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REVIEW

Basic concepts in metal work failure after metastatic spine tumour surgery

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Abstract

Purpose The development of spinal implants marks a watershed in the evolution of metastatic spine tumour surgery (MSTS), which has evolved from standalone decompressive laminectomy to instrumented stabilization and decompression with reconstruction when necessary. Fusion may not be feasible after MSTS due to poor quality of graft host bed along with adjunct chemotherapy and/or radiotherapy postoperatively. With an increase in the survival of patients with spinal tumours, there is a probability of an increase in the rate of implant failure. This review aims to help establish a clear understanding of implants/constructs used in MSTS and to highlight the fundamental biomechanics of implant/construct failures.

Methods Published literature on implant failure after spine surgery and MSTS has been reviewed. The evolution of spinal implants and their role in MSTS has been briefly described. The review defines implant/construct failures using radiological parameters that are practical, feasible, and derived from historical descriptions. We have discussed common modes of implant/construct failure after MSTS to allow further understanding, interception, and prevention of catastrophic failure.

Results Implant failure rates in MSTS are in the range of 2–8%. Variability in patterns of failure has been observed based on anatomical region and the type of constructs used. Patients with construct/implant failures may or may not be symptomatic and present either as early (< 3months) or late failures (> 3months). It has been noted that not all the implant failures after MSTS result in revisions.

Conclusion Based on the observed radiological criteria and clinical presentations, we have proposed a clinico-radiological classification for implant/construct failure after MSTS.

Keywords Metastatic spine tumour surgery · Symptomatic implant failure · Asymptomatic implant failure · Early failure · Late failure

Introduction

Implants are used in the management of various spinal pathologies—the spectrum of which includes spinal trauma, degeneration, deformity, infection and tumour. In spinal metastatic tumours, instrumented fixation is performed in patients with intractable pain, for tumour-related instability or to prevent "iatrogenic" instability after tumour debulking or decompression [1]. Several studies have reported the outcomes of these surgeries with respect to neurological improvement, mobility status and health-related quality of life parameters [2, 3]. However, few authors have analysed implant failures following metastatic spinal tumour surgeries (MSTS) [4, 5]. This review outlines the evolution of implant systems in spine surgery and MSTS. It highlights the common biomechanical modes of implant/construct failure. We

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also propose a clinico-radiological classification for implant/construct failure after MSTS.

History of implants in spine surgery

A spinal implant is a device used to support or replace a part or whole of the vertebral column. The development of spinal instrumentation marks a watershed in the evolution of spinal surgery [6]. Berthold Hadra is credited with the first instrumented spinal stabilization in 1891. He used wires around the spinous processes for the treatment of a cervical fracture dislocation. Fritz Lange in 1909 attempted stabilization of the spine using steel bars that were attached to the spinous processes with steel wires [7].

Instrumentation for degenerative and infective spinal conditions lagged behind trauma applications; as in the early part of the twentieth century, un-instrumented surgeries were in vogue for these conditions. Russell Hibbs and Fred Albee used bone grafts instead of instrumentation in order to achieve stabilization and fusion in spinal tuberculosis [8, 9]. Instrumentation of the degenerative lumbosacral spine was first described by King in 1944 with the introduction of facet screws [10]. It was followed by the introduction of the Harrington system in the 1950s that laid the foundation for modern spinal instrumentation [11]. Over the subsequent decades, spinal instrumentation technology evolved to keep pace with advances in surgical technique in tandem with increasing awareness of the principles of spinal biomechanics [6]. The development and popularization of pedicle screws by Roy-Camille in 1970 marks the next big evolution in spinal instrumentation [12]. It was recognized that the pedicle screw constructs with anchorage in all three columns of the spine allowed for powerful correction of spinal deformities with optimal strength of fixation. This was further refined by the replacement of plates with rods by Steffee et al. [13]. The systems that were subsequently introduced made incremental advances in the surgical treatment of degenerative conditions, deformity corrections, infections and spinal tumour surgeries [14].

History of implants in metastatic spinal tumour surgery

Decompression surgeries have remained pivotal in the management of metastatic spine disease [15]. The role of implants in the surgical treatment of MSTS was recognized in the later part of the twentieth surgery [16]. The use of spinal implants in MSTS increased exponentially after the popularization of pedicle screw rod systems in the 1980s [16]. Kostuik et al. in 1988 studied the role of fixation and decompression in 71 metastatic spinal tumour patients and observed that 81% of these patients had good to excellent results in terms of pain and neurological recovery [17]. However, after this initial period, radiotherapy became the dominant treatment modality until the role of surgical decompression was re-established by Patchell et al. [18]. Superiority of decompression and instrumented stabilization was further strengthened by the large series published by Fourney et al. [19], Bilsky et al. [20] and Wang et al. [21]. The biomechanical principles and stabilization techniques that evolved from the management of degenerative conditions and deformity correction were established in MSTS during this period.

With the introduction of implants in MSTS, posterior spinal fixation and decompression became popular [17]. Subsequently, anterior decompression with or without posterior fixation was introduced for the treatment of spinal metastases [22–24]. En-bloc resections, initially designed for primary tumours, were reported to be useful for managing metastatic spine tumours by several authors such as Tomita et al. [22], Fourney et al. [23] and Li et al. [25]. However, with en-bloc resections, complications, including longer surgical time, massive intraoperative haemorrhage, aortic or vena caval injuries, pulmonary embolisms, paraplegia, deep wound infections and deaths, have been reported in up to 10–35% of patients [22, 23, 25, 26]. There is an increasing trend to perform circumferential decompression and instrumentation through the posterior approach to avoid the morbidity related to anterior approach [27]. With further evolution in radiotherapy and chemotherapy treatment techniques, better local tumour control is now possible [16]. This has led to the introduction of separation surgery that entails debulking of metastatic spinal tumours combined with stand-alone posterior instrumentation [4, 20]. A recent systematic review conducted by Zuckerman et al. suggests that the introduction of separation surgery and minimally invasive surgery led to reduction in complication rates after MSTS [28]. Thus, anterior approach surgeries involving wide total resections are mainly reserved for cervical spine tumours, treatment of solitary metastatic tumours and patients with longer expected survival [24, 29, 30]. This evolution has led to different construct designs to be used for surgical fixation in MSTS. Hence, it is necessary to understand the failure mechanisms of various constructs in order to optimize and tailor MSTS to the specific need of each individual patient.

Implant/construct failures: basic concepts

“Implant failure” is defined as the fracture or unintended displacement of a metal component, such as the screw or rod, or the disassembly of a fixed construct [31]. A “construct” is defined as a three-dimensional structure comprising of all the vertebral segments stabilized by instrumentation, including the retained or reconstructed vertebrae affected by tumour, and the instrumentation used to stabilize them. “Construct failure” is either implant failure and/or mechanical failure of the vertebrae which forms the part of the construct. This is detected by changes in linear or angular radiological measurements. Table 1 highlights the components of implant or construct failure as described below:

1. *Screw ploughing* Translation of the pedicle screw perpendicular to its long axis in either sagittal plane or coronal plane or both without affecting the integrity of pedicle boundaries or vertebral margins is known as screw ploughing or screw toggling.
2. *Screw loosening* Sanden et al. [32] described a radiologically discernible radiolucent halo around the screw as a definite sign of loosening. A radiolucent halo of more than 1 mm is accepted to be radiologically identifiable [32, 33]. Alternatively, the angle change between longitudinal axis of pedicle screw and cranial end plate of more than 2° is highly sensitive and specific to diagnose screw loosening [34].
3. *Screw pull-out* Screw pull-out is defined as the translation of a pedicle screw parallel to its long axis [35]. Screw pull-out is influenced by the volume of bone between the screw threads [36].
4. *Screw cut-out* Cut-out is defined as screw ploughing secondary to continued cyclical loading or cantilever forces acting on the construct resulting in the screw violating the margins of the pedicle, vertebral end plate, margins of the vertebral body or any combination of these.
5. *Screw/rod breakage* Fracture of the screw anywhere from its tip to its base; fracture of rod anywhere along its entire length.
6. *Cage subsidence* Sinking in of the cage along its vertical axis from the original position which can be discerned radiologically. It usually involves violation of the end plate with the cage coming to rest on the cancellous bone or the immediately adjacent pedicle screw/s.
7. *Cage displacement* Anteroposterior or mediolateral displacement or tilting of cage from the original position of placement that can be discerned radiologically.
8. *Cage breakage* Fracture or disengagement of cage components that can be detected radiologically.
9. *Angular deformity* Increase or decrease in the sagittal angulation of the construct by more than 5° when measured from the end vertebrae of the construct. This can be secondary to cyclical loading and bending of implants or relative change in the position of implants in the bone due to the processes described above (i.e. screw ploughing, screw cut-out, cage subsidence or screw loosening).
10. *Peri-construct failure or junctional failure* Tumour progression or skeletal fractures in the adjacent levels that require revision or extension of constructs.

Implant/construct failure in metastatic spine disease (MSD)

The magnitude of load on the spine can be as high as three times the body weight [37]. While spinal implants provide stability and off-load the affected vertebral segments, their mechanical strength reduces with time under these cyclical loads [38]. Spinal implants only bridge the chasm between instability and spinal fusion. Once fusion is achieved, implants are unlikely to fail [38]. However, without fusion cyclical loading will eventually lead to metal fatigue failure of the construct.

The physiological and local factors in MSD may not favour fusion unlike in deformity or degenerative spinal disorders. Attempts at spinal fusion in MSTS are subjected to a particular set of challenges such as patients’ poor general condition, poor nutrition, poor mobility and

Table 1 Mechanisms of failure

Mechanism of failure	Definitions
Screw ploughing	Translation of pedicle screw perpendicular to its long axis (sagittal/coronal)
Screw loosening	Radiolucent halo around the screw of 1 mm or more
Screw pull-out	Translation of pedicle screw parallel to its long axis
Screw cut-out	Continued ploughing leading to disruption of end plate/pedicle walls/vertebral body
Screw/rod breakage	Fracture of screw/rod anywhere along its entire length
Cage subsidence	Sinking in of the cage along its vertical axis from the original position which can be discerned radiologically
Cage displacement	Anteroposterior or mediolateral displacement or tilting of cage
Cage breakage	Fracture or disengagement of cage seen on radiographs
Angular deformity	Increase or decrease in the sagittal angulation of the end vertebrae of the construct
Peri-construct failure	Tumour progression or skeletal fractures in the subjacent levels that require revision or extension of constructs

the physiological stress of tumour growth. Preoperative or postoperative radiotherapy and chemotherapy further compromise the fusion bed and the chance of fusion [39, 40]. Hence, it is important that a surgeon appreciates the risk of implant failure or construct failure while considering surgical management of MSD patients. Some of the factors responsible for failures as highlighted by Mesfin et al. include constructs greater than six levels, preoperative radiation, history of chest wall resection and positive sagittal balance [41].

Mechanisms of failure (Table 2)

The constructs used for MSTS can be broadly divided into the following four subtypes: (1) posterior-only decompression and stabilization with constructs; (2) anterior only decompression and stabilization with constructs; (3) combined anterior and posterior decompression and stabilization with constructs; (4) decompression and stabilization with constructs in junctional regions of atypical loading: cervicothoracic, occipitocervical and lumbosacral fixations.

Posterior-only decompression and stabilization with constructs (Fig. 1)

Posterior stabilization involving decompression, debulking and pedicle screw instrumentation is the most frequently performed surgery in MSTS [4, 16]. The integrity of the anterior half of the vertebral body and anterior longitudinal ligaments (ALL) is important while considering posterior-only stabilization [36, 42]. However, most patients with MSD have a limited life span, and major reconstruction involving extensive anterior or combined anterior and posterior approaches are best avoided [24, 25]. Therefore, they undergo posterior debulking and posterior-only stabilization, regardless of whether anterior column deficiencies are present or not.

The forces acting on the spine preferentially load the implant/construct, and the load on each pedicle screw is dependent on the number of anchor points in the construct [36]. The axial compression force acting on the spine ranges from 100 to 250 N, while the flexion bending moment varies from 1 to 7 Nm, increasing up to 20 Nm on carrying a weight up to 20 lbs [43, 44]. With an increase in the number of the skipped vertebrae, the load on each of the anchor points increases. While majority of the load passes through the implants, a small but significant amount of load passes through the unsupported anterior column as well [45]. In the perioperative period, this can lead to compression or collapse of a weak vertebral body, due to tumour involvement and osteoporosis. Similar events have been reported after posterior-only constructs in patients with osteoporosis [46]. This presents radiologically as an increase in the thoracic kyphosis or a decrease in the lumbar lordosis. The evaluation of 318 patients with MSTS and implant failure, by Amankulor et al., demonstrated that 5 out of 9 failures (> 50%) presented with increased kyphosis [4]. Long constructs with skipped vertebrae were also noted to be more vulnerable to implant/construct failure [4]. The sagittal cantilever forces acting on the construct predispose these patients to screw or rod failures [4, 5, 35, 36]. With a strong screw–bone interface, screw or rod breakage was the more likely mode of implant failure; while patients with weak screw–bone interface more commonly present with screw ploughing or loosening [36]. These changes are noted to be more pronounced in constructs with mono-axial screws.

The effects of radiotherapy (RT) and chemotherapy (CT) on implant failure are complex. Local tumour control via RT and CT has been shown to re-calcify the diseased bone and

Table 2 Implants and constructs with their modes of failure

Constructs	Failure mechanisms
Posterior-only decompression and stabilization with constructs	Increase or decrease in sagittal angulation Screw ploughing Screw cut-out Screw pull-out Screw breakage Rod breakage
Anterior only or combined anterior and posterior decompression and stabilization with constructs	Cage subsidence Cage tilting Increase in kyphosis Screw ploughing
Decompression and stabilization with constructs in junctional regions of atypical loading: occipitocervical/cervicothoracic/lumbosacral fixations	Screw pull-out Screw breakage Rod breakage

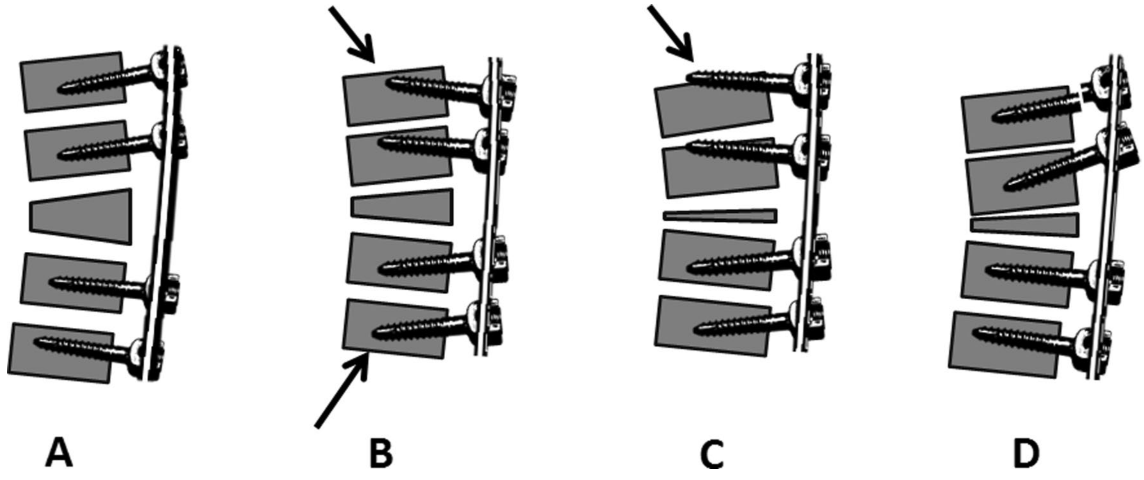


Fig. 1 **a** Posterior construct spanning one skipped vertebrae, **b** screw ploughing with increase in kyphosis, **c** further loading leads to screw cut-out, **d** when the implant–bone interface is strong, it may present as screw/rod breakage rather than screw ploughing, cut-out or pull-out

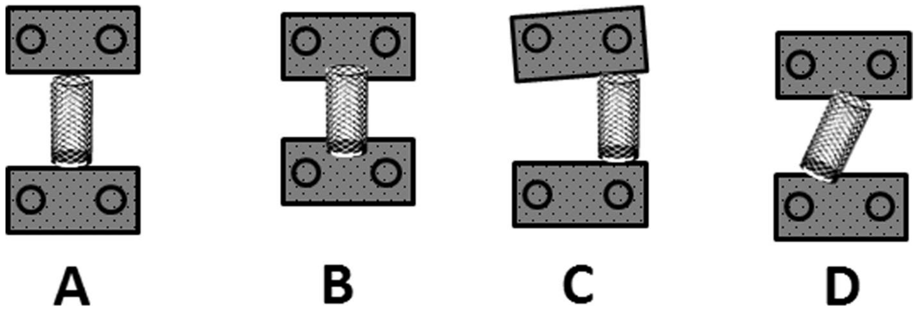
increase its bone mineral density [47, 48]. This may, in turn, lead to stabilization of the construct in a new acceptable position with no further radiological progression of implant/construct failure. Recently, there is a trend to institute CT/RT in the early postoperative period to achieve earlier disease control in these patients [16, 49]. The use of minimally invasive techniques for MSTS allows RT as early as 1 week post-surgery [28]. Although, CT/RT may decrease the bone mineral density of normal bone, tumour affected bone undergoes re-calcification. This eventually results in improved implant stability in the early perioperative period [50–52]. However, if RT is given over a prolonged period of time, there is weakening of the surrounding normal bone and a compromise of the tissue and bone healing potential which can give rise to late peri-construct failure [53, 54]. Higher rates of hardware failure were observed even after preoperative radiation [55]. Similar fusion inhibitory effects are observed after CT [40]. With the advent of stereotactic body radiotherapy (SBRT), radiation can be targeted to the affected vertebral body limiting radiation to the peripheral normal vertebrae [4]. The osteopenic side effects of SBRT on the vertebrae adjoining the target vertebra were less and reduced rates of implant failure were observed after postoperative SBRT [39, 56]. This also led to the evolution of the concept of separation surgery, whereby sufficient clearance of the neural elements facilitates effective SBRT for radio resistant tumours with high-grade epidural spinal cord compression [28].

Patients who are community ambulant or who survive longer may present with late construct and implant failure due to repetitive cyclical loading and metal fatigue. Inability to achieve fusion and a decrease in bone mineral density increase the risk of mechanical failure of the implants [50–52]. While early implant failure may present as screw loosening and screw ploughing, these can progress to screw cut-out or screw pull-out at a later date [4, 5, 57]. Constructs ending at the apex of a kyphosis are also noted to have an increased risk of screw pull-out and junctional failure due to excessive sagittal forces at these regions. Hence, ending the construct proximal or rostral to the apex of the kyphosis has been recommended [46].

Anterior alone decompression and stabilization with constructs (Fig. 2)

In selected MSD patients, partial or total corpectomies are also carried out [4, 22]. The stability is influenced by the

Fig. 2 **a** Anterior reconstruction using mesh cage (normal placement), **b** cage subsidence, **c** cage displacement, **d** cage tilting



amount of vertebral body resected and the site of resection—namely the anterior, middle or posterior column [36]. Partial vertebral body resection may or may not be supplemented with anterior reconstruction. Partial vertebral body resection without anterior reconstruction behaves similar to a posterior-only construct [4]. Anterior reconstruction prevents kyphosis of the construct in the early period [23, 24, 36, 45]. However, a stable and successful anterior reconstruction depends on bony endplates that can resist axial compression and intact posterior ligaments that can provide flexion resistance [58]. The cage or cement used for anterior reconstruction has a higher modulus of elasticity than the bone and has a propensity to sink or tilt after repetitive cyclical loading [59]. When compressive forces are applied against strong adjacent bodies and resilient end plates, tilting or displacements of the cages are common. In contrast compression against weaker vertebral bodies leads to subsidence. These changes are usually associated with an increase in kyphosis of the construct and screw ploughing or cut-out even though they are more stable than posterior alone constructs [4, 5]. In patients with longer survival and with higher functional demand, these systems bear the brunt of repetitive cyclical loading [60].

Combined anterior and posterior decompression and stabilization with constructs

Constructs with combined instrumented fixation are relatively more stable than stand-alone anterior or posterior fixations, due to better biomechanical distribution of loads leading to reduced incidence of implant failure [24, 61, 62]. The higher perioperative complications of such procedures due to the extensiveness of surgical trauma and the poor general health of the majority of patients with MSTS make this operation feasible only in a select few.

Decompression and stabilization with constructs in junctional regions of atypical loading: cervicothoracic, occipitocervical and lumbosacral fixations

Cervicothoracic tumours pose a unique challenge with regard to tumour resection and reconstruction. This is due to the transition from a mobile and lordotic cervical spine to a fixed and kyphotic thoracic spine [63]. Therefore, it is more important to reconstruct the posterior tension band rather than the anterior column. Risk of peri-construct failure also supports posterior supplementation of anteriorly fixed tumours [63]. Higher failure rates of stand-alone anterior reconstruction compared to posterior reconstruction have been reported. Le et al. [64] evaluated 17 patients undergoing MSTS for cervicothoracic tumours and observed 2 out of 3 failures being associated with anterior only reconstructions, while there were no failures noted in the posterior-only fixations. Chest wall resections in patients undergoing cervicothoracic junctional resections have also been shown to increase the risk of implant failure [63]. The common modes of failure include increase in kyphosis or screw/rod breakage [63–65].

On the other hand, occipitocervical and lumbosacral fixations have a strong mechanical hold at one end of the construct than the other. With repeated eccentric loading, these constructs are susceptible to failure. Both these constructs are stressed more at the caudal screws than at the cranial screws [36, 66]. Screw loosening, ploughing and pull-out are more common at the caudal end of occipitocervical constructs and the cranial end of lumbosacral fixations. Rod and screw breakages are common at the cranial end of occipitocervical fixations and at the caudal end of lumbosacral fixations [31, 46, 66]. Augmentation of sacral screws, extending lumbosacral fixations to S2 vertebra, bi-cortical screw purchase, larger diameter screws, dual-rod fixations and fixations extending to the ilium are recommended to reduce fixation failures across the lumbosacral junction [36, 41, 67].

Clinical presentation of implant failure (Fig. 3)

Implant failures can be divided into “early failures” or “late failures” depending on the timing of presentation after the index surgery. Early failures can be characterized by radiological evidence of implant/construct failures with or without clinical symptoms presenting within the first 3 months. Early failures are due to eccentric loading of the weak vertebral bodies due to tumour or secondary osteoporosis. Duration of 3 months is selected to demarcate early and late failures, as CT/RT is/are started about 3 weeks after surgery and it takes another 1–2 months for re-calcification of the affected vertebrae [47]. Therefore, it is reasonable to assume that the maximum load sharing capacity of the affected vertebrae will be attained at 3 months after surgery. The regression of tumour tissue due to chemotherapy and radiotherapy, and the concomitant improvement in bone density in the affected vertebrae, may lead to cessation of further progression of failure. The implant construct may stabilize in the new position and may not require further surgical intervention if this position is acceptable.

Failures presenting 3 months after the index surgery are classified as late failures. This may be partly due to fusion not being attempted in patients with MSTS. Patients with longer survival and higher mobility are at a higher risk of implant failure. Increasing kyphosis with screw ploughing, loosening, cut-out or pull-out is common in late failures [4, 5]. Screw or rod breakage, on the other hand, is noted in

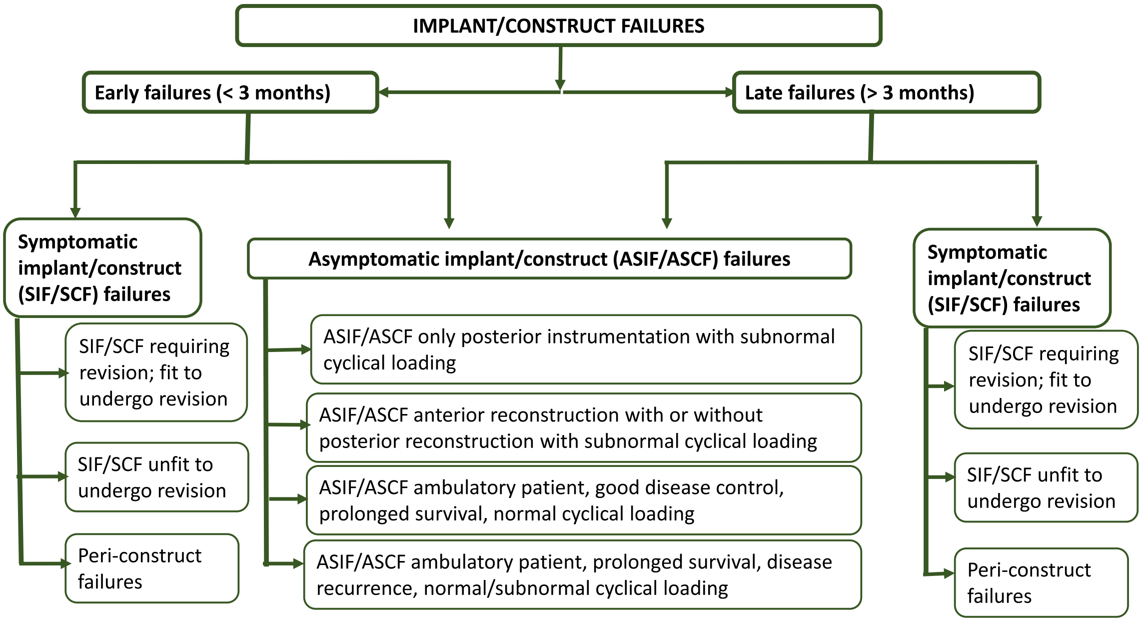


Fig. 3 Flowchart showing presentation of implant failures after metastatic spine tumour surgery

patients with good bone mineral density [5]. Loss of local tumour control or tumour progression in the peri-construct region may lead to weakening of the anterior column or implant–bone interface, thereby necessitating extension of instrumentation or revision. In certain cases, late failures can be inferred to occur secondary to the effects of high dose radiation to the normal tissue. These cause bone loss and late bone fracture and present in a dose- and time-dependent manner [68].

Implant/construct failure may be divided into "asymptomatic failure" and "symptomatic failure" depending on the clinical presentation of the failures. Early failures may be asymptomatic due to low functional demands. Symptoms may be masked by tumour-related pain or by the narcotic/non-narcotic pain killers used to treat tumour pain. Asymptomatic failures may remain asymptomatic or may progress to become symptomatic [69]. Asymptomatic patients may not require any further treatment until they become symptomatic. Mobile patients who are community ambulant are at particular risk of developing symptomatic implant failure due to eccentric loading of the weaker bones. These patients present radiologically as failures of implant–bone interface, bone–bone interface or implant–implant interface [36]. Such patients may require extension or revision of the construct [4]. A selective few patients who undergo MSTS and present as peri-construct failure or junctional failure may require revision of the primary construct as well. Peri-construct tumour progression or the osteopenic effects following RT/CT can be a risk factor for developing peri-construct failure [41, 55, 56]. There will, however, be some symptomatic patients who cannot undergo any treatment due to poor general condition or those who decline surgery due to low functional demands. Bellato et al. observed clinical and radiological evidence of implant failure in nine out of 105 patients (8%), but none of them underwent a revision surgery [5].

Conclusion

A thorough analysis of the limited established literature in fixations for metastatic spine disease and authors' own experience highlight a possibility of group of patients who exhibit definitive radiological failure of fixation but are asymptomatic. Taking into consideration all these factors, radiological implant failure rates after MSTS may be high but many patients may not require any further surgical intervention. A clear understanding of the biomechanical principles, survival span, ambulatory status, and the effects of RT/CT on implant failure would help to minimize the implant failures that lead to revision surgery. Further research with a prospective setup that can explore the above factors is necessary to consolidate the concepts of implant failure after MSTS.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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