Review Article

Periacetabular reconstruction following limb-salvage surgery for pelvic sarcomas

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ABSTRACT

Limb-salvage surgery for pelvic sarcomas remains one of the most challenging surgical procedures for musculoskeletal oncologists. In the past several decades, various surgical techniques have been developed for periacetabular reconstruction following pelvic tumor resection. These methods include endoprosthetic reconstruction, allograft or autograft reconstruction, arthrodesis, and hip transposition. Each of these procedures has its own advantages and disadvantages, and there is no consensus or gold standard for periacetabular reconstruction. Consequently, this review provides an overview of the clinical outcomes for each of these reconstructive options following pelvic tumor resections. Overall, high complication rates are associated with the use of massive implants/grafts, and deep infection is generally the most common cause of reconstruction failure. Functional outcomes decline with the occurrence of severe complications. Further efforts to avoid complications using innovative techniques, such as antibiotic-laden devices, computer navigation, custom cutting jigs, and reduced use of implants/grafts, are crucial to improve outcomes, especially in patients at a high risk of complications.

Contents

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1. Introduction

Limb-salvage surgery for pelvic bone sarcomas remains technically demanding because of the underlying complex anatomy, proximity to major vessels and nerves, and development of large bone and soft tissue defects after tumor resection [1,2]. Pelvic bone resections are classified according to the system of Enneking and Dunham [3,4]: PI, ilium; PII, periacetabulum; PIII, pubic rami; and PIV, sacrum. Periacetabular reconstruction following pelvic resections, including PII, represents the most difficult challenge, and PII-involved pelvic resections are associated with poor functional outcomes compared with the other resection types [5]. Although selected tumors involving neurovascular structures still require hindquarter amputation [6,7], limb-salvage surgery has been a feasible surgical option for better functional outcomes in most patients [8-12].

In the past four decades, various surgical procedures have been developed for periacetabular reconstruction following periacetabular tumor resection. These reconstructive options include endoprosthetic replacement, allograft reconstruction, autograft reconstruction, iliofemoral or ischiofemoral arthrodesis, and hip transposition [5,13]. Each of these options has its own advantages and disadvantages. Thus, there is currently no consensus on what constitutes the standard procedure for acetabular reconstruction [2,8]. In this review, we clarify the characteristics of the various treatment options for periacetabular reconstructions and summarize their respective clinical outcomes. Since more than half of the publications regarding the acetabular reconstructions described the surgical outcomes using an endoprosthesis, we discussed the characteristics of each option for acetabular reconstructions separately; endoprosthesis (Table 1) and other options using an allograft, autograft, arthrodesis, hip reconstruction, and others (Table 2).

2. Endoprosthesis

2.1. Saddle prosthesis

A saddle prosthesis was originally designed in 1979 by Nieder et al. for the reconstruction of severe acetabular defects in revision hip arthroplasty [14]. This type of prosthesis has a bearing surface with a saddle, which has two horns to support the remaining ilium; this prosthesis was promoted for reconstruction after the introduction of periacetabular tumor resection in 1984 [15]. Owing to its design, saddle prosthesis allows a simpler reconstruction that eliminates the need for acetabular component fixation [16] (Fig. 1). However, the saddle prosthesis is indicated only in patients in whom sufficient ilium would remain after tumor resection, and this design feature is associated with several long-term complications, including iliac wing destruction and proximalization of the prosthesis, which can result in dislocation or leg-length discrepancy [14,17-19]. Jansen et al. performed a cohort study involving 17 patients and reported on the long-term outcomes of six patients with a mean/median follow-up of 12.1 years. The mean MSTS and TESS scores were 47% and 53%, respectively, and 13 of 17 patients (76%) required walking aids for mobilization [17]. Complications were identified in 14 of 17 patients (82%) and included wound complication (53%), dislocation (41%), and leg-length discrepancy (12%). Menendez et al. developed the PAR periacetabular endoprosthesis, a modular third-generation saddle prosthesis [20]. This prosthesis resulted in a decreased, although still high, rate of failure at the ilium–saddle interface compared with the second-generation saddle prosthesis and provided acceptable function, with a mean MSTS score of 67% [20]. In a systematic review of 135 patients from eight studies, the mean MSTS functional score in surviving patients was 51%, and deep infection was the most common complication, occurring in 24% of patients [13]. Considering the high risk of complications and poor functional outcomes, researchers have stated that the saddle prosthesis cannot be recommended for pelvic reconstruction following internal hemipelvectomy [16,17].

2.2. Modular-type prosthesis

Modular hemipelvic prostheses with multiple components producing their own versions have been developed by Guo et al [21]. The design of the modular-type prosthesis consists of iliac fixation components, pubic connection plates, and acetabular components. The cost-effectiveness compared with custom-made prosthesis is one advantage of this prosthesis. The modular-type prosthesis was indicated in patients with a pelvic tumor other than type IV (sacrum), tumors that extensively invaded the inside of the pelvis, or tumors that involved the sciatic nerve [21]. Early results indicated an acceptable outcome, with a mean MSTS score of 62% and a deep infection rate of 14% [21]. Guo et al. later reported on the mid-term outcomes, including an increased rate of major complications requiring surgical intervention (39%) and a slight decrease in functional scores (57%), which were drawbacks commonly observed in the prosthetic reconstruction [22]. The long-term outcomes with this prosthesis remain unclear.

Porous tantalum implants have recently been applied in periacetabular reconstruction after pelvic tumor resection [23]. This prosthesis was originally established for large bone defects in revision total hip arthroplasties, which successfully achieved mechanically stable hip constructs with low rates of failure secondary to loosening [23,24]. Tantalum components have the advantage of coming in multiple shapes and sizes, without the need for costly customization and to obtain osseous ingrowth and stable fixation in situations where there is compromised bone stock [23]. Abdel et al. reported on the early results of 10 periacetabular reconstructions using these implants after pelvic bone sarcoma resection. The complication rate was 50%, among which dislocation was the most common (33%). None of the included cases experienced implant failure, and acceptable functional outcomes were achieved as shown by a mean Harris hip score of 75 points [23]. The limitation of this procedure is that the use of prosthesis is indicated in patients whose remaining ilium would be sufficient to support it. Further study with a larger cohort and longer follow-up must elucidate the clinical benefit of the use of this prosthesis.

2.3. Flanged acetabular cup with a constrained joint mechanism

A flanged acetabular cup with a constrained joint mechanism (C-THA) was developed by Uchida et al. in 1985 [25]. This prosthesis included three components: a metallic outer cup with blade plate, a bearing insert made of high-density polyethylene, and a femoral component. The inner head of the femoral component was firmly connected to a bearing insert and a cup by tightening screws inserted through the cup holes [25]. The early results of 18 patients with this system included deep infection in 17% and dislocation in 11% [25]. The medium- to relatively long-term out-

Table 1
Summary of the major studies for periacetabular reconstruction using an endoprosthesis following pelvic tumor resection.

Type of prosthesis	Name/company (country)	No. of patients	Follow-up period (mean, months)	Functional score (mean, %)	Deep infection (%)	Major complication* (%) /any type of complication (%)	Implant/graft survival	Author	Year	Refs
Saddle prosthesis	Link (Germany)	17	42	MSTS, 57% TESS, 58%	18%	47%/65%	NA	Cottias	2001	[15]
	Link (Germany)	16	37	MSTS, 47%	8%	31%/NA	NA	Kitagawa	2006	[18]
	Link (Germany)	15	36	MSTS, 50%	27%	NA/40%	2-year, 40% 3-year, 20%	Renard	2000	[19]
	Link (Germany)	15	124 (6 pts)	MSTS, 57%	20%	47%/NA	54%	Donati	2012	[16]
	Link (Germany)	17	146 (6 pts)	MSTS, 47% TESS, 53%	53% (incl. superficial infection)	NA/82%	42%	Jansen	2013	[17]
	PAR hemipelvic endoprosthesis/Link (Germany)	17	29.4	MSTS, 67%	24%	56%/NA	2-year, 84% 5-year, 60%	Menendez	2009	[20]
Modular prosthesis	Modular hemipelvic endoprosthesis/Link (Germany) and Chunli (China)	28	30	MSTS, 62%	14%	18%/49%	NA	Guo	2007	[21]
	Modular hemipelvic endoprosthesis/Chunli (China)	100	52.9	MSTS, 57.2%	15%	39%/45%	NA	Guo	2010	[22]
	Trabecular Metal/Zimmer (USA)	10	59	Harris hip score, 75	0%	20%/50%	100%	Abdel	2017	[23]
Flanged acetabular cup with a constrained joint	C-THA (Japan)	18	39	Excellent 1, good 11, fair 1, poor 6	17%	NA/33%	89%	Uchida	1996	[25]
	C-THA/JMM (Japan) and Kobelco (Japan)	25	163	MSTS, 55%	32%	52%/NA	76%	Ueda	2013	[2]
	C-THA/JMM (Japan) and Kobelco (Japan)	80	65	MSTS, 43%	39%	NA/59%	2-year, 73% 5-year, 62%	Ogura	2018	[26]
Custom-made endoprosthesis	Stanmore (UK)	35	84	MSTS, 70%	26%	40%/60%	NA	Abudu	1997	[31]
	Howmedica (Germany)	12	57	MSTS, 39%	25%	67%/83%	42%	Ozaki	2002	[1]
	Howmedica (Germany)	9	62	NA	22%	NA/56%	78%	Muller	2002	[34]
	Kinergy Mechatronics (China)	10	34	Good 7, fair 2, poor 1	30%	40%/NA	NA	Dai	2007	[32]
	Stanmore (UK)	98	65	TESS, 59.4%	30%	32%/58%	5-year, 76% 10-year, 65% 20-year, 51%	Jaiswal	2008	[33]
	MUTARS/Implant cast (Germany)	40	24	MSTS, 50%	30%	58%/75%	3-year, 61.4%	Witte	2009	[35]
Stemmed acetabular components	Ice-cream cone prosthesis/Stanmore (UK)	27	39	TESS, 69%	11%	19%/37%	96%	Fisher	2011	[36]
	Pedestal cup/Zimmer (Germany)	19	39	MSTS, 49%	47%	NA/79%	5-year, 50%	Bus	2014	[44]
	Pedestal cup/Zimmer (Germany)	48	79	MSTS, 71%	17%	NA/40%	5-year, 61%	Hipfl	2017	[45]
	LUMiC prosthesis/Implantcast (Germany)	47	47	MSTS, 70%	28%	NA/30% (mechanical) NA/38% (non-mechanical)	10-year, 52% 5-year, 82.7% (mechanical reasons) 5-year, 91.8% (infection)	Bus	2017	[44]

*Complications which required at least one further operation; NA, not available.

comes were reported by Ueda et al., who showed that complications included deep infection, dislocation, and aseptic loosening at rates of 32%, 16%, and 8%, respectively, with a mean MSTS score of 55% at the final follow-up [2]. A nationwide survey of the outcomes with this system in Japan was conducted by Ogura et al. A similarly high complication rate (59%), with deep infection (39%) and dislocation (5%), was observed in the 80 patients studied [26]. Overall, the advantages of this system include iliofemoral stability and cost-effectiveness compared with custom-made prostheses. The limitations appear to be a relatively high rate of complications, including deep infection, dislocation, mechanical trouble, and wound complications, which may be reduced by the immediate use of a rectus abdominis myocutaneous flap to eliminate dead space and cover the exposed bone [26].

Table 2
Summary of the major studies for periacetabular reconstruction using an allograft, autograft, hip transposition, and arthrodesis, following pelvic tumor resection.

Surgical procedures	No. of patients (acetabular cases)	Follow-up period (mean, months)	Functional score (mean, %)	Deep infection (%)	Major complication* (%) /any complication (%)	Implant/graft survival	Author	Year	Refs
Allograft/APC	22 (19)	48	Good 1, fair 2	36%	27%/72%	73%	Ozaki	1996	[54]
	17	NA	MSTS, 62%	12%	29%/88%	71%	Bell	1997	[48]
	19	57	Excellent 1, good 6, fair 5, failure 6	26%	42%/42%	63%	Yoshida	2000	[55]
	13 (10)	58	MSTS, 56.4%	15%	NA/38%	N/A	Langlais	2001	[53]
	35	120 (survivor)	MSTS, 72%	23%	NA/50%	75%	Donati	2011	[51]
	33	33	MSTS, 70%	15%	NA/55%	87.3%	Campanacci	2012	[49]
Pasteurized autograft	11	40	MSTS, 61%	9%	18%/27%	91%	Kim	2007	[64]
	14	87	MSTS, 81.7%	21%	57%/NA	5-year, 64.3% 10-year, 32.1%	Jeon	2007	[63]
	10	45	MSTS, 70.5%	10%	NA/20%	NA	Guo	2017	[60]
Extracorporeally irradiated autograft	15	54	EMSOS, 54%	20%	NA/87%	NA	Sys	2002	[67]
	18	52	MSTS, 77% TESS, 71%	17%	NA/83%	17%	Wafa	2014	[68]
Frozen autograft	3	32	Excellent 1, good 1, fair 1	67%	NA/67%	NA	Tsuchiya	2005	[69]
	5	101	Excellent 2, good 1, fair 2	20%	NA/20%	20%	Igarashi	2014	[59]
Arthrodesis	21	97	MSTS, 71% TESS, 76%	NA	NA/NA	NA	Fuchs	2002	[72]
	5	50	MSTS, 63% TESS, 70%	0%	0%/40%	NA	Carmody Soni	2012	[75]
	4	136	MSTS, 69%	25%	50%/50%	75%	Nagoya	2012	[74]
Ipsilateral femoral autograft	10	40	MSTS, 83%	10%	50%/80%	100%	Laffosse	2012	[78]
Hip transposition	17	46	MSTS, 66%	0%	0% (due to infection and LR)/ 41%	NA	Hillmann	2003	[58]
	20	69	MSTS, 61%	0%	0% (due to infection and LR)/ 30%	100%	Hoffmann	2006	[9]
	62	29	MSTS, 62%	32%	40%/NA	NA	Gebert	2011	[82]
	7	57	MSTS, 63%	0%	29%/NA	100%	Kunisada	2019	[79]

*Complications which required at least one further operation; NA, not available.

Fig. 1. Radiograph of a patient who underwent periacetabular reconstruction using a saddle prosthesis.

2.4. Custom-made prosthesis

While conventional methods, such as saddle prosthesis and modular pelvic prosthesis, were developed for skeletal reconstruction following acetabular resections, the drawbacks of these metallic, non-anatomical prostheses, made of titanium- or cobalt-base alloys, included aseptic loosening, infection, and prosthetic and periprosthetic fracture [27]. These drawbacks may be attributed to the material's microstructure, lack of design, or methods of fixation [27-30]. A custom-designed prosthesis, with exact geometry and surface morphology, may be a feasible solution for the optimal reconstruction of the pelvis following excision (Fig. 2) [1,31-35]. The reported functional scores have been superior in patients with custom-made prosthesis compared with those with modular hemipelvic reconstruction (mean MSTS score, 57.2%) [22]. The earliest report was published in 1997 by Abudu et al., which demonstrated satisfactory functions, with a mean MSTS score of 70% in 35 patients who underwent reconstruction using a custom-made prosthesis (Stanmore Implants Worldwide Ltd., Stanmore, UK) [31]. The same group later reported the long-term outcomes of 98 patients with a mean TESS score was 59.4% [33]. However, the complication rate, of which deep infection was the most common (approximately 30%), was reported as high as 60% in both

Fig. 2. Radiograph of a patient who underwent periacetabular reconstruction using a custom-made prosthesis.

studies [31,36]. The use of MUTARS™ (Implantcast, Buxtehude, Germany) achieved reasonable functional outcomes with a mean MSTS score of 50%, despite being associated with a similarly high complication rate of 75% [35]. In a systematic review of these publications, Brown et al. reported that periacetabular reconstruction using a custom-made prosthesis provided a mean MSTS score of 63%, with an implant survival rate of 61%, although deep infection was common, occurring in 42 of 182 patients (23%) [13].

Due to the large volume of tissue removal, a conventional custom-made prosthesis using solid metal would be extremely heavy. The emerging 3D printing–manufacturing technology offers better chance of developing prosthesis with a porous structure to minimize the weight of the implants and to ultimately increase the strength of the interface [27]. This technique includes additive manufacturing, rapid prototyping, and computer-automated, solid freeform, or layered manufacturing [27,37]. Recent studies using 3D-printed prostheses have shown good short-term functional results [38,39]. Liang et al., from the Beijing group that previously developed a modular hemipelvic prosthesis, produced three types of 3D-printed pelvic prosthesis: an iliac prosthesis, standard hemipelvic prosthesis, and a screw-rod connected hemipelvic prosthesis. These prostheses were made from titanium alloy using an electronic beam-melting technology, and their characteristics include the porous nature of the implant–bone interface, allowing osseointegration [40]. Early results, with a mean follow-up of 20.5 months, indicated that the mean MSTS score was 19.1 (64%), whereas complications included delayed wound healing in 20% and dislocation in 6% [40]. Although longer follow-up is necessary to elucidate the efficacy, this system provides a promising alternative in patients requiring acetabular reconstruction.

Overall, the main advantages of this custom-made prosthesis are acceptable cosmoses, precise matching, reduced operation time, immediate stability, and possibility of rapid recovery. However, the expensive costs in manufacturing are a major drawback: the average cost of a custom-made prosthesis produced by Stanmore implants is £5285 [36], and the cost for a 3D model can vary from $200 to $1,000, depending on factors such as the materials used, the size of the print, and the type of printer used [41,42]. In addition, the complication rates remain relatively high even in the cohort of patients with 3D-printed implants, of which deep infection is the most common; therefore, further efforts must be made to minimize the risk of these complications. Angelini et al. proposed the coverage of the prosthesis with well-vascularized muscles by enlarging the porous surface for strict adherence of the soft tissues to the prosthesis and making large holes to guarantee the fixation of muscles/tendons through the prosthesis [43].

2.5. Stemmed acetabular components

The outcomes of reconstruction using a prosthesis with stemmed acetabular components were first reported by the Birmingham group [36]. This type of prosthesis was developed in 2003, and it acquired its name because it resembles the appearance of an ice-cream cone. The ice-cream cone prosthesis is an accommodating implant that can be used when there is only little remaining ilium [36]. In a report of short- to medium-term outcomes of 27 patients, Fisher *et al.* found a 37% complication rate, which included dislocation (15%) and deep infection (11%), with a mean TESS score of 69%. The infection rate in this study was relatively lower than that in other reconstructions, a finding that may be attributed to the technique that involved a large volume of antibiotic-laden cement to support the prosthesis [36].

The pedestal cup prosthesis, which consists of a hemispherical acetabular component and a porous-coated one-size titanium stem, was developed in Germany and was originally designed for use after an extensive revision of a total hip replacement [44]. Bus *et al.* from Leiden University reviewed 19 patients who underwent reconstruction using a pedestal cup. Complications occurred in 15 patients (79%), with a 50% rate of implant survival at 5 years and a mean MSTS score of 49%. The authors considered these data to be poor results, and as such, they advised careful consideration of using this type of prosthesis in acetabular reconstructions [44]. Consequently, Hipfl *et al.* from Vienna University reviewed 48 patients who underwent hip reconstruction using a pedestal cup. Complications occurred in 40% of cases, of which deep infection was the most common. The revision risk was 39% at 5 years and 48% at 10 years. The mean MSTS score was better than the outcomes reported by Bus *et al.* (71%). Therefore, the authors concluded that this type of reconstruction is a satisfactory option but needs further modifications to minimize the risk of complications [45].

The LUMiC prosthesis is a modular device that was also developed in Germany and is built on a separate hydroxyapatite (HA)-coated stem and acetabular cup. The stem is hexagonally shaped and has two wings to secure its rotational stability [46]. Bus et al. reviewed the outcomes of 47 patients who underwent reconstruction using this type of prosthesis. A total of 30% and 38% of patients experienced one or more mechanical and nonmechanical complications, respectively, and the incidence rates of implant failure were 17.3% and 9.2% because of mechanical issues and infections, respectively [46]. Although a longer follow-up was needed, the short-term outcomes of this prosthesis (median follow-up of 3.9 years) demonstrated a low frequency of mechanical complications and failure [46].

Overall, the surgical outcomes of stemmed acetabular components have been favorable compared with those of other types of prosthesis, with a lower incidence of implant failure and better functional outcome. An interesting finding with regard to the optimum length of the inserted stem was reported by Fujiwara et al. from Birmingham who reported a high risk of complications and functional loss of acetabular reconstruction when the insertion of the coned stem into the remaining ilium was less than half of the stem length [47]. These data suggest that a situation in which the size of the remaining ilium is large enough for surgeons to stabilize the prosthesis with a coned stem longer than half length will be a good indication for this procedure [47].

2.6. Allograft/allograft prosthetic composite (APC)

Bone allografts have been widely used for pelvic reconstruction with (allograft-prosthesis composite, APC) or without the use of a prosthesis (Fig. 3) [48-55]. The advantages of using allografts include osteointegration [54,56], revascularization, and partial replacement with host bone [57]. In addition, allografts can be shaped and customized to match the pelvic resection, and as a result, the complex osseous architecture can be fully restored for locomotion [50]. In patients in whom it is anticipated that insufficient ilium would remain after the resection, no prosthesis type can be used because of the small bone to support them, and allograft/APC is one of the only remaining candidates. However, the use of a large pelvic allograft is considered to be technically difficult and appears to be controversial [51].

With regard to the functional outcome, previous studies have reported relatively good functional outcomes, with a mean MSTS score ranging from 56% to 72% [13,48,53,55]. In a comparative study of acetabular reconstructions by Hillmann et al., the mean MSTS score of six patients was 60%, which was better than that of prosthetic reconstruction or amputation [58]. Two Italian studies by Campanacci et al. and Donati et al. reported superior functional outcomes by allograft/APC, with an average MSTS score of 70% and 72%, respectively, indicating that this procedure is a valid option for acetabular reconstruction [49,51]. Interestingly, APC with a stemmed cup and an artificial ligament resulted in better MSTS scores (average, 89%) [51]. A systematic review of 133 patients across nine studies reported a mean MSTS functional score of 72% for surviving patients at the final follow-up [13].

However, high complication rates are a major problem of allograft/APC reconstruction. Hillmann *et al.* [58] and Ozaki *et al.* [54] reported the rates of deep infection as high as approximately 40% and those of any complication as high as 72%. Various types of complications other than deep infection have been reported, including allograft fracture, nonunion, prosthetic dislocation, migration, and loosening. In a systematic review by Brown et al., deep infection was the most common complication (15%), followed by local recurrence (11%), dislocation (8%), problems with wound healing (5%), prosthetic migration or failure (5%), and late allograft fracture (4%) [13]. These complications resulted in a relatively high rate of allograft failure, ranging from 13% to 37%.

Fig. 3. Radiograph of a patient who underwent periacetabular reconstruction using an allograft-prosthesis composite.

Given the substantial risk of complications, this procedure is best indicated in patients not requiring further local or systemic treatment. Donati et al. recommended this procedure only in patients for whom postoperative radiotherapy is not planned [51], whereas Campanacci et al. indicated periacetabular reconstruction with an APC for patients with pelvic chondrosarcoma, in which no adjuvant chemotherapy or radiotherapy is routinely required [49]. Despite a high risk of complications, allograft/APC appears to be a valid reconstructive option, allowing bone stock restoration, and satisfactory functional recovery if patients are carefully selected.

3. Autograft

Autografts are another commonly used method for biological reconstruction. The reconstruction using autologous neoplastic bone requires devitalization, which can be achieved by autoclaving, pasteurizing, irradiation, or freezing of the bone. The indication of the use of autografts is similar to that of allografts; however, the use of autografts is more common in some Asian countries where donations of bone are poor [59]. The advantages and disadvantages of each procedure are separately discussed.

3.1. Pasteurized autograft

Heating is a simple way to devitalize tumor cells. Autoclave, which uses a high temperature (131 °C), is effective for killing tumor cells [60,61]. However, autoclaved bone has several disadvantages, such as mechanical weakness and loss of the bone morphogenetic protein (BMP) [62,63]. Low-heat treatment at 60 °C– 65 °C for 20–30 min, the so-called pasteurization, preserves bone induction properties while still having a lethal effect on tumor cells [64,65]. Kim *et al.* reviewed 11 patients whose resected bone was treated with pasteurization and reimplanted into the host bone with total hip arthroplasty. Bone union was achieved in eight patients (72%) at an average of 12 months, and graft fracture and deep infection occurred individually in two patients (11%), with 10 graft survivals (91%) at the last follow-up [64]. The mean MSTS score at the final follow-up was 61% [64]. Jeon *et al.* reported on the outcomes of 14 patients who underwent this procedure, which resulted in a good MSTS score of 81.7% [63]. However, eight grafts (57%) were removed because of the development of deep infection in three (21%), loosening in three (21%), and fracture in two patients (14%). Furthermore, the five patients with early failure had low MSTS scores (65.3%). A recent paper from the same group described the 20-year survival rate of 142 procedures at 39.8%, a percentage that was below the group's expectations [61]. As a result, the authors concluded that there is little survival gain over tumor prosthesis, and thus, this procedure may not be a viable primary procedure for treating large skeletal defects [61].

3.2. Irradiated autograft

Extracorporeal irradiation and reimplantation of resected bone were first described by Uyttendaele *et al.* in 1988 [66]. Sys *et al.* from the same department reviewed the outcomes of 15 patients who underwent reconstruction using an irradiated autograft treated with 300 Gy. Complications were noted in all, except two patients (87%), and included deep infection in three (20%) and nonunion in one patient (7%). The overall functional scores were fair [67]. Thus, low union rate, high risk of infection, and bone absorption appear to be the disadvantages of this procedure, whereas the advantages include no donor morbidity, good adaptation to the recipient, and ease of the technique. Wafa *et al.* reviewed 18 patients with an autograft treated with 90 Gy and reported good

functional outcomes with a mean MSTS of 77% [68]. Deep infection, nonunion, and partial graft resorption were observed in three (17%), three (17%), and one patient (6%), respectively [68]. The authors described that the key indication for this procedure is a patient with a PI-II tumor that could be resected with clear margins, where the remaining bone has sufficient quality [68].

3.3. Frozen autograft

On the basis of the *in vitro* and *in vivo* studies on the hypothermic effects of liquid nitrogen, Tsuchiya *et al.* developed a technique for biological reconstruction using a frozen autograft [59,69]. Compared with autografts treated by autoclaving or pasteurization, the advantage of this procedure includes the preserved activity of BMPs in frozen autografts treated with liquid nitrogen [70]. After excision of the tumor, soft tissues attached to the tumor-bearing bone are removed and the tumor is curetted. [69]. Then, the excised portion was frozen in liquid nitrogen for 20 min, thawed at room temperature for 15 min, thawed in distilled water for 10 min, and then replaced with reconstruction by an plate or composite use of a prosthetic replacement.. [59]. When necessary, a bone graft or cement was added for mechanical support [59]. Tsuchiya *et al.* reported on the outcomes of 28 patients who underwent reconstruction using frozen autografts following malignant bone tumor resection, with a total of three patients with pelvic tumors included. Of these, two patients (67%) presented with postoperative infections, and the functional outcomes were excellent, fair, and poor in each with a median follow-up of 32 months [69]. Igarashi *et al.* from the same group reported on the long-term outcomes of 36 patients with a mean follow-up of 101 months, in which a total of five patients with pelvic tumors were included [59]. Although one of the five patients included (20%) had a postoperative infection, which was ultimately removed, the other four patients did not show any infection and achieved bone union within a mean duration of four months (range, 3–6) postoperatively. Furthermore, the functional outcomes were excellent in two, good in one, and fair in two patients [59]. Although the infection rates facilitated by this technique were reportedly higher in pelvic compared to extremity tumors [59,69], the introduction of an iodine plate or a prosthesis reduced these rates after the use of frozen autografts in a cohort of 62 patients, including patients with pelvic tumors [71].

4. Arthrodesis

The advantage of the arthrodesis includes a durable and stable construct, although patients lose their hip range of motion [72,73]. Depending on the resected area of the pelvis, iliofemoral, ischiofemoral, sacrofemoral, or combined arthrodesis has been performed [74]. Fuchs *et al.* reported on the outcomes of 21 patients who underwent iliofemoral arthrodesis [72]. Three of these patients (14%) developed nonunion but had good functional outcomes, a mean TESS score of 76% (range, 49%–96%), and a mean MSTS score of 71% (range, 53%–80%) [72]. Carmody Soni *et al.* reviewed five patients who underwent ischiofemoral arthrodesis. These patients had a mean MSTS score of 63% (range, 53%–73%) and a mean TESS score of 70% (range, 43%–87%), and four out of these five patients (80%) were able to ambulate independently without assistive devices [75]. Nagoya *et al.* introduced a free-vascularized fibular graft to reconstructive hip arthrodesis. In his study, one out of the four patients reviewed (25%) had a deep infection, and the treatment led to pseudoarthrosis [74]. Although the mean MSTS score of these patients was 69%, this score depended on the resection area: 93% in type II, 43% in types I–II, 57% and 83% in types I–II–III resections [74]. Collectively, this procedure provides rela-

tively good functional outcomes with stiff hips, although the risk of nonunion after primary fusion remains a significant issue [76]. Thus, the ideal candidate for hip arthrodesis appears to be a young adult with high activity demands, although the patients must accept the loss of their mobile hip.

5. Other reconstructions

Periacetabular reconstruction using the ipsilateral proximal femur and a total hip prosthesis was performed by Puget *et al.* [77]. The size of proximal femur resection was determined intraoperatively according to the dead space following tumor resection, and the femur was oriented with its head either in the iliac or ischium position to place the trochanter in the area where the acetabulum had been resected. The greater trochanter was reamed to reshape it into a new acetabular cavity, and the acetabular cup was then implanted. In a study of 10 patients using this method, the autograft was completely integrated in five and partially integrated in three patients, with no cases of fracture or nonunion. Although 50% of patients required surgical revisions, the mean MSTS was 83%, and all patients who were still alive at the time of the review could walk without assistance [78].

Hip transposition, also termed "resection arthroplasty," is a reconstructive technique that stabilizes the bone and soft tissues without using implants or grafts [79]. In this procedure, the femoral head is moved proximally to the lateral side of the sacrum or the underside of the resected ilium after acetabulum resection (Fig. 4) [9,80]. In 1988, Winkelmann first assessed this procedure in children [81], and Hillmann et al. identified that hip transposition had the lowest risk of complications compared with reconstructions using an endoprosthesis or an allograft [58]. Hoffmann et al. evaluated the quality-of-life results of this procedure and reported better functional outcomes compared with other types of reconstructions (mean MSTS score, 61%). Gebert et al. reviewed 62 patients and identified wound healing issues in 14 cases (23%) and deep infection in 20 cases (32%), which seemed to be attributed to the use of mesh or other artificial materials [82].

Although hip transposition is characterized by a lower risk of severe complications, it results in a significant leg-length discrepancy following surgery [81]. Indeed, Rödl et al. reported on four patients who underwent limb lengthening to correct a leg-length discrepancy after hip transposition. The average lengthening was 6.4 cm for leg-length discrepancies, with an average of 10.3 cm

Fig. 4. Radiograph of a patient who underwent hip transposition arthroplasty.

and a healing index of 32 days per cm elongation [81]. The authors concluded that leg-length discrepancy after hip transposition could be corrected with distraction osteogenesis and should be performed only on long-term survivors with at least 5 years of event-free survival [81].

Kunisada et al. reported on the advantage of temporary external fixation after hip transposition [79]. Because the original procedure includes immobilization in bed for 2 weeks followed by an additional cast or splint for a further 4 weeks, the authors applied temporary external fixation for early rehabilitation following hip transposition. This procedure facilitated early postoperative physical therapy, allowing bedside standing after a median of 7 days postoperatively and gait training after a median of 15 days postoperatively. The patients in this cohort achieved good functional results (mean MSTS score, 63%) without major surgical complications [79].

6. Comparison of various procedures

Despite the limited number of studies, several researchers have reported the surgical outcomes, comparing various procedures of periacetabular reconstruction. Schwameis et al. and Puchner et al. from Vienna reviewed the surgical outcomes of pelvic reconstructions after all types (PII-involved and PII-uninvolved) of tumor resection in 2002 and 2017, respectively [10,83]. Both of these studies drew the same conclusion: the endoprosthetic reconstruction after periacetabular resection had a higher rate of complications and reoperation [10,83], which resulted in lower functional scores than other types of reconstruction [83]. Similarly, in 2003, Hillmann et al. from Münster reported outcomes of various reconstructive procedures following all types of pelvic resections. They concluded that autograft implantation and hip transposition are recommended because of lower complication rates and good function: the complication rate and functional score were 63% and 37% with prosthesis, 69% and 60% with allograft, 33% and 66% with autograft, 41% and 66% with hip transposition, and 34% and 79% without reconstruction, respectively [58]. Later, in 2006, Hoffmann et al. from the same group focused on the functional outcome following PII-involved pelvic resections. Patients who underwent hip transposition demonstrated significantly better functional results (MSTS, 60.7%) and quality-of-life outcomes than those with prosthetic reconstruction (MSTS, 39.6%) [9]. A similar trend was observed in a report from Tokyo, which showed that endoprosthetic reconstruction demonstrated poor functional outcomes because of high complication rates, whereas hip transposition or arthrodesis resulted in satisfactory functional outcomes [8].

A recent study from Birmingham compared the surgical outcomes, according to the type of pelvic resection, in the largest cohort of patients who underwent acetabular reconstruction (n = 122; custom-made prosthesis, ice-cream cone prosthesis, extracorporeal irradiated autograft, and nonskeletal reconstruction). The overall functional scores were significantly lower in patients with major complications than in those without (mean MSTS, 52% versus 74%) [84]. In patients who underwent periacetabular resections involving the ilium, the functional scores were higher with a custom-made prosthesis (MSTS, 82%) if no major complication occurred, whereas nonskeletal reconstruction resulted in the highest scores (MSTS, 78%) if patients had major complications [84]. In patients treated with periacetabular resections that do not involve the ilium, ice-cream cone prosthesis, supported with antibiotic-laden cement, resulted in superior functional outcomes (MSTS, 79%). These data indicate the decision-making process of acetabular reconstruction, according to the type of resection and risk of major complications.

Overall, studies comparing various procedures of acetabular reconstruction commonly described the high risk of complications and functional loss in prosthetic reconstruction, whereas nonskeletal reconstruction resulted in a low incidence of complications and reasonable functional outcomes despite leg-length discrepancy. Therefore, the use of massive implants/grafts should be avoided, especially for patients who are at a higher risk of complication.

7. Innovative techniques

Recent studies have highlighted the advantages of computer navigation in pelvic tumor surgery [85-92]. The use of navigation in pelvic and sacral tumors was first reported by Krettek et al. [88] and Hunfer et al. [93]. These studies described small case series that underwent navigation assisted surgery using 3D images that were preoperatively obtained from CT or MR images. Navigation was helpful for tumor identification and during osteotomies and contributed to a complete resection with tumor-free margins [88,93], indicating that computer-assisted surgery is a potential method for increasing accuracy in resections of pelvic and sacral tumors [88,93]. The accuracy and reproducibility of navigated pelvic osteotomy was assessed in a basic research by Sternheim et al. [90]. Navigated cuts in Sawbones were significantly more accurate than non-navigated cuts, showing that the accuracy of pelvic osteotomies can be improved with navigation to within 5 mm of the planned cut [90]. To date, more sarcoma centers have reported the results of navigated pelvic tumor resections. Jeys et al. reported a reduced intralesional resection rate following navigated resection of pelvic and sacral tumors, in which clear bone resection margins were obtained in all cases [87]. The same group from Birmingham further reported that navigated resection of pelvic and sacral tumors resulted in reduced operation time and blood loss [89] and improved disease-free survival compared with non-navigated resections [85,89]. A time-saving method using intraoperative CT-based navigation without point surface matching has also been useful in accurate resections of pelvic tumors [94].

Computer navigation also provides advantages in pelvic reconstructions. Implant engineers can design a custom, computer-aided design prosthesis with the exact surgical requirements defined in the navigation software [95]. Then, the navigation system allows the correct orientation to precisely match these prostheses to the planned osteotomy plane [85,91]. The navigation also contributes to the precise insertion of the coned stem prosthesis following pelvic tumor resection. Fujiwara et al. from Birmingham compared the clinical outcomes of navigated versus non-navigated acetabular reconstruction using ice-cream cone prosthesis. The navigated reconstruction resulted in the lower rate of major complications that require surgical intervention and superior functional outcomes compared with the non-navigated reconstruction [96]. Specifically, the navigation assisted correct insertion of the ice-cream cone prosthesis, avoiding protrusion of the stem, insertion into the sacroiliac joint, and the acetabular cup angle out of the safe zone (30°–50°) [96].

Recent studies have demonstrated that patient-specific instrumentation (PSI) can be used for pelvic resection with the same accuracy as computer navigation [97-99]. In addition, a cadaveric study by Wong et al. revealed that PSI required less resection time than navigation [99]. Blakeney et al. first reported a case of pelvic chondrosarcoma, which was successfully excised with clear margins using a customized osteotomy guide followed by total hip arthroplasty [100]. Although further studies must investigate the clinical benefit of the PSI technique, this system has great potential in improving surgical accuracy in pelvic surgery and seems complementary to computer navigation.

Techniques preventing deep infection are also important if surgeons use a massive implant/graft during the acetabular reconstruction. The Birmingham team reported a low rate of deep infection of the acetabular reconstruction using an ice-cream cone prosthesis by supporting it with an antibiotic-laden cement [96]. They added vancomycin (1 g per mix) into the bone cement to stabilize the distal portion of the cone stem, which minimized deep infection and allowed effective control if it occurred [36,86]. Other solutions during skeletal acetabular reconstruction may include the use of implants modified by adding antibacterial surfaces, such as antibiotics, antiseptics, and metals. In a systematic review and *meta*-analysis, silver-coated implants have been proven to be safe and effective in prosthetic joint infection (PJI) and re-infection rate, particularly when used in higher risk patients and after two-stage revisions to resolve PJI [101]. Outcomes with a silver-coated pelvic prosthesis are rarely reported, with the exception of one study by Wafa et al. from the Birmingham group. Wafa et al. conducted a case–control study of primary reconstructions and revisions with and without Agluna silver-coated custom-made prosthesis, which found that the overall infection rate in the silver-coated group was significantly lower (11.8%) than that in the control uncoated group (22.4%) [102]. However, the infection rate was significantly higher in the pelvis than in the other sites, which showed no statistical difference between the groups (57% versus 57%). These data indicate that the use of massive prosthesis with antibacterial surfaces alone may not be effective in avoiding the PJI, requiring additional techniques, such as antibiotic-laden cement or less use of massive implants or grafts.

8. Conclusions and perspectives

Over the last few decades, various types of hip reconstructions have been developed to meet the needs of surgeons and patients. This literature review highlights the benefits and risks of each procedure. It is important to underline that the use of massive implants/grafts still induces a high overall complication rate, with deep infection being the most frequent of these complications as well as the main cause of reconstruction failure. Further efforts should be made to minimize the risk of deep infection, which may involve the use of antibiotic-laden cement/prostheses or less use of massive implant/graft.

In terms of functional outcomes, there is no optimal reconstruction that guarantees excellent and stable function. Several authors in literature have demonstrated that functional outcomes were poorer in patients with major complications requiring additional surgeries compared with patients who did not require reoperation [2,8]. Thus, avoiding these major complications seems to be crucial regardless of the type of reconstruction. Among various reconstructive options, hip transposition arthroplasty exhibited the lowest overall complication rates. Despite substantial leg-length discrepancy, functional scores were acceptable with the use of a shoe lift. Non-use of massive implants/grafts may result in a reduced incidence of severe complications and subsequent better functional outcome, especially for patients who are at a higher complication risk, e.g., patients undergoing adjuvant chemotherapy and/or radiotherapy.

Overall, avoidance of severe complications appears to be the key to successful hip reconstruction regardless of the type of reconstruction. Emerging technologies such as 3D-printed prosthetic implants may provide novel reconstructive options [39], but this would also pose a certain risk of infection depending on the volume of prosthesis. Computer navigation and custom-made osteotomy cutting guides are new promising tools [100,103]. The operation time is likely to be reduced with the assistance of these devices, which may result in a decreased risk of complications.

Future efforts should be made to develop safer procedures/methodologies for tumor resection and reconstruction that have a significant lower risk of complications and can achieve satisfactory outcomes in patients with pelvic sarcomas.

9. Fundings

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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