Launching an Image-Guided Percutaneous Osteosynthesis Program: A PRISM–RE-AIM Implementation Framework

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ABSTRACT

Image-guided percutaneous osteosynthesis (IGPO) is an emerging minimally invasive technique for stabilizing metastatic, insufficiency-related, and selected traumatic skeletal lesions. Although technical feasibility and clinical outcomes are increasingly reported, guidance on launching and sustaining IGPO programs remains limited. This expert narrative review proposes an implementation framework based on the Practical, Robust Implementation and Sustainability Model and Reach, Effectiveness, Adoption, Implementation, Maintenance. Key IGPO, musculoskeletal interventional radiology, and implementation-science publications were identified from PubMed and authors' reference libraries. Selected French and Canadian institutional experiences were synthesized through framework-guided author discussions. This approach was not a systematic review or formal qualitative study. The framework emphasizes institutional readiness, stakeholder engagement, patient selection, imaging and anesthesia access, staffing, radiation safety, adverse event monitoring, follow-up, and progressive scale-up. Suggested metrics include technical success, procedure duration, radiation exposure, adverse event grade, pain, mobility, length of stay, reintervention, and patient-reported outcomes.

ABBREVIATIONS

CT = computed tomography, DLP = dose-length product, IGPO = image-guided percutaneous osteosynthesis, IR = interventional radiology, PRISM = Practical, Robust Implementation and Sustainability Model, RE-AIM = Reach, Effectiveness, Adoption, Implementation, Maintenance

Since the introduction of X-rays into skeletal care (1), image guidance has evolved from diagnostic confirmation to procedural navigation (2–5). This historical trajectory, summarized in **Table 1**, provides useful context but is not the central focus of this review. The contemporary relevance of image-guided percutaneous osteosynthesis (IGPO) lies in its emerging position at the interface between interventional radiology (IR), orthopedic surgery, oncology, trauma care, and palliative medicine.

IGPO reflects a broader evolution of musculoskeletal IR from diagnostic access and local tumor control toward image-guided mechanical stabilization. Building on experience gained through bone biopsy, thermal ablation, cementoplasty, and vertebroplasty (6), IGPO enables selected bone lesions to be stabilized through a percutaneous approach under computed tomography (CT) (7) or cone-beam CT (8) guidance.

IGPO has now been applied across multiple anatomical regions, including the axial and appendicular skeleton, using fixation devices adapted to local biomechanical and anatomical constraints (9–16). By enabling precise, minimally invasive stabilization under imaging guidance, it offers additional therapeutic perspectives for selected traumatic (17) and oncologic (4) bone lesions.

The clinical role of IGPO should be understood in relation to conventional open orthopedic fixation. IGPO is not intended to replace surgery, and its value should not be framed as a general superiority claim. Open surgical techniques remain indispensable when anatomical reduction, neural decompression, extensive reconstruction, soft tissue management, or high-load fixation is required. They also remain the reference approach for unstable fractures, complex deformities, and situations requiring direct visualization or broad reconstruction. IGPO instead occupies a complementary therapeutic space in carefully selected patients and lesions, particularly when the clinical objective is targeted stabilization, pain control, early mobilization, or support of an oncologic or palliative care pathway.

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RESEARCH HIGHLIGHTS

- A staged implementation-science approach can help structure image-guided percutaneous osteosynthesis (IGPO) program launch through needs assessment, stakeholder engagement, resource preparation, local adaptation, pilot-case selection, iterative quality improvement, and progressive scale-up.
- The Practical, Robust Implementation and Sustainability Model and Reach, Effectiveness, Adoption, Implementation, Maintenance framework links organizational, technical, and contextual determinants with practical evaluation metrics, providing an adaptable implementation framework for IGPO program development.
- Selected French and Canadian experiences illustrate how imaging access, referral pathways, anesthesia availability, reimbursement structures, institutional culture, and multidisciplinary collaboration may influence IGPO implementation.

This complementary positioning is central to patient selection. IGPO may be considered for symptomatic or mechanically threatening bone lesions when the objective is targeted stabilization rather than open reduction, decompression, or extensive reconstruction. Relevant criteria include pain burden, impaired mobility, actual or impending instability, feasibility of a safe percutaneous trajectory, and mechanical demands compatible with percutaneous fixation. IGPO may be particularly relevant in older patients, especially those aged 70–75 years or above (15); patients with frailty, reduced performance status, or limited physiological reserve; and those with comorbidities that increase the risk of open surgery or prolonged recovery. These may include severe cardiopulmonary disease, chronic kidney disease, diabetes, anticoagulation or bleeding risk, malnutrition, immunosuppression, or poor wound healing capacity. No universal lesion size threshold can be proposed, because feasibility depends more on anatomical location, residual bone stock, cortical destruction, load-bearing requirements, and clinical context than on size alone. Contraindications are uncommon but include the absence of a safe access route, mechanical instability requiring open reduction or reconstruction, neurological compression requiring decompression, uncontrolled infection, uncorrected coagulopathy, or a risk-benefit balance inconsistent with the patient's expected survival or goals of care. In oncologic patients, systemic treatment plans, radiotherapy timing, rehabilitation, discharge objectives, and expected survival should also be considered (10,18–21). These indications and limitations should be assessed through multidisciplinary discussion involving IR, orthopedic surgery, oncology, anesthesia, and rehabilitation teams.

Although clinical and technical reports have shown expanding applications of IGPO in oncologic and traumatic settings, the existing literature remains predominantly procedure-centered. It offers limited guidance on how to develop IGPO as a sustainable clinical service. Centers

Table 1. Historical Timeline: From X-Rays to 3-Dimensional Navigation in Interventional Radiology

Period	Key milestone	Description
1895	Discovery of X-rays	Wilhelm Conrad Röntgen discovers X-rays in Würzburg and publishes his findings on December 28, 1895. This marks the birth of radiology and the first visualization of the human skeleton.
1896	First surgical applications	Within a year, X-rays are used to localize foreign bodies and assess fractures. Pioneers such as John Hall-Edwards (Birmingham) and Eugène-Louis Doyen (Paris) perform the first orthopedic procedures guided or verified by radiography.
1902–1905	Birth of modern osteosynthesis	Belgian surgeon Albin Lambotte designs the first metallic plates and screws for fracture fixation, with radiographic control of implant positioning. He is considered the father of modern osteosynthesis.
1970s–1990s	Rise of intraoperative fluoroscopy and interventional radiology	Real-time fluoroscopic guidance becomes standard in orthopedic surgery, establishing the durable integration of imaging into skeletal fixation. In parallel, interventional radiology emerges as a new discipline, introducing minimally invasive image-guided procedures such as embolization or vertebroplasty, paving the way for future percutaneous bone interventions.
1990s–2020s	Emergence of 3D image guidance and first image-guided osteosyntheses	The advent of interventional CT and cone-beam CT enables 3D planning, navigation, and control of percutaneous procedures. During this period, the first CT-guided and cone-beam CT–guided percutaneous osteosyntheses are reported, demonstrating the feasibility and safety of minimally invasive fixation by interventional radiologists.
Present day	Percutaneous fixation under CT/cone-beam CT	Interventional musculoskeletal radiology increasingly performs percutaneous osteosynthesis under CT/cone-beam CT guidance with millimetric precision and minimal invasiveness. Although not yet widespread, this practice reflects the growing convergence of procedural expertise and advanced imaging technology.
2025 and beyond	Global development of image-guided percutaneous osteosynthesis	The coming decade will see the worldwide diffusion of image-guided percutaneous fixation as a standard interventional radiology activity. Increasing availability of navigation software and training programs will facilitate the integration of osteosynthesis into musculoskeletal and oncologic interventional practices across academic and community hospitals.

CT = computed tomography; 3D = 3-dimensional.

seeking to establish such programs must address questions beyond technical feasibility: how to identify appropriate indications, organize referrals, secure imaging and implant resources, integrate anesthesia support, train operators, ensure radiation safety, define shared decision-making with surgeons, monitor outcomes, and scale activity without compromising quality or safety. These challenges are shaped by local context, including institutional resources, surgical culture, reimbursement structures, interdepartmental relationships, and healthcare system organization.

This review addresses that gap by proposing an adaptable implementation framework for IGPO program development. The review applies Practical, Robust Implementation and Sustainability Model (PRISM) (22) and Reach, Effectiveness, Adoption, Implementation, Maintenance (RE-AIM) (23) framework to organize practical considerations for IGPO program readiness, workflow design, adoption, evaluation, and sustainability. PRISM organizes intervention characteristics, patient and clinician perspectives, organizational environment, implementation infrastructure, and external context, whereas RE-AIM provides pragmatic domains for evaluating reach, effectiveness, adoption, implementation fidelity, and maintenance. Together, these frameworks align with the Standards for Reporting Implementation Studies (24) principles and help link contextual determinants to implementation strategies and measurable outcomes.

Drawing on experiences from France and Canada, where IGPO developed under different institutional and cultural conditions, this review aims to help centers define the role of IGPO alongside orthopedic surgery and establish safe, efficient, and sustainable programs adapted to their own healthcare environment.

METHODS AND FRAMEWORK DEVELOPMENT

This article was designed as an expert narrative review and implementation framework rather than a systematic review. Key publications on IGPO, cementoplasty, interventional oncology, and implementation science were identified from PubMed and the authors' reference libraries. Search terms included combinations of image-guided osteosynthesis; percutaneous fixation; percutaneous screw fixation; cementoplasty; IR; musculoskeletal intervention; implementation science; PRISM; RE-AIM; Consolidated Framework for Implementation Research; Exploration, Preparation, Implementation, Sustainment; and Standards for Reporting Implementation Studies.

Articles were selected for relevance to procedural indications, clinical outcomes, workflow organization, program development, training, radiation safety, adverse event monitoring, implementation evaluation, and long-term sustainability. Particular attention was given to studies describing technical feasibility, clinical outcomes, multidisciplinary pathways, quality metrics, and implementation-science frameworks applicable to procedural innovation. No formal systematic review, risk-of-bias assessment, statistical pooling, or meta-analysis was performed.

PRISM and RE-AIM were selected because they provided a complementary structure suited to the objectives of this review. PRISM was considered particularly relevant for analyzing how intervention characteristics, patient and stakeholder perspectives, organizational setting, implementation infrastructure, and external context influence adoption and sustainability of IGPO programs. RE-AIM was used to translate these determinants into pragmatic evaluation domains, including reach, effectiveness, adoption, implementation fidelity, and maintenance. Other frameworks, such as the Consolidated Framework for Implementation Research (25) and the Exploration, Preparation, Implementation, Sustainment (26) framework, were considered relevant but were not selected as the primary structure because the objective was not to perform an exhaustive determinant mapping or a staged implementation study. Instead, PRISM–RE-AIM was chosen to combine contextual analysis with practical outcome-oriented evaluation in a format directly applicable to procedural program development.

The French and Canadian contextual elements were derived from selected institutional experience and framework-guided discussions among authors involved in IGPO implementation in both healthcare systems. These 2 countries were selected because IGPO developed within distinct organizational, cultural, and resource environments, including differences in referral pathways, IR infrastructure, anesthesia support, reimbursement, and multidisciplinary collaboration. This contrast was used not as a formal health system comparison but to strengthen the transferability of the proposed framework across diverse institutional contexts.

DETERMINANTS OF IGPO IMPLEMENTATION (PRISM)

This section analyzes the key determinants that influence adoption and sustainability of an IGPO program, using PRISM as a guiding structure (**Table 2**). For each determinant, centers should define local requirements, barriers, and measurable actions before initial clinical cases are scheduled.

Characteristics of the Intervention

IGPO possesses several inherent attributes that support its dissemination within IR services, including its minimally invasive nature, procedural precision with advanced image guidance, and adaptability to a wide range of anatomical targets. It can be performed using CT (27), cone-beam CT (2), or hybrid imaging environments, allowing flexible integration into existing procedural infrastructures. When combined with cementoplasty or percutaneous tumor ablation, IGPO offers both mechanical stabilization and

Table 2. Practical, Robust Implementation and Sustainability Model Determinants Applied to Image-Guided Percutaneous Osteosynthesis Program Implementation

	Definition (implementation science)	Application to IGPO program
PRISM domain		
Intervention characteristics	Attributes of the procedure affecting feasibility, adaptability, complexity, and compatibility	CT/cone-beam CT–guided minimally invasive stabilization; adaptable across anatomical regions; combinable with cementoplasty or ablation; requires operating room–level sterility, radiation safety expertise, implant logistics, and monitoring of the learning curve using procedure time, trajectory adjustments, radiation exposure, and adverse events
Patient and stakeholder perspectives	Needs, expectations, and acceptability among patients and clinical partners	Perceived acceptability among oncology, orthopedic trauma, anesthesia, pain, and palliative care teams; addresses unmet needs related to pain, instability, high surgical risk, and rapid functional recovery
Internal setting	Organizational resources, culture, workflow, and structural readiness	Availability of CT/cone-beam CT and anesthesia support; trained IR technologists and nursing teams; sterile environment validated for implant procedures; logistics for hardware storage and procurement; institutional support for IR-led musculoskeletal interventions
External environment	Factors outside the institution influencing implementation (policy, reimbursement, and national infrastructure)	Variation in CT/cone-beam CT access, reimbursement or billing pathways, implant regulation, radiation safety requirements, and national infrastructure for musculoskeletal IR
Organizational perspectives and fit	Alignment of procedure with institutional priorities and professional identity	Integration into existing IR musculoskeletal workflows; complementarity with vertebroplasty/cementoplasty; IR presented as a clinical partner rather than technician; collaborative culture enabling shared decision-making with surgeons

CT = computed tomography; IGPO = image-guided percutaneous osteosynthesis; IR = interventional radiology; PRISM = Practical, Robust Implementation and Sustainability Model.

local disease control in a single session, making it particularly appealing for patients with metastatic bone disease (14) or complex structural compromise (17).

For operators already proficient in bone biopsy, vertebroplasty, and trajectory-based bone access, a staged training pathway is recommended (14). Initial supervised cases should preferentially involve anatomically accessible targets with wide safety margins, such as iliac wing or sacral insufficiency/metastatic lesions. More complex regions, including the cervical spine, proximal femur, sternum, and periarticular appendicular lesions, should be reserved for operators with greater experience because of proximity to neurovascular structures, smaller osseous corridors, and higher biomechanical demands. Training may combine hands-on workshops, simulation, observation in experienced centers, implant-handling sessions, and mentored initial cases; in experienced musculoskeletal interventional radiologists, approximately 1–5 mentored cases may be required before independent practice, depending on anatomy and case complexity.

Nonetheless, the procedure requires a secure procedural environment, including operating room–level sterility, rigorous radiation safety practices, and familiarity with orthopedic implants and their handling. These characteristics make IGPO technically feasible when appropriate institutional conditions are met, provided that appropriate institutional conditions and workflow structures are in place. Environment and equipment for IGPO are presented in **Figure 1**, with representative examples shown in **Figures 2** and **3**.

Patient and Stakeholder Perspectives

The demand for minimally invasive skeletal stabilization is substantial across oncologic, metabolic, and selected traumatic indications. Patients who may benefit include selected elderly (15) or frail patients, individuals with painful metastatic lesions (18) or insufficiency fractures (28), and patients with severe pain limiting mobilization who have high surgical or anesthetic risk because of cardiopulmonary comorbidity, systemic disease burden, limited functional reserve, or palliative goals of care. IGPO is best considered when the lesion is symptomatic or mechanically threatening, a safe image-guided trajectory exists, and open surgery is undesirable, disproportionate, or associated with excessive anesthetic or surgical risk. Relative contraindications include uncontrolled infection, uncorrectable coagulopathy, lack of a safe trajectory, severe instability requiring open reduction or decompression, extensive bone destruction precluding adequate implant purchase, and inability to ensure appropriate postprocedural follow-up. Lesion location, cortical destruction, bone stock, proximity to neural or vascular structures, and feasibility of cement augmentation should be assessed before selecting the implant strategy. Early cases

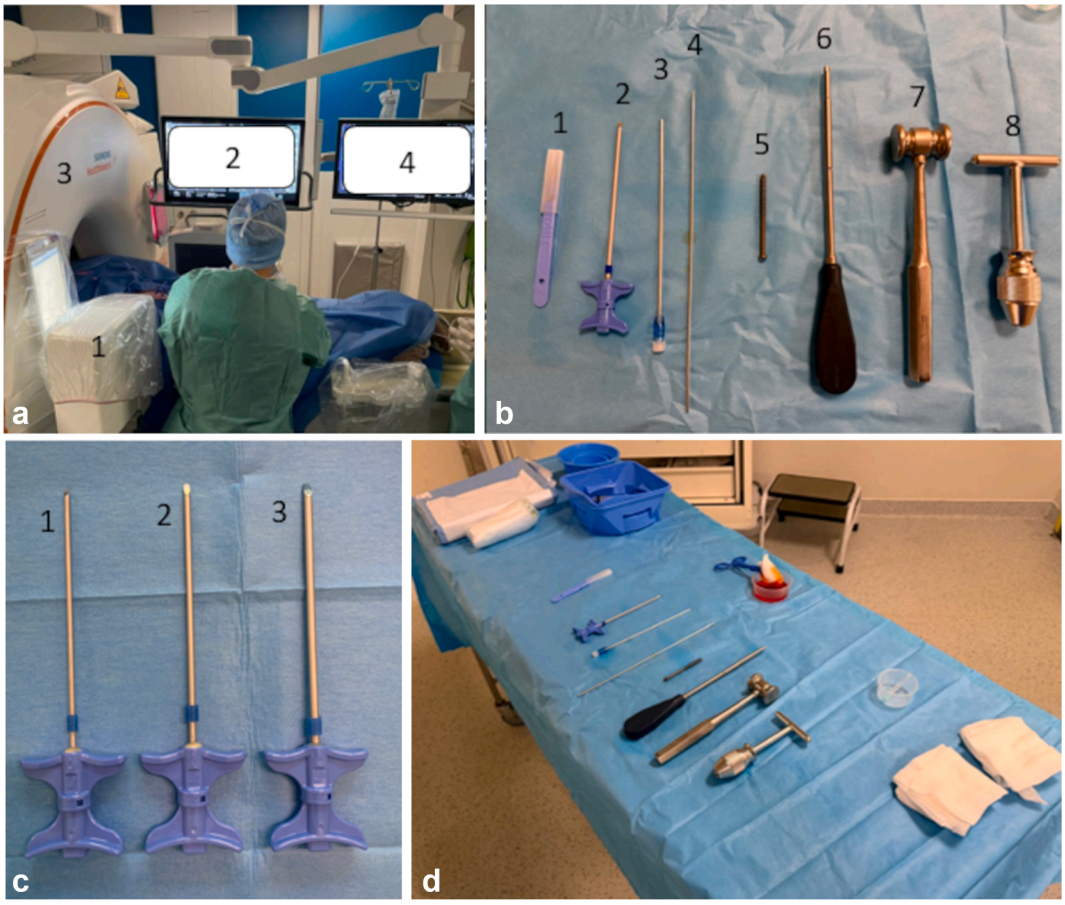


Figure 1. Environment and equipment for image-guided percutaneous osteosynthesis. The panel is intended to demonstrate the dual-modality procedural environment and spatial organization. **(a)** Interventional suite showing the fluoroscopy unit (1) with its monitor (2) and the computed tomography (CT) scanner (3) with its console (4). **(b)** Instruments required for the procedure: scalpel (1) for a small skin incision, trocar (2), trocar pusher (3), guide wire (4), screw (5), screwdriver (6), hammer (7), and T-handle chuck (8). **(c)** Trocars used during the procedure: 13-gauge (1), 11-gauge (2), and 8-gauge (3) trocars (t'AM; Strim Health Care, Thonon-les-Bains, France), selected according to the screw diameter to introduce the guide wire. **(d)** Interventional table. Only a limited number of instruments were required: osteosynthesis and standard aseptic equipment. Cementoplasty equipment may be added depending on the indication.

should preferentially involve anatomically accessible lesions with wide safety margins, whereas complex regions such as the cervical spine, proximal femur, sternum, and periarticular appendicular skeleton should be reserved for more experienced teams.

Stakeholder acceptance is facilitated when IGPO is presented as complementary to, rather than competitive with, surgical fixation (14,29,30). Relevant stakeholders include oncologists, orthopedic and trauma surgeons, anesthesiologists, pain specialists, rheumatologists, rehabilitation teams, nursing staff, radiologic technologists, and hospital administrators. Early multidisciplinary discussion is particularly useful for defining referral criteria, clarifying procedural roles, anticipating anesthesia or sedation requirements, and aligning postprocedural follow-up. In oncology-driven centers, unmet needs are often dominated by painful or unstable metastases and insufficiency fractures, whereas in trauma-focused institutions, demand may be more frequently related to sacroiliac, pelvic, or vertebral injuries.

Internal Setting: Organizational Resources and Workflow Readiness

Institutional resources and workflow structures play a decisive role in determining whether IGPO can be safely and sustainably implemented. Imaging availability, particularly access to CT, remains one of the primary determinants of procedural capacity. Although cone-beam CT offers flexible 3-dimensional navigation and is widely available in many IR suites, it does not always replace CT for complex multiplanar planning, especially when IGPO is combined with thermal ablation, particularly cryoablation (20).

In many institutions, interventional CT time directly competes with high-volume diagnostic activity, making it difficult to reserve sufficiently long slots for complex

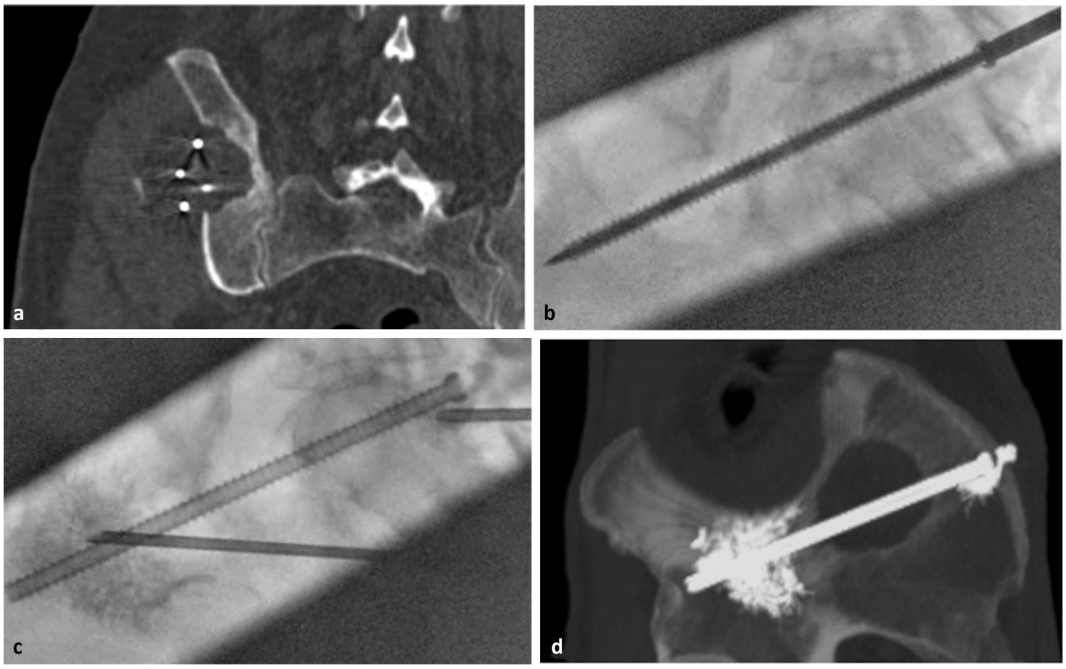


Figure 2. Computed tomography (CT)–guided and fluoroscopy-guided percutaneous osteosynthesis of the left iliac wing with combined cryoablation, cementoplasty, and screw fixation in metastatic bone disease. A 72-year-old man with metastatic lung cancer presented with pelvic pain and gait limitation related to an osteolytic lesion of the left iliac wing. The procedure was performed under general anesthesia through a percutaneous posterior approach. **(a)** Coronal CT showed the 4 cryoablation probes (IceRod; Boston Scientific, Marlborough, MA) (black arrow) inserted into the lesion; the ice ball is outlined by a white dashed line. **(b)** Lateral fluoroscopy during screw insertion showed controlled advancement of the screw (white arrow) along the guide wire trajectory (white arrowhead) using a screwdriver (black arrow). **(c)** Lateral fluoroscopy showed the screw (white arrow) within the left iliac wing; 2 11-gauge trocars (black arrowheads) were positioned at the screw tip for polymethyl methacrylate cement injection (white arrowheads). **(d)** Final sagittal CT confirmed homogeneous polymethyl methacrylate distribution (white arrowheads) around the distal screw (white arrow), without relevant leakage; the lytic cavity (white dashed circle) and iliac wing were stabilized. The patient experienced complete pain relief within 24 hours, resumed full weight-bearing the next day, and was discharged on postoperative Day 1.

procedures such as IGPO. Although these interventions may initially appear time-consuming compared with routine diagnostic examinations at the department level, the overall economic balance can be favorable at the hospital level when reduced length of stay, lower adverse events rates, and improved functional recovery are taken into account. The availability of dedicated interventional CT capacity—through protected time slots or, ideally, a CT scanner reserved for procedural activity—becomes an important facilitator for program growth. Such protected resources ensure procedural continuity, reduce cancellations, and shield IGPO from fluctuations in diagnostic demand. Clearly articulating these downstream benefits to department leadership and hospital administration is often important for securing such dedicated interventional resources and protecting the program from being marginalized by diagnostic pressure.

Human resources constitute an essential determinant of IGPO implementation. A practical core team should include at least 1 experienced musculoskeletal interventional radiologist and 2 trained staff members, either 1 IR nurse and 1 radiologic technologist or 2 radiologic technologists, depending on local practice and regulatory requirements. At least 1 team member should be familiar with sterile implant handling, cement preparation, and operating room–level sterile technique. A second operator or dedicated assistant may be useful during early cases or complex trajectories. Anesthesiology or procedural sedation support should be planned according to patient frailty, expected procedure duration, positioning, anticipated pain, and whether ablation or cementoplasty is combined with fixation. The procedural suite must meet operating room standards, including validated infection control protocols and appropriate sterile equipment handling. Materials such as screws, spindles, nails, trocars, cement, and ancillary devices should be managed through coordination with purchasing, pharmacy, and sterilization services.

Finally, the clinical infrastructure surrounding the procedure is critical. Preprocedural consultations, postoperative follow-up, and long-term imaging surveillance must be integrated into existing outpatient pathways. Departments with mature musculoskeletal IR activity generally exhibit smoother IGPO implementation because the procedure builds naturally on established expertise and procedural workflows.

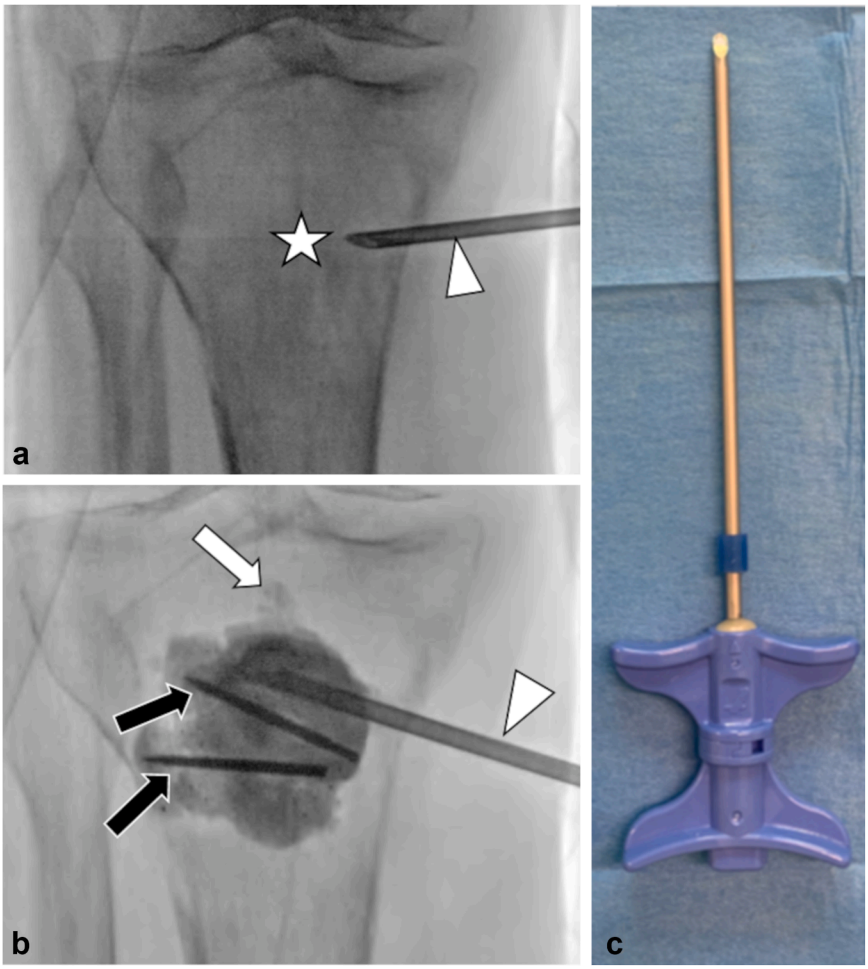


Figure 3. Computed tomography (CT)–guided and fluoroscopy-guided percutaneous osteosynthesis with spindles and cementoplasty of a painful tibial metastasis from lung adenocarcinoma. A 68-year-old woman presented with a painful lytic metastasis of the proximal tibia, cortical permeation, pain score of 9 of 10, and inability to stand without assistance. The procedure was performed under short general anesthesia. **(a)** Frontal fluoroscopy confirmed the trocar tip (white arrowhead) within the lytic lesion (star). **(b)** Final frontal fluoroscopy showed polymethyl methacrylate cement (white arrow) embedding both spindles previously inserted (black arrows), creating a reinforced construct. **(c)** Photograph of the 11-gauge trocar used for the technique; only 1 trocar and a single 5-mm skin incision were required. The metallic spindles acted as internal reinforcement within the polymethyl methacrylate cement. The procedure resulted in complete pain relief, restoration of full ambulation, improved patient-reported quality of life from 0 to 100 of 100, next-day discharge, and immediate full weight-bearing.

External Environment: System-Level Factors

System-level factors, including healthcare policies, national reimbursement structures, and referral networks, exert important influence on IGPO implementation. Regulatory frameworks governing orthopedic implants and radiation use vary across countries and institutions, shaping the scope of practice and affecting institutional readiness. Established tumor boards, trauma referral pathways, and multidisciplinary networks strongly determine patient flow and can either facilitate or hinder adoption. Favorable reimbursement mechanisms, institutional support for procedural innovation, and a collaborative surgical culture accelerate implementation, whereas competition for CT resources, limited anesthetic availability, or administrative restrictions may slow program development.

Understanding these broader contextual variables enables institutions to anticipate challenges, align goals with system-level constraints, and strategically plan their implementation trajectory.

In several systems, reimbursement structures for interventional musculoskeletal procedures remain heterogeneous, influencing not only adoption but also long-term sustainability. Transparent cost-benefit communication is, therefore, essential to secure durable institutional support.

Securing institutional support often requires a clear administrative argument that articulates not only the clinical benefits of IGPO but also its organizational and economic advantages, underscoring the importance of

Table 3. Illustrative Contextual Determinants Influencing Image-Guided Percutaneous Osteosynthesis Implementation in Selected French and Canadian Settings

Domain	France	Canada
Historical development	Early adoption in high-volume oncology centers with established cementoplasty and vertebroplasty expertise	Later adoption, initially concentrated in tertiary centers with strong orthopedic oncology collaboration
Imaging infrastructure	Frequent availability of IR-dedicated CT and cone-beam CT slots, facilitating longer combined procedures	Broad cone-beam CT availability in angiography suites but greater competition for diagnostic CT access
Scope of practice	IGPO often perceived as a natural extension of musculoskeletal interventional radiology	IGPO more commonly developed through shared IR-orthopedic pathways and collaborative role definition
Multidisciplinary culture	Oncology-driven pathways and tumor boards may facilitate early referrals; procedures are often coordinated primarily by interventional radiology teams	Initial referrals may arise from pain medicine, oncology, or orthopedic oncology; joint procedural models can facilitate access to implants, billing strategies, and shared clinical responsibility
Institutional facilitators	Established cementoplasty workflows; IR autonomy in bone interventions; reimbursement pathways; dedicated interventional CT access; end-to-end patient care from consultation to follow-up	Strong collaborative frameworks; shared responsibility with orthopedic oncology; flexible procedural models; local billing agreements; end-to-end patient care from consultation to follow-up
Main barriers	Variable access outside tertiary or cancer centers; regional heterogeneity; anesthesia availability; need for dedicated implant inventory	Variable access outside tertiary centers; diagnostic CT availability constraints; need to adapt procedures to cone-beam CT capabilities; coordination of implant supply and multidisciplinary scheduling
Current applications	Initially oncology-focused, with progressive expansion toward selected traumatic indications	Predominantly oncology-focused, with development shaped by local referral pathways and orthopedic collaboration

Note–This comparison is illustrative and based on selected institutional experience. It should not be interpreted as a representative national comparison or as evidence of superiority of one healthcare system over another; observed differences may reflect local program maturity, institutional organization, resource availability, and author experience.
CT = computed tomography; IGPO = image-guided percutaneous osteosynthesis; IR = interventional radiology.

leadership, multidisciplinary alignment, and effective communication with hospital management.

Comparative Synthesis: France versus Canada

Key contextual differences are summarized in Table 3. France and Canada were selected as illustrative comparator settings because they represent contrasting health system and institutional environments within the authors' direct experience. The comparison is not intended to describe all French or Canadian practices but to illustrate how local resources, referral pathways, reimbursement structures, and procedural cultures may influence IGPO implementation.

In France, adoption was facilitated by long-standing expertise in cementoplasty and vertebroplasty and the presence of well-established tumor boards that routinely considered minimally invasive stabilization for metastatic lesions. Many institutions benefited from IR-allocated CT time slots, which promoted procedural consistency and workflow maturation and facilitated combined procedure (4,16,18,19).

In the Canadian centers represented in this experience, IGPO implementation occurred more recently and often required clarification of scopes of practice, shared responsibilities, and billing models with orthopedic teams. Despite cone-beam CT availability, competition for diagnostic CT time represented a structural limitation. The time interval between procedure request and intervention emerged as a critical determinant, particularly for outpatients with severe pain or impaired mobility. In selected cases performed under local anesthesia or moderate sedation, IR pathways may reduce dependence on operating room and anesthesiology availability; however, this potential advantage is context-dependent and should be evaluated locally rather than assumed. Adoption, therefore, progressed through targeted training, demonstration of clinical value, and gradual expansion of collaborative relationships. These contrasting experiences underscore how external context shapes program development and highlight the importance of tailoring implementation strategies to local environments.

EVALUATION OF IGPO DEPLOYMENT (RE-AIM) (TABLE 4)

The RE-AIM framework provides a structured approach to evaluating the clinical, organizational, and sustainability outcomes of an IGPO program after its implementation.

Reach

IGPO primarily benefits patients with painful metastatic lesions, sacral or iliac insufficiency fractures, and selected traumatic injuries in medically vulnerable individuals. The extent to which these patients access IGPO depends on institutional imaging capacity, referral patterns, and multidisciplinary awareness. Longitudinal monitoring of referrals by physician, specialty, and indication enables assessment of current reach and identification of gaps, where targeted outreach or expanded service promotion

Table 4. Reach, Effectiveness, Adoption, Implementation, Maintenance Framework Applied to the Implementation of an image-guided percutaneous osteosynthesis Program

	Definition (implementation science)	Application to IGPO program
RE-AIM domain		
Reach	Proportion and representativeness of patients accessing the intervention	Number and proportion of eligible patients discussed, referred, treated, or excluded; influenced by referral networks, imaging availability, awareness among clinicians, and patient access
Effectiveness	Clinical benefits, unintended effects, and patient-centered outcomes	Pain relief, opioid reduction, mobility improvement, quality of life, technical success, SIR-graded adverse events, reintervention, and follow-up completeness
Adoption	Uptake by clinicians, departments, and institutions	Uptake by referring clinicians, operators, departments, and institutional leadership; influenced by training, orthopedic collaboration, perceived clinical value, and availability of imaging and anesthesia resources
Implementation	Quality, consistency, and resource requirements of the delivered program	Fidelity to standardized protocols for sterility, imaging guidance, radiation protection, anesthesia planning, implant handling, adverse event reporting, and documentation of procedural metrics such as procedure duration, radiation dose, trajectory adjustments, and room occupancy
Maintenance	Long-term integration, sustainability, and adaptation of the program over time	Sustained referral activity; regular audit of outcomes and complications; registry participation; continued training; protocol updates; maintenance of imaging, anesthesia, and implant resources

IGPO = image-guided percutaneous osteosynthesis; RE-AIM = Reach, Effectiveness, Adoption, Implementation, Maintenance.

could improve access. Similarly, monitoring patient demographics allows identification of underserved groups, guiding tailored interventions to enhance equity of care.

Effectiveness

Across published series, IGPO has been associated with improvements in pain, mobility, functional status, and selected patient-reported outcomes (10,13,14,16). Institutions should monitor effectiveness using preprocedural and postprocedural pain scores, opioid use, mobility or weight-bearing status, discharge destination, length of stay, and quality-of-life instruments such as EQ-5D or PROMIS when available. Mechanical stabilization should be evaluated alongside safety using standardized adverse event reporting, preferably the Society of Interventional Radiology (SIR) adverse event classification (31), including cement leakage, hardware malposition or loosening, bleeding, infection, neural or vascular injury, pain flare, fracture progression, and reintervention.

Adoption

Adoption reflects the willingness of clinicians and institutions to integrate IGPO into routine practice (32). As in many procedural innovations, adoption also depends on the heterogeneous attitudes of clinicians and allied professionals, ranging from early supporters who actively champion IGPO to novices requiring structured exposure, and occasional resistant stakeholders whose concerns must be addressed through transparent communication and demonstration of clinical value. Prior IR experience with bone interventions, a structured training pathway, effective communication with surgical and anesthetic teams, and institutional support for procedure time all facilitate adoption. Barriers may arise from ambiguity in scopes of practice, limited imaging availability, or cultural differences between services. The comparative experiences of France and Canada emphasize the importance of early multidisciplinary engagement and professional trust in accelerating adoption.

Implementation (Fidelity and Workflow)

To evaluate implementation of an IGPO program, radiologists should systematically assess how consistently and accurately the procedure is delivered in real-world practice. Key considerations include fidelity to standardized protocols, adherence to imaging guidance, hardware placement, patient positioning, technical success, and the need for patient-specific or logistical adaptations. Implementation evaluation should also capture consistency across operators and sites, resource utilization, procedure duration, imaging suite time, consumables, radiation metrics (20), fluoroscopy time, CT dose-length product (DLP) (20), cone-beam CT dose-area product, and safety outcomes graded using the SIR adverse event classification (31). These data, supplemented by staff feedback on workflow barriers and facilitators, can identify areas for training, process optimization, and iterative improvement.

High implementation fidelity not only optimizes clinical outcomes but also strengthens institutional confidence in the activity. Early implementation experience consistently shows that the selection and success of initial IGPO cases play a disproportionate role in shaping institutional acceptance, as a well-chosen initial case can build confidence among clinicians, administrators, and procedural teams.

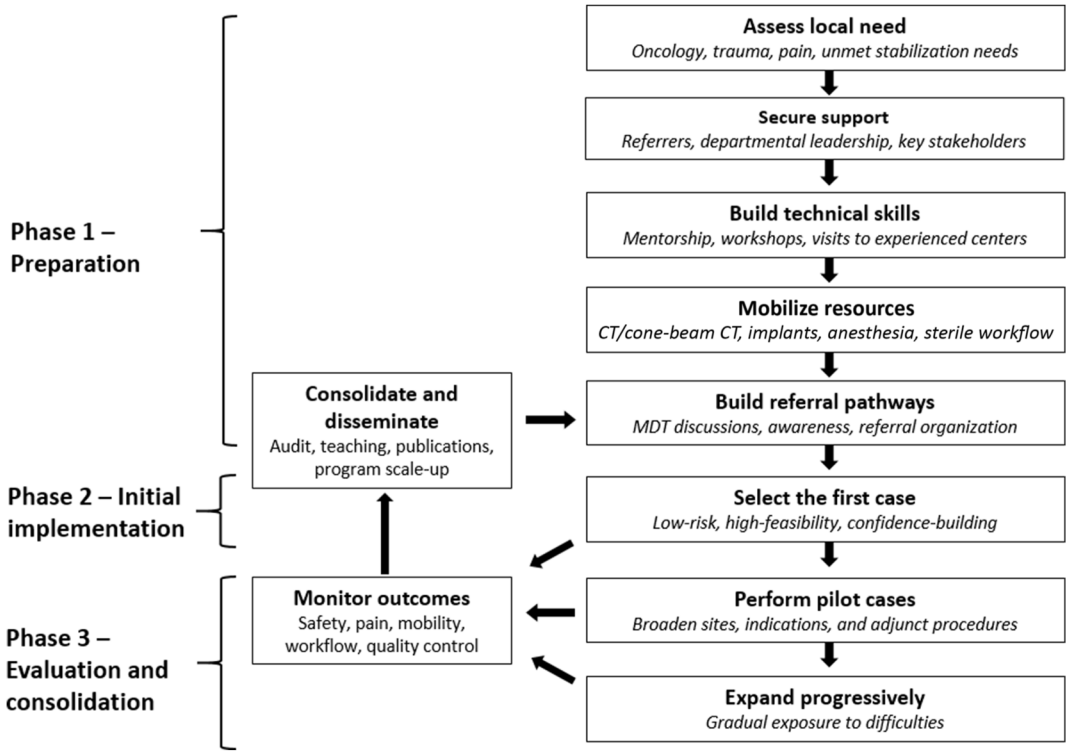


Figure 4. Stepwise implementation and consolidation of a new interventional image-guided percutaneous osteosynthesis activity. The process included initial institutional preparation, progressive clinical implementation with careful case selection, and consolidation through outcome assessment, data collection, and scientific dissemination. Feedback loops emphasized continuous quality improvement and support acquisition. CT = computed tomography.

Maintenance and Sustainability

Long-term sustainability relies on continuous monitoring, quality assurance, and integration into routine multidisciplinary care. Prospective registries should capture referral source, indication, lesion site, hardware and cement use, technical success, procedure duration, radiation exposure, SIR adverse event grade, pain score, opioid use, mobility or weight-bearing status, length of stay, discharge destination, patient-reported outcomes when available, and reintervention. Regular follow-up clinics and iterative refinement of procedural protocols maintain performance standards. As expertise increases, indications may progressively expand to anatomically complex regions, such as the cervical spine, periarticular appendicular skeleton, sternum, and complex pelvic ring lesions.

INTEGRATED CONCEPTUAL MODEL

The integrated PRISM–RE-AIM model is intended as a practical bridge between contextual diagnosis and program evaluation. Rather than restating each framework separately, it links PRISM determinants to concrete implementation actions and RE-AIM outcomes. In this model, local determinants such as imaging access, anesthesia support, implant availability, referral pathways, multidisciplinary engagement, training capacity, and reimbursement constraints are first identified and translated into site-specific workflows, governance structures, and quality-monitoring processes.

These implementation actions are then evaluated through RE-AIM domains: reach of eligible patients, effectiveness in terms of technical and clinical outcomes, adoption by referring teams and operators, fidelity to standardized workflows, and maintenance over time. Feedback from these outcomes is used to adjust protocols, training, referral criteria, resource allocation, and follow-up pathways. The model is, therefore, iterative rather than prescriptive: it does not define a single implementation pathway but helps institutions adapt IGPO deployment to their own resources, clinical priorities, and regulatory environment. For practical use, the framework can be applied as a stepwise implementation sequence: first, assess institutional readiness, including imaging access, anesthesia support, implant availability, sterility requirements, and referral pathways; second, define eligible indications and multidisciplinary decision-making criteria with orthopedic, oncologic, anesthesia, and rehabilitation teams; third, pilot the workflow on selected cases with standardized planning, radiation safety procedures, and adverse event reporting; fourth, monitor early outcomes, including technical success, pain relief, mobility, adverse events, procedure time, and resource use; and finally, refine protocols, expand indications cautiously, and maintain quality through training, audit, registry participation, and iterative feedback. A stepwise pathway for IGPO program implementation is presented in Figure 4.

DISCUSSION

The main contribution of this review is to reposition IGPO implementation as a program development process rather than solely as a technical extension of musculoskeletal IR. By applying PRISM (33) and RE-AIM (23) to IGPO, the proposed framework links contextual determinants, such as institutional readiness, imaging access, staffing, referral pathways, and multidisciplinary engagement, to measurable implementation outcomes, including reach, effectiveness, adoption, implementation fidelity, and maintenance. This approach complements the predominantly technical IGPO literature by providing a structure for planning, monitoring, and refining early program deployment. Generalizable elements include operating room–level sterility, standardized imaging workflows, rigorous trajectory planning, multidisciplinary engagement, structured training in implant handling, radiation safety practices, adverse event reporting, and reliable postoperative follow-up pathways.

Published IGPO series remain heterogeneous; however, available quantitative data provide useful benchmarks for program evaluation. Technical success has generally been high, ranging from approximately 97% in pelvic fixation by internal cemented screw (34) to 99% in cone-beam CT–guided pelvic fixation series. Clinical benefit has also been reported, including pain score reduction from 6.1 to 2.1 at 6 weeks after pelvic fixation by internal cemented screw (34), with reduced opioid use. These values should be interpreted as realistic reference points for local program monitoring rather than universal quality thresholds and may be complemented by institutional tracking of procedure duration, CT or cone-beam CT room occupancy, radiation exposure, anesthesia escalation, reintervention, and early mobility or discharge outcomes. Although adverse events after IGPO are uncommon, they must be anticipated, recognized, and graded using standardized adverse event classifications, such as the SIR system (31). In a dedicated safety analysis of percutaneous image-guided screw fixation, per-procedural adverse events occurred in 2.7% of fractures, early adverse events in 3.6%, and delayed adverse events in 17.7% of fractures with follow-up (35), emphasizing the importance of structured clinical and imaging surveillance. Expected events include intraprocedural implant malposition, cement leakage, bleeding, cortical breach, or neurological irritation; early hematoma, symptomatic cement leakage, infection, acute pain worsening, or reintervention; and delayed secondary fracture, implant loosening or failure, infection, pain recurrence, or late reintervention.

Radiation protection should also be considered a core quality indicator for IGPO programs, particularly because procedures may combine CT or cone-beam CT guidance, fluoroscopy, cementoplasty, ablation, and implant placement. Standard protocols should include preprocedural trajectory planning to minimize repeated acquisitions, low-dose CT or cone-beam CT protocols when feasible, collimation, limitation of fluoroscopy time, distance and shielding for staff, real-time dose monitoring, and systematic recording of DLP (20,36) or dose-area product. Recent IGPO-related work combining cryoablation, screw fixation, and cementoplasty has also reported DLP as a procedural metric, supporting its use as a practical benchmark for dose monitoring in complex combined procedures.

Similar implementation issues have been addressed in other IR procedures (37). For example, SIR quality improvement standards for percutaneous lung ablation emphasize patient selection, procedural quality, outcome thresholds, adverse event monitoring, and follow-up as key components of safe program development. These parallels support the relevance of applying implementation-science frameworks to IGPO while recognizing its additional requirements related to orthopedic co–decision-making, implant logistics, sterility, anesthesia planning, and mechanical stability assessment.

Other determinants, however, vary substantially by context. Imaging availability—particularly access to CT—differs widely across institutions and represents a key limiting factor in many settings. In France, the presence of IR-dedicated CT time often facilitated early adoption, whereas Canadian programs frequently faced structural competition with diagnostic CT demand. Economic and reimbursement constraints also shape implementation: activity-based systems may require appropriate billing pathways and justification of implant and procedural costs, whereas globally budgeted systems may be limited primarily by CT or cone-beam CT access, staffing, anesthesia support, and competition with diagnostic imaging. Institutional cultures and the maturity of multidisciplinary referral pathways similarly affect program development. The establishment of sustained referral activity also depends on the confidence of referring clinicians and multidisciplinary partners, which is progressively built through procedural reliability, transparent communication, and shared clinical decision-making. As the contrasting French and Canadian experiences illustrate, local context profoundly shapes implementation trajectories, requiring flexible and adaptive strategies.

The existing IGPO literature largely focuses on technical feasibility and clinical outcomes but seldom addresses organizational structures, interdisciplinary coordination, or program sustainability. The early launching phase of IGPO programs, during which workflows, referral patterns, and professional trust are actively constructed, is rarely described, particularly in IR. This gap supports the need for implementation-focused analyses capable of translating selected institutional experience into adaptable guidance. By anchoring IGPO implementation within PRISM and RE-AIM, this review provides a structured framework that institutions can adapt to their own resources, referral patterns, patient populations, and regulatory environment.

The France-Canada comparison presented in **Table 3** should be interpreted as an illustrative contextual synthesis rather than a representative national survey or

formal health system comparison. Its objective was not to define country-level standards or imply superiority of one system over another but to show how the same technical intervention may require different implementation strategies according to imaging capacity, anesthesia access, reimbursement structures, referral pathways, institutional culture, and local program maturity. Because this comparison is qualitative and based on selected institutional experience rather than systematic national sampling, apparent differences may also reflect institutional organization and author experience. Future research should focus on refining quality indicators, comparing workflow models, and quantifying learning curves using reproducible benchmarks such as technical success, procedure duration, CT or cone-beam CT room occupancy, radiation exposure, number of trajectory adjustments or implant repositioning, anesthesia escalation, adverse event rates, reintervention, and early clinical outcomes, alongside training strategies including simulation, mentorship, and multidisciplinary case review. Prospective, multicenter initiatives and dedicated IGPO registries should be developed to define and monitor quality indicators mapped to RE-AIM domains. Reach metrics may include the number of eligible patients discussed, treated, or excluded, and reasons for nontreatment. Effectiveness metrics should include technical success, pain scores, opioid use, mobility or performance status, length of stay, discharge destination, reintervention, and patient-reported outcomes using validated instruments when feasible, such as EQ-5D or PROMIS. Implementation metrics should include adverse events graded according to standardized classifications such as the SIR system, radiation exposure, procedure duration, procedure room time, anesthesia requirements, implant and cement use, and delayed adverse events. Adoption and maintenance metrics should include the number of referring departments and trained operators, follow-up completeness, sustained referral activity, registry participation, and workflow stability over time. Such registries would help quantify learning curves, compare workflows across centers, identify context-specific barriers, and support consensus guidelines. Future evaluations should also include economic endpoints, including implant and cement costs, anesthesia resources, patient throughput, delayed reinterventions, and potential cost offsets related to earlier mobilization or avoidance of open surgery in selected patients.

CONCLUSION

The implementation of an IGPO program extends well beyond procedural expertise. It requires alignment between clinical needs, organizational readiness, imaging and anesthesia resources, multidisciplinary collaboration, patient selection, radiation safety, adverse event monitoring, and quality improvement. The combined PRISM–RE-AIM framework presented in this review provides a structured approach that can be adapted to local institutional conditions. Drawing on selected experiences from France and Canada, this framework suggests that effective implementation depends on preparation, coordination, conservative initial case selection, prospective outcome monitoring, and iterative refinement. When these conditions are met, IGPO may be integrated into oncologic, metabolic, and selected trauma pathways as a minimally invasive option for skeletal stabilization in appropriately selected patients. By explicitly addressing the launching phase of an IGPO program, this review provides practical guidance for early organizational planning, workflow development, and quality monitoring in IR.

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