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AI CO-PILOT FOR INTERVENTIONAL RADIOLOGY: A CONCEPTUAL FRAMEWORK FOR ENHANCING WORKFLOW, SAFETY, AND EQUITY

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Abstract

Background:
Vascular and interventional radiology (VIR) procedures require high precision under fluoroscopic guidance, yet procedural inefficiencies persist due to anatomical complexity, navigation uncertainty, and operator-dependent variability.

Objective:
To review current applications of artificial intelligence (AI) in VIR and propose a conceptual framework for integrating AI across the procedural workflow.

Methods:
A structured narrative review was conducted using PubMed, Scopus, and IEEE Xplore databases (2018–2025). Keywords included "artificial intelligence," "interventional radiology," "embolization," "navigation," and "dose optimization." Studies focusing on AI applications in procedural planning, intra-procedural guidance, and outcome prediction were included.

Results:
Current AI applications are largely task-specific, including bile-duct segmentation, tumor feeder detection, and radiation dose optimization. However, these systems operate in isolation and lack integration into a unified procedural workflow.

Conclusion:
We propose a clinically adaptive AI framework integrating pre-procedural planning, intra-procedural navigation, and post-procedural optimization. Such systems have the potential to enhance procedural efficiency, reduce complications, and standardize outcomes in VIR.

INTRODUCTION:

Vascular and interventional radiology (VIR) procedures such as percutaneous transhepatic biliary drainage (PTBD), Trans-arterial chemoembolization (TACE) via variant mesenteric/hepatic branches, and other Embolization such as nasal, renal, gastrointestinal lesions require precise image-guided access under fluoroscopy. In routine practice, however, small anatomic uncertainties translate into real morbidity e.g. respiratory motion during PTBD can lead to pleural transgression with pneumothorax or hemothorax; superficially

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targeted ducts may traverse highly vascular hepatic tissue and produce hemobilia or arterioportal/arteriovenous fistula. In Central venoplasties of tightly stenosed segment, unrecognized right-atrial/IVC structures during wire manipulation can result in catheter-induced vascular dissection. Non-target embolization during TACE may cause bowel or cutaneous ischemia, Non-target nasal embolization can inadvertently occlude critical arterial supplies that communicate with the ophthalmic and cerebral circulation. While prolonged fluoroscopy and repeated angiographic runs increase the risk of radiation-related skin injury and contrast-induced nephropathy. [1-3]

Artificial intelligence (AI) tools already segment bile ducts, detect tumor feeders, and model radiation dose, but almost all operate as single-task solutions. What is missing is an integrated, procedure-aware AI assistant that links access planning, motion-robust navigation, embolization-risk prediction, and dose/contrast optimization across the entire VIR workflow.

METHODS:

This study presents a conceptual framework informed by a structured narrative review of existing literature and clinical workflow analysis in vascular and interventional radiology. A systematic search was conducted using PubMed, Scopus, and IEEE Xplore databases for studies published between 2018 and 2025. Search terms included "artificial intelligence," "interventional radiology," "embolization," "navigation," "dose optimization," and "image-guided interventions."

Studies were included if they described AI applications in procedural planning, intra-procedural decision support, vascular segmentation, or radiation optimization. Both clinical and technical studies were reviewed. Findings were synthesized to identify current limitations and inform the development of an integrated AI workflow model.

Proposed AI Framework for VIR Workflow Integration

We propose a conceptual, workflow-integrated artificial intelligence (AI) system designed to support vascular and interventional radiology procedures across three key stages:

1. Pre-Procedural Phase

- Deep learning–based segmentation of vascular and biliary anatomy from CT/MRI datasets
- Transformer-based models for detection of anatomical variants and high-risk zones
- AI-assisted procedural planning using predictive modeling for optimal access points and catheter pathways

2. Intra-Procedural Phase

- Real-time computer vision models applied to fluoroscopy for AI-enhanced overlays
- Reinforcement learning–assisted navigation for wire and catheter manipulation
- Predictive modeling of embolization territories using machine learning algorithms
- AI-driven optimization of radiation dose and contrast administration using adaptive models

3. Post-Procedural Phase

- Outcome prediction using supervised learning models based on procedural and patient data
- Complication risk stratification using predictive analytics
- Continuous learning system using feedback loops and model retraining to improve performance over time

This integrated framework moves beyond isolated AI tools and introduces a unified, adaptive system capable of supporting clinical decision-making throughout the interventional workflow.

Proposed AI System Architecture for VIR

The proposed framework is supported by a multi-modal artificial intelligence architecture integrating pre-procedural imaging (CT/MRI), intra-procedural fluoroscopy, and procedural metadata. Deep learning models, including convolutional neural networks (CNNs) and transformer-based architectures, are employed for automated segmentation of vascular and biliary

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anatomy, anomaly detection, and feature extraction.

For intra-procedural guidance, real-time image analysis is enabled through computer vision models applied to fluoroscopic sequences, allowing dynamic overlay of anatomical structures and risk zones. A reinforcement learning–based decision module may further optimize catheter and wire navigation by learning optimal pathways from historical procedural datasets.

Additionally, predictive models using supervised machine learning techniques can estimate embolization outcomes, complication risk, and procedural success probabilities. These components are integrated into a unified pipeline enabling continuous feedback, adaptive learning, and context-aware decision support throughout the intervention.

Table 1: Procedural Challenges, Current AI, and Visionary Opportunities

Procedural Challenge	Clinical Implication	Current AI Solutions (Published Evidence)	Visionary AI Opportunities / Future Direction
1. Unrecognized subtle biliary anatomy during PTC (e.g., non-dilated system, accessory ducts)	Blind puncture → hematoma, fistula formation, hemobilia	Deep-learning bile-duct segmentation and anomaly-detection models improve image guidance.[4]	Real-time puncture-safety overlay integrating patient-specific anatomy and risk zones
2. Cannulation difficulty in TACE via SMA branches	Complex arterial feeders → incomplete embolization or non-target ischemia or abandoned procedure	Automated tumor-feeder detection (AFD) using cone-beam CT improves feeder identification.[5]	AI suggesting optimal cannulation trajectory and predicting success probability for multiple feeders
3. Embolization planning for renal or gastrointestinal aneurysms	Risk of non-target embolization → ischemia	Machine-learning and simulation models assist in vascular-territory prediction.[6]	Fully integrated virtual-embolization simulation with real-time color-coded risk mapping
4. Cannulation error during nasal or sinonasal embolization	Non-target embolization of ophthalmic or cerebral arteries → vision loss, stroke, or facial necrosis	AI-based vascular segmentation using angiographic datasets can enhance recognition of dangerous anastomoses and collateral flow patterns.	AI-driven safety alert system that highlights high-risk vascular territories in real time, warning the operator before embolic injection.
5. Radiation and contrast-dose optimization	Operator-dependent variation → inconsistent patient risk	AI-driven dose-optimization frameworks personalize acquisition protocols.[7],[8]	AI calculating individualized contrast and radiation dose based on anthropometry, anatomy, and procedure duration

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Procedural Challenge	Clinical Implication	Current AI Solutions (Published Evidence)	Visionary AI Opportunities / Future Direction
6. Wire navigation in occluded venogram	Failure to cross occluded segment → prolonged procedure or plasty failure, dissection	AI-based vessel-tracking algorithms reconstruct the native-lumen pathway from pre-procedure imaging and support real-time navigation	AI reconstructing the native vessel pathway for the main occluded segment, enabling the radiologist to manipulate the wire precisely along the true lumen for successful plasty

Table 2: Current AI vs Proposed AI Co-Pilot Framework

Feature	Current AI Applications	Proposed AI Co-Pilot Framework
Scope	Task-specific (segmentation, detection)	End-to-end workflow integration
Workflow Coverage	Partial	Pre + Intra + Post procedural
Real-time Support	Limited	Continuous real-time guidance
Data Integration	Single-modality	Multi-modal (CT, MRI, Fluoro)
Decision Support	Isolated outputs	Context-aware recommendations
Adaptability	Static models	Continuous learning system
Clinical Impact	Incremental	Transformational

Evaluation and Validation Strategy

The proposed AI framework may be evaluated using both technical and clinical performance metrics. Technical evaluation includes segmentation accuracy (e.g., Dice similarity coefficient), navigation prediction accuracy, and real-time inference latency. Clinical evaluation may involve procedural success rate, fluoroscopy time reduction, radiation dose exposure, contrast volume usage, and complication rates such as non-target embolization.

Prospective validation in clinical settings would be required to assess safety, generalizability, and real-world impact. Integration with existing imaging systems and regulatory compliance will be essential for successful translation into practice.

Ethics statement:

This study is a narrative review and conceptual framework and does not involve human participants, patient data, or experimental interventions. Therefore, ethical approval and informed consent were not required in accordance with institutional and international guidelines. No identifiable human data were used, and all concepts presented are based on previously published literature and hypothetical models.

Use of artificial intelligence (AI):

The authors used artificial intelligence tools (e.g., ChatGPT) to assist in language editing and manuscript structuring. All content was critically reviewed, verified, and approved by the authors, who take full responsibility for the integrity and accuracy of the work.

DISCUSSION:

Current artificial intelligence (AI) applications in vascular and interventional radiology (VIR) primarily address isolated components of the procedural workflow, such as tumor-feeder detection (5) and radiation dose modeling (7, 8). While these advancements demonstrate clear clinical utility, they remain functionally siloed and do not provide integrated support across the continuum of interventional procedures. This fragmentation limits the full potential of AI in enhancing procedural efficiency, safety, and decision-making.

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A more impactful approach would involve the development of a unified, procedure-aware AI platform capable of integrating pre-procedural planning, intra-procedural navigation, embolization simulation (6), and real-time dose optimization into a cohesive system. Such a platform could leverage multi-modal imaging data and continuously adapt to procedural dynamics, thereby providing context-sensitive guidance to the operator.

In this framework, AI could assist in recommending optimal catheter selection and navigation strategies based on three-dimensional angiographic analysis (5), while simultaneously predicting embolization outcomes and delineating vascular territories to minimize the risk of non-target ischemia (6). Furthermore, dynamic optimization of radiation and contrast parameters during live imaging could standardize procedural safety and reduce operator-dependent variability (7, 8). Importantly, continuous learning from accumulated procedural data would allow such systems to refine predictive accuracy over time and provide enhanced decision support, particularly for less experienced operators.

From a technical perspective, the integration of deep learning, computer vision, and reinforcement learning within a unified framework represents a shift from task-specific AI tools toward intelligent, workflow-aware systems. Multi-modal data fusion and real-time inference capabilities are critical for enabling seamless interaction between AI systems and interventional radiologists, ensuring that decision support is both timely and clinically relevant.

Despite these promising prospects, several barriers hinder clinical translation, including the need for robust validation across diverse patient populations, integration with existing imaging and procedural platforms, and compliance with regulatory frameworks governing AI-based medical technologies. Addressing these challenges will require close collaboration between clinicians, engineers, and industry stakeholders to ensure that AI systems are not only technically robust but also clinically practical and ethically sound.

LIMITATION:

This study presents a conceptual framework based on a structured narrative review and does not include experimental validation or prospective clinical data. The proposed system architecture has not been implemented or tested in real-world settings, and its performance remains theoretical.

Additionally, the integration of multi-modal data, real-time processing requirements, and interoperability with existing imaging systems pose significant technical challenges. The availability of large, annotated datasets required for training robust AI models may also limit scalability, particularly in resource-constrained settings.

Regulatory approval, ethical considerations, and user acceptance represent further barriers to clinical translation. Future studies should focus on prototype development, prospective validation, and assessment of clinical impact in diverse healthcare environments.

CONCLUSION:

Artificial intelligence has demonstrated significant value in image analysis, radiation optimization, and procedural planning within vascular and interventional radiology. However, current applications remain fragmented and limited in scope. The proposed workflow-integrated AI co-pilot framework represents a shift toward comprehensive, real-time decision support across the entire procedural continuum.

By bridging planning, execution, and outcome optimization, such systems have the potential to enhance procedural efficiency, improve patient safety, and standardize outcomes. Further research focusing on validation, implementation, and clinical integration is required to translate this concept into practice.

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