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Innovative Teaching of Pelvic Tumor Embolization in the Era of Precision Medicine: From Anatomical Variation Identification to AI-assisted Decision Making in Clinical Practice

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Abstract: Preoperative vascular embolization for pelvic tumors is a key technique to reduce intraoperative bleeding and improve tumor resection rates, but its teaching needs systematic improvement to address complex anatomy and operational risks. This article proposes an integrated teaching improvement plan of "3D anatomical reconstruction—multimodal imaging navigation—hierarchical technical training—intelligent feedback": Preoperative teaching: Build dynamic 3D vascular models based on CT/MRI fusion technology, combined with a graded case library of target blood vessels (grades I–III) and in vitro simulation experiments with embolization materials to strengthen the ability to identify anatomical variations and make material selection decisions; Intraoperative teaching: Establish standardized operating procedures through DSA real-time image-guided superselective catheterization (error ≤1 mm) and emergency response drills for complications (such as a 5-minute response to spinal artery misembolization), and integrate AI-assisted segmentation (U-Net algorithm) and ICG fluorescence navigation to improve operational accuracy; Postoperative teaching: Establish a quantitative evaluation system and MDT review mechanism, combined with a VR simulation platform and hierarchical certification (Junior NAE/Senior SAE) to achieve closed-loop skill management. The teaching support system introduces forward-looking courses on biodegradable embolization agents (PLGA drug-loaded microspheres) and robot-assisted technology. Through dynamic OSCE assessment and electronic file tracking, improve the technical success rate of students and reduce the complication rate. In the future, it is necessary to promote the construction of a multi-center teaching alliance to facilitate personalized teaching optimization based on real-world data.

Keywords: Pelvic tumor; Preoperative vascular embolization; Multimodal imaging; Hierarchical teaching; Intelligent navigation

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1. Preoperative teaching improvements

1.1. Integrated teaching of anatomy and pathophysiology

3D vascular network reconstruction teaching: Combining CT/MRI fusion technology (such as CTA 3D volume rendering, MIP reconstruction) to dynamically display anatomical variations of the internal iliac artery branches (obturator artery, superior and inferior gluteal arteries) and median sacral artery, focusing on analyzing vascular anomalies caused by tumor invasion (such as arteriovenous fistulas, tumor lake formation) [1].

Case library of tumor blood supply grading: Establish a case library of target vessel grading based on DSA dynamic imaging (grade I trunk, grade II tumor branch, grade III nourishing blood vessels), requiring students to identify embolization priorities through a simulation system, such as the selective embolization strategy for the S3/4 segment feeding artery in sacral chordoma [2].

1.2. Multimodal imaging decision training

Standardized process for image interpretation: Design a CTA/DSA joint interpretation course, emphasizing the screening value of CTA for arterial injuries ≥2mm (sensitivity 75.5%, specificity 97.3%), and comparing the limitations of DSA in detecting tiny blood vessels (<1 mm) [1]. Train students to select the optimal imaging tool based on tumor location (such as pelvic regions II+III).

Integration of functional imaging and embolization planning: Introduce PET-CT metabolic activity analysis to guide the amount of embolization agent (e.g., increasing PVA particle density in high metabolic areas) and combine MR spinal cord angiography to exclude dangerous anastomoses (such as spinal artery common trunks) [3–4].

1.3. Simulation scenarios for the selection of embolic materials

Comparative experiments on material properties: Demonstrate the permeability and stability of different embolic agents through in vitro vascular models, such as:

The mechanical blocking effect of PVA particles (50–1000μm) on grade II branches;

The capillary bed permeation advantage of Onyx glue in hypervascular metastatic tumors (embolization depth up to 5 cm);

The medium-term embolization characteristics of gelatin sponge in emergency NAE (recanalization in 7–21 days).

Risk-benefit decision training: Simulate non-target embolization scenarios (such as accidental embolization of the superior gluteal artery), requiring trainees to weigh the pros and cons of liquid embolic agents (higher tumor necrosis rate) and particulate embolic agents (lower risk of complications) based on tumor type (such as renal cancer metastasis) [5–6].

2. Intraoperative teaching improvements

2.1. Technical standardization under real-time image guidance

Layered teaching of super-selective catheterization:

Junior trainees: Master the positioning technique of microcatheters (such as 2.7F) in the anterior division of the internal iliac artery;

Senior trainees: Train super-selective skills for grade II branches such as the lateral sacral artery, requiring the catheter tip to be ≤1 cm from the tumor edge to avoid reflux.

Dynamic embolization endpoint determination: Analyze the degree of tumor staining resolution through real-time DSA imaging, with ≥70% as the technical success criterion, and verify the preservation of blood supply in non-target areas (such as the nutrient vessels of the sciatic nerve) through intraoperative CT perfusion.

2.2. Simulation of emergency treatment for complications

High-risk scenario drills: Design emergency situations such as accidental embolization of spinal arteries and gluteal muscle necrosis, requiring trainees to complete the following operations within 5 minutes:

Identify signs of non-target embolization (such as abnormal retention of contrast agent);

Initiate remedial measures (such as intra-arterial injection of papaverine to improve collateral circulation);

Jointly initiate an autologous blood transfusion system with the anesthesiology department (when the estimated blood loss is >1500 ml).

Multidisciplinary team (MDT) combat simulation: Set up a joint operation scenario involving surgery, interventional radiology, and imaging departments. For example, in the embolization of giant cell tumors of the sacrum, surgeons need to simultaneously plan the posterior approach resection range, while interventional radiology adjusts the embolization target to preserve the S1 nerve root blood supply [7].

2.3. Integration of new technologies into teaching

Practical operation of intelligent embolization planning system: Utilizing AI to assist in DSA image segmentation (such as the U-Net algorithm), real-time annotation of dangerous blood vessels (e.g., obturator nerve accompanying artery), reducing operation time by 30%.

Intraoperative fluorescence navigation technology: Demonstration of ICG fluorescence angiography combined with near-infrared imaging, dynamically monitoring the ischemic range of the tumor after embolization, and validating it through comparison with postoperative pathological specimens.

3. Postoperative teaching improvements

3.1. Efficacy analysis and complication management courses

Establishment of a quantitative evaluation system:

Stratified statistics of intraoperative blood loss: Comparing differences between the SAE group (1850±320 ml) and the NAE group (3100±580 ml);

Analysis of transfusion needs: Clinical indications for an average of 2.1 units of blood transfusion within one week after surgery (hemoglobin <7 g/dL or symptomatic anemia) [8].

Complication case database construction: Categorizing and organizing cases of non-target embolization (incidence rate of 7%), postoperative syndrome (incidence rate of fever/pain 15–28.6%), and developing tiered treatment plans (e.g., NSAIDs + fluid replacement vs. glucocorticoid pulse therapy).

3.2. Long-term follow-up and recurrence warning teaching

Identification of imaging recurrence markers: Through CTA/MRI follow-up courses, teaching trainees to identify the following high-risk signs:

Tumor edge enhancement (indicating residual lesions);

Formation of new vascular networks (common 6–12 months after embolization).

Integrated analysis of biomarkers: Combining postoperative pathology (such as Ki-67 index) with molecular detection (such as HIF-1α expression) to predict the degree of tumor necrosis and recurrence risk after embolization.

3.3. Multidisciplinary review and continuous improvement

MDT case discussion: Monthly organization of joint reviews involving interventional radiology, surgery, and pathology, focusing on the analysis of the following issues:

Technical defects in cases of incomplete embolization (such as untreated III-level nourishing vessels);

Deviations in surgical timing selection (surgical procedures performed >48 hours after gelatin sponge embolization leading to vascular recanalization).

Dynamic teaching database updates: Optimization of embolic agent selection and dose recommendations based on real-world data (such as hemoglobin gap to estimate blood loss).

4. Optimization of the teaching support system

4.1. Virtual reality (VR) simulation platform

Development of a pelvic vascular embolization VR training system to simulate complex scenarios (such as pelvic fractures with arterial injuries), requiring trainees to complete the entire process of CTA interpretation, embolization path planning, and complication management within 30 minutes.

4.2. Tiered training and certification system

Primary certification: Mastering NAE techniques and gelatin sponge applications;

Advanced certification: Proficient in SAE, Onyx glue embolization, and AI-assisted operations;

Assessment criteria include technical success rate (≥70% tumor staining resolution) and complication rate (<10%).

4.3. Integration of international cutting-edge technology into the curriculum

Offer a special topic on biodegradable embolic agents (such as PLGA drug-loaded microspheres), comparing the tumor necrosis rate and the synergistic effect of local chemotherapy with traditional materials;

Introduce intraoperative robot-assisted embolization technology, demonstrating high-precision catheter manipulation (with an error of ≤1 mm).

5. Teaching effectiveness evaluation and feedback

5.1. Objective structured clinical examination (OSCE)

Establish a 5-station assessment: image interpretation, embolization scheme design, complication management, MDT communication, and postoperative follow-up planning.

The scoring criteria refer to the SNO guidelines (for example, a 20% improvement in local control rate is considered excellent).

5.2. Dynamic teaching feedback system

Use electronic archives to track trainee operation data (such as the ratio of embolic agent usage to blood loss) to generate personalized capability radar charts;

Publish a teaching white paper every quarter, comparing the impact of different teaching methods on technical success rates.

6. Conclusion

The teaching of preoperative vascular embolization for pelvic tumors necessitates the establishment of a four-dimensional system encompassing “anatomy, imaging, technique, and management.” By utilizing virtual simulation, tiered certification, MDT collaboration, and the integration of intelligent technologies, a comprehensive upgrade of skills from theoretical knowledge to practical application can be achieved. In the future, a multi-center teaching alliance should be formed to facilitate dynamic curriculum optimization based on real-world data.

Disclosure statement

The authors declare no conflict of interest.

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