal experience with this for non-Ewing's tumors has been uniformly poor.

The timing of chemotherapy around major pelvic resections is an area of concern. It is established in extremity osteosarcoma, for example, that delays in resumption of chemotherapy after surgery negatively impact survival [52]. Additionally, a prospective randomized trial showed no difference in oncologic outcomes in osteosarcoma treated with immediate surgery followed by chemotherapy compared to a standard regimen of preoperative chemotherapy, surgery, and postoperative chemotherapy [53]. The magnitude (and complication profile) of large pelvic tumor surgeries is such that patients are at high risk to experience significant postoperative delays in chemotherapy resumption. This has led some centers (including the authors') to complete most or all chemotherapy prior to surgical resection in select pelvic sarcoma patients judged to be at high risk for perioperative complications. It must be stated that data regarding this practice are still being gathered, and patients undergoing "front-loading" of chemotherapy are carefully monitored with serial imaging studies for disease response.

Finally, readers should know that the oncologic staging of pelvic sarcomas has recently changed. An analysis by the American Joint Commission on Cancer (AJCC) highlighted the adverse prognosis of axial location on sarcomas. In light of this, the recently released eighth Edition AJCC Staging Manual has incorporated anatomic location in the staging of bone sarcomas (with specific criteria for pelvic tumors) in an attempt to better predict the clinical outcome of these difficult cases [54]. Accumulating data will hopefully demonstrate whether this change has value in clinical care.

2.10 Conclusions

The field of pelvic tumor has undergone a series of advances since the first major pelvic resections were undertaken over a century ago. Modern imaging, improved disease understanding, and adjuvant therapies are the pillars of these advancements. However, the morbidity of these treatments remains formidable and the prognosis guarded. Unfortunately, the words of Gordon-Taylor, a pioneering pelvic tumor surgeon, remain true in this field over a half century after they were written [9]:

> *I still cherish the hope of a golden era of cancer therapy when gross mechanical destruction of disease and cruel mutilation of tissue shall be no more. Unfortunately, these times are not yet.*

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