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REVIEW ARTICLE

Musculoskeletal interventional oncology: current and future practices

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ABSTRACT

Management of musculoskeletal (MSK) tumours has traditionally been delivered by surgeons and medical oncologists. However, in recent years, image-guided interventional oncology (IO) has significantly impacted the clinical management of MSK tumours. With the rapid evolution of relevant technologies and the expanding range of clinical indications, it is likely that the impact of IO will significantly grow and further evolve in the near future.

In this narrative review, we describe well-established and new interventional technologies that are currently integrating into the IO armamentarium available to radiologists to treat MSK tumours and illustrate new emerging IO indications for treatment.

INTRODUCTION

Management of musculoskeletal (MSK) tumours has been traditionally accomplished through a therapeutic paradigm based on surgery, radiation and medical oncology (chemotherapy, bisphosphonates and analgesics). However, in recent years, the therapeutic armamentarium applicable to MSK tumours has been expanded with the advent of interventional oncology (IO). Within IO, bone metastases have represented the main target owing to recent applications of percutaneous bone ablation and consolidation procedures.^{1,2} Increasingly, other types of tumours are demonstrating a favourable response to IO with recent promising published results that may pave the way for widely accepted therapeutic alternatives to conventional therapies. Moreover, with the recent introduction of new interventional technologies, it is likely that the therapeutic portfolio of IO for MSK tumours will increase in the near future.

In this narrative review, we describe well-established and new interventional technologies that are currently integrating into the IO armamentarium available to radiologists

to treat MSK tumours and illustrate new emerging IO indications for treatment.

MSK TUMOUR ABLATION

Established ablation technologies

Percutaneous image-guided monopolar radiofrequency ablation (RFA) and cryoablation (CA) represent the two most established ablation technologies used for MSK tumours thus far.

Monopolar RFA works by generating high power to make an electrical current flowing between an electrode placed inside the tumour and some grounding pads placed on the patient's thighs.³ The result is frictional heating inside the target tumour, which results in a coagulative necrosis of the tumour.

On the other hand, CA is based on the Joule-Thompson effect, in which temperature either increases or decreases when a gas undergoes rapid expansion/compression, depending on its atomic properties. Current CA systems use pressurized argon that expands in a tiny chamber at

the distal tip of the needle, thus creating an iceball.⁴ CA achieves tumour destruction through several different mechanisms including physical and osmotic damage to cellular membranes, ischemic and hypoxic damage due to vascular impairment, apoptosis and potential cryoimmunological effect that is, however, still not clearly understood.⁴

From a clinical point of view, significant experience has been gained with these two ablation techniques both in terms of safety^{5,6} and clinical outcomes, with the latter being focused on pain management (in around 80% cases), or complete tumour destruction (*i.e.* curative treatment, in the remaining 20% cases).^{7–11}

Given the similar safety and clinical results granted by monopolar RFA and CA, there are some general (although not fixed) rules taking into account patient and tumour features that may help in the selection of the most adapted ablation technology. In particular, CA is preferentially used with large tumours needing a wide ablation area; tumours presenting with osteoblastic consistency; and procedures performed under local anaesthesia/mild sedation. On the other hand, RFA is preferentially used with small (ideally <3–4 cm) tumours, without sclerotic appearance, and procedures performed with deep sedation/general anaesthesia.

New ablation technologies

Bipolar radiofrequency ablation

Bipolar radiofrequency ablation (b-RFA) has been recently optimized to treat spinal bone tumours. Compared to monopolar RFA, b-RFA achieves coagulation necrosis through the same frictional heating used by the monopolar systems, although very low power (≤ 20 Watt) is needed, since the electrical current circulates between two dipoles located at the distal tip of the same electrode. Therefore, there is no need for grounding pads and very focused, morphologically consistent, and predictable ablation zones are obtained. These qualities render b-RFA particularly relevant for the treatment of tumours of the vertebral body, often in combination with vertebral augmentation to prevent secondary vertebral collapse.^{12,13} One of the main advantages of b-RFA in the spine is its relative reduced risk of harm to the spinal cord provided complete integrity of the posterior vertebral wall, which is not the case with other technologies such as CA and microwave ablation (MWA).¹⁴

It is worth noting that several reports have shown cumulative analgesic effect and local tumour control when b-RFA and vertebral augmentation were combined with radiotherapy (RT). In fact, in a systematic review on RFA used for spinal tumours, the best pain relief (on average 5/10 points on the 0–10 visual analogue scale) was achieved when RFA, vertebral augmentation and RT were applied on the same vertebral level.¹⁵ Similarly, Prezzano et al¹⁶ have recently showed that local tumour control is higher when RFA and RT are combined on the same tumour compared to RFA alone (at mean 8.2 months follow-up, recurrence rates were 9.1 vs 47.1%, respectively).

Magnetic Resonance Image-Guided Focused Ultrasound (MRgFUS)

MRI-guided focused ultrasound (MRgFUS) is another innovative technology that is increasingly used to treat MSK tumours.¹⁷ It combines high-intensity focused ultrasound (HIFU) to achieve tumour destruction and MR imaging (MRI) to guide the ablation beam, whilst MR thermometry allows monitoring of temperatures of the surrounding non-target tissues.

HIFU is based on mechanic waves that propagates into tissues provided an adequate acoustic window without gaseous, liquid or metallic interfaces between the transducer and the target tumour (Figure 1). Therefore, patient positioning is crucial to obtaining the best acoustic window. In the particular setting of bone tumours, when the mechanic waves reach the bone cortex some waves are absorbed and some reflected. The energy absorbed by the periosteum leads to the destruction of its rich neurovascular network, thus inducing a local coagulative necrosis representing the main mechanism by which pain relief is achieved in the treatment of bone metastases. In addition, if the target tumour does not present any cortical cover, MRgFUS can provide energy focused directly to the target tumour with subsequent coagulative necrosis.¹⁸

One line of current clinical research in the domain of MRgFUS is focused on designing mobile transducers that would ideally allow their adaptation to patients' decubitus rather than vice-versa, which may be particularly useful for MSK tumours, since it may facilitate the identification of the best acoustic window.¹⁹ Another line of current clinical research on HIFU in the MSK field is exploring combination of HIFU with some basic percutaneous procedures such as hydro-displacement or bone consolidation to increase the number of lesions being potentially treatable with this technology. In this respect, Bing et al²⁰ have reported in a series including 115 bone metastases and 52 osteoid osteomas, that 26 (50%) osteoid osteomas were directly suitable for HIFU and 17 (32.7%) if it would have been combined with hydrodissection; on the other hand, 41 (35.7%) metastases were directly suitable for HIFU and 43 (37.4%) if hydrodissection and/or bone consolidation were also performed.

Finally, a promising but still early line of research is based on targeted drug delivery with temperature sensitive liposomes (TSLs) carrying the drug to the target tumour through the peripheral blood stream, similarly to that which is provided by electrochemotherapy. Once inside the tumour, TSLs can be activated by mild hyperthermia (40–45°C) induced with HIFU, thus delivering the drug directly inside the tumour²¹ with subsequent avoidance of adverse events typical of systemic drug release. Unfortunately, at the moment, there are no clinical studies about this technique in humans.

Other ablation modalities

MWA has recently integrated into the armamentarium of percutaneous ablation techniques for the treatment of MSK tumours. MWA relies on an electromagnetic field (915 MHz or 2.45 GHz) applied to the target tumour through one or multiple antennae. The final purpose is to force the dipoles inside the tumour to continuously realign with the main direction of the applied

Figure 1. Schematic representation of MRgFUS of a periosteal osteoid osteoma of the femoral diaphysis. (A) The transducer (white arrow) is suspended in a tank filled with degassed water, generating mechanical waves or “sonications” (dotted white arrows), which pass through coupling mediums (dark green pads) focussing on the target nidus through the acoustic window (double-headed blue arrow). (B) The subsequent “sonications” are systematically planned (green triangles) to cover the entire lesion volume (red areas represent areas of the tumour that have been already cauterised). MRgFUS, MRI-guided focused ultrasound

electromagnetic field, thus producing frictional energy, that is then converted into heat with subsequent coagulative necrosis. Theoretically, MWA is relatively insensitive to tissue characteristics such as impedance and perfusion.²² Moreover, MWA energy is expected to radiate through all biological tissues, thus rendering this source of energy particularly powerful in creating large ablation zones within few minutes. For this reason, MWA has been extensively applied in parenchymal organs.^{23–26} However, it is still not completely clear whether such powerful tool may be safely applied in MSK tumours that are potentially prone to developing a wide range of catastrophic adverse events including secondary bone fractures and thermal-mediated iatrogenic injuries to nerve roots (both of which represent typical adverse events that may complicate MSK tumour ablation procedures). The few published series on MWA of MSK tumours^{27–33} do not allow a definitive assessment of its potential role in such a specific clinical scenario due to high heterogeneity of the ablation protocols and relatively limited follow-up. Moreover, with the goal of these series being mainly limited to evaluate “pain relief” which may theoretically be achieved even with very limited ablation zones, safety profile cannot be completely delineated.

In the end, another interesting but still “unexplored” ablation modality is represented by electroporation with or without associated intravenous infusion of chemotherapeutic drugs (*i.e.* electrochemotherapy). The principle of electroporation is to achieve a non-thermal tumour destruction through the “permeabilization” of cellular membranes. In fact, local application of high-voltage short-pulsed electric current through thin electrodes deployed on the tumour borders results in multiple holes within cellular

membranes. This phenomenon causes cells to lose their “intracellular impermeability” with a subsequent apoptotic cascade. When combined with chemotherapeutic infusion, electroporation allows the penetration of the chemotherapeutic drug inside the cells,^{34,35} thus combining the cytotoxic damage to the apoptotic cascade. Unfortunately, this treatment has been sporadically reported for the management of MSK tumours^{36,37}; and there is only one Phase II published study including 29 patients with painful bone metastases, which has reported that 84% (20/24) of the included patients had experienced significant pain improvement and reduction of narcotics consumption at mean 7 month follow-up. Moreover, the radiographic evaluation performed at follow-up longer than 3 months in 20 patients had highlighted “partial response” in 1 (5.0%) patient, “stable disease” in 17 (85%) patients, and “progression” in 2 (10.0%) patients.³⁵

Protective measures useful for MSK tumour ablation

MSK tumour ablation is considered overall safe.^{5,6} Nevertheless, iatrogenic nerve damage represents a relatively common event occurring whilst treating spine and peripheral MSK tumours.^{6,9} Thankfully, most of these neural complications are transient and recover with conservative management.^{6,9} Nonetheless, several months are needed to achieve complete recovery. Moreover, in very few cases complete neural deficit can occur following nerve exposure to extreme temperatures (*i.e.* <15°C or >42°C³⁸). In addition, many other organs including skin, cartilage and hollow/parenchymal abdominopelvic organs may be accidentally injured during MSK tumour ablation. Accordingly, several

Figure 2. (A) Painful soft-tissue gluteal metastasis (arrow) from renal cell carcinoma in a 67-year-old male patient; of note, the proximity of the sciatic nerve to the target tumour (dotted white arrow). (B) The tumour was treated with percutaneous CT-guided cryoablation (iceball*); a 22G needle (yellow arrow) was used to achieve hydro-displacement (double-headed white arrow) of the sciatic nerve (white arrow). (C) Painful extra abdominal desmoid tumour of the anterior abdominal wall (white arrow) in a 72-year-old male patient; of note, the proximity of the intestinal loops (dotted white arrow). (D) The tumour was treated with percutaneous CT-guided cryoablation (iceball*); a 15G blunt-tip needle (yellow arrow) was used to achieve CO₂-displacement (double-headed white arrows) of the intestinal loops.

different protective measures have been proposed,³⁹ and include hydro/carbo/balloon-displacement, thermal and functional neural monitoring.^{6,38–44}

Common protective measures

The most common protective measures used during percutaneous (MSK) tumour ablation include physical displacement and thermal monitoring around the at-risk structure. This occurs because these protective techniques are relatively inexpensive, readily available and very effective in the majority of cases.

Physical displacement of the at-risk structure from the ablation zone can be achieved through fluid injection via 20–22G needles. Simple saline (with minimal contrast dilution to optimize CT-visibility⁴⁵) is the most common injected fluid (Figure 2). However, with RFA, 5% electrically inert dextrose solution is used instead of saline to avoid uncontrolled electrical conduction resulting in unpredictably large ablation zones.^{39,46} CO₂ is another inert fluid that can be injected to achieve physical displacement of the at-risk structure, especially when “antideclivous” displacement is desired (Figure 2).^{39,46} Compared to liquids, CO₂ is rapidly reabsorbed, and therefore frequent intraoperative checks are warranted. The use of angioplasty balloons represents another option to achieve physical displacement, although it may be somehow unpractical in many MSK scenarios.³⁹

Lastly, thermal monitoring is obtained with 20–22G thermocouples deployed between the at-risk structure and the ablation area. One of the most interesting aspects of thermal monitoring is that

it can be coaxially combined with hydrodisplacement, especially in spinal cases,⁴¹ thus permitting safe performance of ablation at extreme tumoricidal temperatures whilst keeping a constant physiological temperature around the at-risk structure, thanks to the simultaneous injection of cold/warm liquids (which cannot be obtained with CO₂-based displacement since it does not allow temperature mitigation).⁴⁷

Advanced protective measures

All the advanced protective measures deal with functional neural monitoring in the form of electrostimulation and evoked potentials (EPs).^{38,40–43,48}

Electrostimulation allows monitoring of one single motor nerve⁴² through visual evaluation of muscle contraction following a percutaneous electrical stimulation of the corresponding motor nerve; on the other hand, sensitive and motor function of multiple nerves is granted with EPs.

EPs are differentiated into motor EPs (MEPs), allowing supervising of the motor corticospinal neural network; and somatosensory EPs (SSEPs) allowing supervising of the ascending sensory pathways. With MEPs, transcranial stimulation is applied at the motor cortex to create an electrical signal descending along the motor tracts till the neuromuscular junction where it produces muscle contraction; the signal related to such contraction is continuously registered and analysed during ablation and compared to the baseline signal (registered before starting the procedure) to understand whether alterations of

nerve conduction have occurred.⁴⁹ Similarly, with SSEPs a transcutaneous electrical stimulation of a peripheral nerve is applied to create a signal traveling through the dorsal nerve root to the thalamus and finally to the sensory cortex, where such signal is continuously registered and compared to the baseline signal registered at the beginning of the procedure just before ablation.⁵⁰ Once data are interrogated, MEPs and SSEPs are expected to come within a certain time interval (latency) and with a certain strength (amplitude) and pattern. Any signal decrease in amplitude, increase in latency, or change in pattern suggests possible neural compromise and warrants immediate suspension of the ablation procedure.

However, it should be noted that many drugs used during anaesthesia as well as some systemic (*e.g.* hypotension, hypoxemia) and local (patient's decubitus) conditions may produce alterations of MEPs and SEEPs that are not related to the ablation procedure.

Recent experiences with EPs in MSK tumour ablation have showed that persistent intraoperative EPs changes correlate with reporting post-operative neurologic sequelae, which is not the case with transient or no EPs changes.^{51,52}

BONE TUMOUR CONSOLIDATION

Fractures are estimated to be the commonest adverse events in patients presenting with bone tumours with an associated significant social and economic burden.^{53,54} As such, it is not surprising that percutaneous minimally invasive treatments in MSK IO have primarily focused on fracture stabilization. In this regard, patients are generally evaluated by a multidisciplinary tumour board including orthopaedic surgeons. The board generally recommends surgical treatment (ideally tumour excision and subsequent prosthetic reconstruction) for oligometastatic patients with a relatively long-life expectancy; and percutaneous bone consolidation in multimetastatic non-surgical patients with more limited life expectancy.

Percutaneous osteoplasty was the first technique introduced with applicable clinical results in terms of pain relief and fracture consolidation.^{55–59} From a biomechanical point of view, osteoplasty works perfectly well in areas subjected to high-compressive stresses, such as the vertebral body, the acetabulum (Figure 3) or the epiphyseal area of long bones.^{1,60} On the contrary, suboptimal biomechanical resistance is expected in areas where torsional or bending stresses are predominant such as in meta- or diaphyseal areas of long bones.^{61–63} In fact, it has been reported that up to 8% of long bone tumours treated with osteoplasty subsequently re-present with a secondary stress fracture in the cemented area.⁶⁴ Accordingly, several different methods have been described with the intent of increasing the biomechanical efficacy of osteoplasty performed with poly-methyl methacrylate (PMMA) injection into long bones.^{65–69} Unfortunately, many of these described techniques still lack a formal biomechanical validation, limiting the available repertoire of percutaneous biomechanically validated consolidation procedures in long bones to flexible or bundle intramedullary nailing.^{70–73}

Concerning the biomechanical reinforcement granted by standard osteoplasty in areas undergoing compressive stress, recent studies have suggested that effective biomechanical stabilisation is achieved when extensive and complete filling of the bone defect is obtained, thus preventing new, or worsening of pre-existing fractures.⁷⁴ Unfortunately, there are no currently available tools allowing immediate intraprocedural evaluation of PMMA filling of the bone defect, and therefore such evaluation is still based on a simple qualitative visual evaluation performed by operators, who often overestimate the real extent of filling.⁷⁵ Accordingly, intraprocedural tools facilitating volumetric assessment of PMMA distribution and filling of the bone defect are currently being developed and will be briefly discussed in the next section. Moreover, it is worth noting that PMMA working time, as well as PMMA leakages in critical areas (*e.g.* anterior epidural space) may play a crucial role in limiting the quantity of injected PMMA. Nevertheless, it has been suggested that symptom relief does not depend on the quantity of injected PMMA⁷⁶; therefore,

Figure 3. 57-year-old male patient with a painful lytic metastasis from lung cancer of the posterior column of the acetabulum (B *). Intraoperative (A) sagittal fluoroscopic and (B) CBCT images with the planned trajectory (arrows) facilitating bone trocar (dotted white arrows) deployment to perform (C) osteoplasty through a posterior trans-ischiatic approach. CBCT, cone beam CT.

Figure 4. 68-year-old male patient with a metastatic pheochromocytoma. (A) Axial enhanced CT image showing a symptomatic hypervascular metastasis of the left scapula (white arrow). During the same interventional session, the tumour was embolized (B, C) and (D) cryoablated with (E, F) complete devascularization at 1 month contrast-enhanced MRI.

effective relief may be achieved even with small injected quantities of PMMA.

According to all the previous considerations, standard PMMA osteoplasty should be considered as a pure palliative treatment providing fracture stabilisation and pain relief. In fact, no formal local tumour control is granted by this technique. Nevertheless, many research efforts are currently geared towards understanding whether a purely mechanical treatment such as osteoplasty may better contribute to improving local tumour control through combination of PMMA with radioactive isotopes.⁷⁷ Nevertheless, no robust clinical experiences are currently available in this area.

IMAGING GUIDANCE

MSK IO procedures have been traditionally performed under CT- and fluoroscopy-guidance, alone or in combination. With the increasing complexity of interventions (e.g. combined

ablation and embolisation; Figure 4), many MSK IO procedures are commonly performed in rooms equipped with both modalities. The primary advantage of combined CT and fluoroscopic imaging is the possibility of acquiring excellent real-time spatial resolution in the axial plane with CT and on sagittal/coronal planes with fluoroscopy. There are different methods of combining CT and fluoroscopic guidance; the simplest being a CT room equipped with a mobile C-arm, to more complex solutions such as cone beam CT (CBCT) and 4DCT (four-dimensional CT) units. These latter set-ups have several different advantages compared to the former (Table 1), including the possibility to acquire CT volumes, high-quality fluoroscopy, and the availability of various software facilitating the deployment and navigation of interventional tools.

In the authors' institution where both 4DCT and CBCT facilities are available, the choice where to schedule MSK IO procedures is simply based on how many CT volumes are expected

Table 1. Difference in terms of image quality, speed of image acquisition, irradiation and promptness to switch from one modality to another with the three different available combinations of CT and CBCT imaging and fluoroscopy

		Quality of imaging	Speed of image acquisition	Irradiation	Promptness for switch from CT or CBCT to fluoroscopy and vice-versa
CT& Mobile C-arm Fluoroscopy	CT	High	High	Low	High
	Fluoroscopy	Poor	High	High	
CBCT Unit	CBCT	Medium-High	Low	Medium-High	Low
	Fluoroscopy	High	High	Low	
4DCT Unit	CT	High	High	Low	High
	Fluoroscopy	High	High	Low	

CBCT, cone beam CT; 4DCT, four-dimensional CT.

Figure 5. 64-year-old female patient presenting with (A) a lytic painful acetabular metastasis (white arrow) from lung cancer. The bone tumour was treated with percutaneous cryoablation and osteoplasty. (B) The bone defect corresponding to the metastasis was identified on the intraoperative CT images, and marked to produce a virtual image (blue area) which is superimposed on the fluoroscopic images in order to give operators immediate visual feedback of devices positioning relative to the target tumour. The same virtual image may be also used intraoperatively during PMMA injection to evaluate its distribution filling of the bone defect. (C) Coronal CT image showing the final result of PMMA injection reflecting the morphology of the virtual image in B. PMMA, polymethyl methacrylate.

to be acquired. When more than five volumetric acquisitions are expected, 4DCT is preferred, since it provides 3D volumes in few seconds, covering a 16cm length in the craniocaudal plane without the need for the operator to leave the room during imaging acquisition and with little additional radiation to the patient.

Concerning software availability on the CT and CBCT units, the most relevant to MSK IO procedures include those facilitating needle navigation to the target (Figure 3), tumour embolisation, and visual qualitative evaluation of the PMMA filling of a bone defect (Figure 5).

It should be mentioned that new generation CBCT units integrate advanced navigation tools that combine machine deep learning and artificial intelligence (Figure 6) to recognise the bone segment (vertebral levels) included in the acquired volume and then propose the best bone trocar trajectory to access the bone (*i.e.* vertebral body). For example, an intercostopedicular or transpedicular access is respectively recommended in the thoracic or lumbar setting. The system allows guidance during the deployment of the bone trocar according to virtual images available on the screen, without any need for further fluoroscopy exposure unless required by the operator to check trocar positioning. This results in significant reduction of the radiation dose⁷⁸ to both patient and radiologists. Moreover, with regards to reducing operator irradiation during fluoroscopic procedures, robotic systems have also been trialled, although their clinical application is still not available on a large scale.^{79,80}

Other innovative modalities of image guidance for MSK IO procedure include MRI and positron emission tomography-CT (PET-CT). The former has a great interest in soft-tissue IO procedures given the high spontaneous contrast-resolution allowing easy target identification, the application of MRI-fluoroscopy whilst navigating in-bore with the devices through the target and the absence of ionising radiation.^{81,82} The current limitations of MRI guidance include the need for more expensive MR-compatible

tools, the need for large bore MR units allowing patient positioning at the isocentre with the operator's arm stretched inside the bore to manipulate the interventional devices (unless using open-bore magnets with reduced magnetic field strength and image quality), as well as staff availability of trained radiographers who can facilitate imaging acquisition along the needle axis to allow intraprocedural MR-fluoroscopy to become available to the operator.⁸³ On the other hand, functional imaging and guidance with PET-CT is reserved for very few selected cases with bone intramedullary or soft-tissue lesions that are indiscernible on standard modalities of guidance.⁸⁴ Nevertheless, these procedures are associated with high radiation burden^{84,85} to both patients and operators.

EMERGING INDICATIONS

MSK tumour ablation

Amongst MSK tumours, painful bone metastases have been the main focus for IO pain management, typically with RFA or CA; therefore, a large amount of evidence supports the use of these techniques in the palliative field with pain relief achieved through complete or even partial (*i.e.* bone/tumour interface) bone tumour ablation.^{1,7,8,86} At the same time, a progressively growing body of evidence is emerging to prove that complete tumour destruction in oligometastatic patients or in those with an oligo-progressive disease is feasible, safe and effective. In this perspective, Cazzato et al⁹ have investigated the role of RFA and CA in 46 patients with 49 bone metastases originating from different primary cancers. At mean 34.1 ± 22 months follow-up, local progression at the treated site was observed in 28.5% tumours, accounting for 1- and 2-year local progression free survival of 76.8 and 71.7%, respectively. Treated bone metastasis larger than 2 cm were more likely to present local progression after ablation. Deschamps et al¹⁰ conducted a similar study in 89 consecutive patients with 122 bone metastases; and in their intent-to-treat analysis, the 1-year complete treatment rate was 67%. Prognostic factors favouring complete local tumour control included oligo-metastatic/metachronous status, small size of the target tumour

Figure 6. CBCT unit integrating an advanced navigation tool that through combined machine deep learning and artificial intelligence is able to (A) automatically recognise the vertebral levels included in the acquired volume and to automatically propose the optimal (intercostopedicular on transpedicular) needle trajectory (white arrows) to enter the vertebral level during a vertebroplasty procedure; and (B) to guide needle deployment on virtual images without need for fluoroscopy (unless needed by the operator to check needle positioning), with a subsequent relevant reduction of the radiation dose. (C) Intraoperative image showing the operator looking at virtual images to advance the trocar through the established trajectory.

(<2 cm), absence of cortical bone erosion, and absence of neurological structures within the ablation zone or track.

Moreover, there are sporadic reports of the use of ablation techniques for the treatment of benign and/or locally aggressive bone tumours.^{87–91} In particular, interesting results were obtained with osteoid osteomas treated with laser ablation,⁹² or with CA with the cryoprobe placed just next to the cortical bone (*i.e.* without need for bone drilling).⁹³ Moreover, recent CA and RFA studies have reported on the effective treatment of osteoblastomas.^{87,88}

Other benign or locally aggressive bone tumours such as chondroblastomas, giant cell tumours and aneurysmal bone cysts, have been treated with IO techniques (namely ablation), often in combination with other IO and non-IO techniques.^{89–91} However, literature reports are still not robust enough to support IO as first-line treatment unless other more established treatment strategies are deemed at higher risk. Therefore, in these cases, IO treatment must only proceed following a carefully documented multidisciplinary discussion.

Another new and exciting clinical indication for IO which is playing an increasingly primary role, is the managing of extra abdominal desmoid tumours (Figure 2). These are defined as clonal fibroblastic proliferations in the deep soft tissues, where they show infiltrative growth and tendency toward local recurrence without any potential to metastasise.⁹⁴ Traditionally, these tumours have been treated with a combination of surgery and RT.⁹⁵ However, both of these treatments carry drawbacks in terms of morbidity and local recurrence.⁹⁵ As a result, the current first-line treatment for evolving and symptomatic desmoid tumours is based on medical therapies including non-steroidal anti-inflammatory drugs, modulators of oestrogen receptors, tyrosine-kinase inhibitors and chemotherapies (*i.e.* methotrexate, vinblastine/vinorelbine, anthracyclines).⁹⁶ Surgery and/or RT is indicated in case of tumour progression despite medical therapies.⁹⁷ Nevertheless, different reports have confirmed the effectiveness of CA in achieving symptomatic relief and to a certain extent, local tumour control. Tremblay et al⁹⁸ retrospectively reported their single-institution series (23 patients) with extra-abdominal desmoid tumours treated with percutaneous CA as first-line (61%) or salvage (39%) treatment with a curative (52%) or palliative (48%) intent. At a median of 15.4 months (3.5–43.4) follow-up, symptomatic improvement was demonstrated in 89% patients. At 12 months, the average change in viable volume was –80% (range –100% to +10%) and response by modified response evaluation criteria in solid tumours (mRECIST) was “complete response” in 36% cases, “partial response” in 36% cases, and “stable disease” in 28% cases. Two patients sustained a major procedural complication (significant neuropraxia). Similarly, Schmitz et al,⁹⁹ reported on CA of 26 extra abdominal desmoid tumours in 18 patients. At mean 16.2 ± 20.0 months imaging follow-up, no residual viable tumour was observed in 9/23 patients (39.1%); some degree of volume reduction was evident in 22/23 tumours (95.7%); and progressive disease was observed in 1/23 patient (4.3%). No major complications were observed. These results are particularly encouraging and may pave the way to a therapeutic shift towards CA, which

is, unfortunately, currently considered as an “untried investigational treatment,”⁹⁷ although it may well convert to a main stream strategy to replace surgery/RT to treat symptomatic or evolving desmoid tumours on medical therapies.

Bone consolidation

In areas with biomechanical stresses other than compression, IO may utilise screw-mediated osteosynthesis, especially in the pelvic area and proximal femur, where double/triple-screw osteosynthesis of the femoral neck may be performed,^{100–103} provided no extensive infiltration of the trochanteric region, nor cortical disruption or articular involvement.^{1,60,104} Indications include the treatment of non-displaced or minimally displaced (pathologic or bone insufficiency) fractures as well as impending fractures in non-surgical cases.

Deschamps et al¹⁰⁵ reported about 100 consecutive cancer patients with 141 pathologic pelvic fractures managed with percutaneous osteosynthesis performed with cemented screws under fluoroscopy and CBCT guidance in 107 sessions. In their experience, the mean post-procedure hospitalisation was 2 days. Complications ensued in 14/100 patients (14%) being consistent with focal pain at procedure site for longer than 48 h ($n = 5$), hematoma ($n = 3$), progressive fracture despite fixation ($n = 2$), infection ($n = 1$), tumour track seeding ($n = 1$), and screw displacement ($n = 2$). In the 88 patients who completed early follow-up, the mean numeric rating scale pain score significantly improved at 6 weeks (from 6.1 ± 2.5 to 2.1 ± 3.0); similarly, opioid use was reduced at the same time interval ($91.3 \text{ g} \pm 121$ pre-procedure vs $64.6 \text{ g} \pm 124$ post-procedure). Cazzato et al¹⁰⁶ reported on the clinical outcomes and local evolution of treated fracture sites following percutaneous image-guided screw-mediated osteosynthesis of pathological (47.2%), bone insufficiency (13.9%) and

impending (38.9%) fractures in 32 consecutive cancer patients at two tertiary centers. Additional osteoplasty was performed in 63.9% of fractures. Hospital stay was consistently ≤ 3 days, and 87.1% of treated fractures improved at 1 month follow-up. Three major complications (early screw-impingement radiculopathy; accelerated coxarthrosis; late coxofemoral septic arthritis) and one minor complication were observed. Interestingly, unfavourable local changes at the treated fracture site at a mean 8.7 month imaging follow-up occurred in 3/24 sites (12.5 %). The unfavourable changes included poor consolidation ($n = 1$) and screw loosening ($n = 2$; one symptomatic), warranting the need for continuous clinical/imaging follow-up. There were no cases of secondary fractures. Given these clinical advantages, many other bone sites outside the pelvic ring are being increasingly treated with percutaneous osteosynthesis.^{107–109}

CONCLUSIONS

IO has significantly improved the management of MSK tumours in the last few decades and it is likely that this trend will continue in the future due to the increasing availability of advanced imaging modalities and navigation tools. In particular, it is expected that an increasing number of MSK IO procedures will be performed for relatively new clinical scenarios including curative ablation in oligometastatic cancer patients, CA for extra abdominal desmoid tumours and percutaneous screw-mediated osteosynthesis for bone-metastasis related fractures.

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Not required

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