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APPLICATION AND PROGRESS OF CT ANGIOGRAPHY–X-RAY IMAGE FUSION TECHNOLOGY IN ENDOVASCULAR SURGERY: A LITERATURE REVIEW

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Abstract: CT Angiography (CTA)-X-ray image fusion technology has seen significant advancements in recent years, offering a more precise and efficient imaging solution for endovascular interventions in vascular diseases. By integrating preoperative CTA images with intraoperative X-ray fluoroscopy, this technology enables dynamic visualization of vascular structures and interventional devices, allowing clinicians to perform complex procedures with greater accuracy. Compared with conventional imaging techniques, CTA-X-ray image fusion reduces reliance on contrast agents, minimizes radiation exposure, and shortens operative duration. This paper systematically introduces the definition, principles, and procedural workflow of this technology, outlining its key technical developments and clinical applications. The ability to provide real-time guidance for interventional procedures enhances the accuracy of device deployment, particularly in complex vascular anatomies. Furthermore, its application has expanded across various vascular interventions, demonstrating significant potential in improving surgical outcomes. As the technology continues to evolve, its role in endovascular therapy is expected to become increasingly prominent, contributing to more precise and safer interventional strategies.

Keywords: Image fusion; Endovascular intervention; Multimodal imaging; CT angiography; X-ray

1 INTRODUCTION

The rapid advancement of endovascular therapeutic techniques has enabled interventions for increasingly complex vascular diseases. The management of such conditions relies heavily on radiologic imaging, with preoperative and postoperative computed tomography angiography (CTA) and intraoperative fluoroscopic imaging serving as fundamental modalities in vascular assessment. CTA provides high-resolution imaging of vascular anatomy across the entire body, allowing for comprehensive evaluation of vascular lesions and their spatial relationship with surrounding structures. This detailed visualization facilitates meticulous preoperative planning and long-term monitoring. Intraoperative fluoroscopy, in contrast, offers real-time tracking of interventional device progression, providing essential procedural guidance for endovascular interventions.

Despite their advantages, both imaging techniques have inherent limitations. CTA generates static images that, while crucial for surgical planning, lack real-time procedural guidance. Conversely, X-ray fluoroscopy delivers real-time imaging but is inadequate for visualizing soft tissue characteristics such as vessel morphology, tortuosity, calcifications, and lesion dimensions, making it challenging for clinicians to precisely determine vascular spatial positioning. Additionally, alternative imaging modalities, including magnetic resonance imaging (MRI), magnetic resonance angiography (MRA), and three-dimensional digital subtraction angiography (3D-DSA), also suffer from constraints in real-time vascular visualization and accurate localization of interventional devices, limiting their utility in guiding endovascular procedures [1-4].

To address these challenges, CTA-X-ray image fusion technology has been proposed. This technique integrates the high -resolution preoperative imaging of CTA with the real-time intraoperative capabilities of X-ray fluoroscopy, enabling continuous visualization of vascular structures and interventional devices throughout the procedure. By enhancing procedural precision, this technology facilitates accurate stent deployment, reduces contrast agent usage, shortens operative time, and optimizes surgical accuracy. The integration of static and dynamic imaging offers a significant advancement in procedural safety and efficiency for complex endovascular interventions. The following sections provide a comprehensive review of the clinical applications and recent developments of CTA real-time X-ray image fusion in vascular disease diagnosis and treatment.

2 DEFINITION AND PRINCIPLES OF CTA-X-RAY IMAGE FUSION

CTA-X-ray image fusion is a technique that integrates three-dimensional (3D) reconstructions of computed tomography angiography (CTA) data with intraoperative X-ray fluoroscopic imaging during endovascular interventions. This process involves image registration, alignment, and fusion to generate a composite image that dynamically synchronizes reconstructed vascular structures with real-time fluoroscopic views. By superimposing the 3D vascular reconstruction from CTA onto live X-ray fluoroscopy, clinicians can more accurately determine the spatial relationships between interventional instruments and vascular anatomy throughout the procedure [1,5-7].

The core principle of image fusion is based on the alignment of features that are simultaneously visible in both the CTA 3D reconstruction and the X-ray fluoroscopic image. These reference points may include anatomical structures, such as bones, or artificially introduced markers, such as radiopaque fiducials. By registering these features, the fused image preserves critical spatial information, including vascular position, geometry, and its relationship with surrounding tissues. This enhanced visualization facilitates more precise interventional guidance, improving procedural accuracy while reducing contrast medium usage and operative duration [8-11].

3 IMPLEMENTATION STEPS OF CTA-X-RAY IMAGE FUSION

The process of CTA-X-ray image fusion can be broadly categorized into two critical steps: image segmentation and image alignment and fusion. Among these, the accuracy of image alignment is pivotal to the success of the fusion process, as it directly determines the effectiveness and reliability of the fused image.

3.1 Image Segmentation

Image segmentation is a fundamental problem in image processing and analysis, aimed at partitioning an image into distinct regions that are mutually exclusive and internally homogeneous. Each segmented region represents a meaningful component of the image, adhering to specific criteria for consistency. Segmentation forms the basis for subsequent 3D reconstruction, with its accuracy directly influencing the precision of the final reconstructed model [5].
In the realm of medical imaging, segmentation techniques are primarily categorized into traditional methods relying on digital image processing and modern approaches based on deep learning algorithms [12]. Software tools such as Mimics, 3D Slicer, Simpleware, and Amira facilitate rapid segmentation and 3D reconstruction of medical images, aiding clinicians in extracting regions of interest (e.g., diseased tissues, vascular structures) [13]. By providing a clearer understanding of the anatomical features, segmentation plays a critical role in enhancing surgical precision, offering valuable guidance for interventional procedures.

3.2 Image Alignment and Fusion

Image alignment refers to the process of identifying a spatial configuration in which corresponding points from two distinct images coincide precisely, ensuring agreement in both anatomical structure and spatial location. The objective is to achieve congruence across all anatomical points of interest, or at least those relevant to diagnostic and surgical considerations, in both images [14,15].
In recent years, numerous methods for image alignment have been proposed, including the alignment of geometric moments, polynomial transformations such as correlation coefficients and spline interpolation, as well as mutual-information-based techniques aimed at enhancing the accuracy of three-dimensional alignment and fusion. Although the refinement of alignment accuracy remains a central challenge, the pursuit of fully automated, human-independent methods may not always be practical, as it often complicates the algorithmic process and increases computational time. A more feasible approach is to combine human-computer interaction to expedite alignment processes. Current image fusion technologies typically rely on image correlation coefficients, supplemented by manual calibration, to achieve accurate alignment [5].
Medical imaging provides crucial structural data, which, when combined through image fusion, enables comprehensive spatial analysis. Fusion of multimodal images, such as CTA 3D reconstructions and X-ray fluoroscopic images, offers precise localization, size, and geometry of anatomical structures (e.g., blood vessels), as well as their spatial relationships with surrounding tissues, thereby facilitating more efficient surgical planning and execution [16-18].

4 CLINICAL APPLICATIONS OF CTA-X-RAY IMAGE FUSION

CTA-X-ray image fusion technology offers substantial advantages in endovascular interventions, particularly for complex and anatomically challenging procedures. By enhancing visualization and spatial localization, image fusion significantly reduces surgical complexity and procedural difficulty. The following sections will explore the diverse clinical applications of CTA-X-ray image fusion across various interventional scenarios [7].

4.1 CTA-X-ray Image Fusion in Aortic Diseases

CTA-X-ray image fusion technology plays a critical role in endovascular repair of aortic diseases, offering significant advantages in reducing contrast agent usage, shortening procedure time, and enhancing surgical precision. In the treatment of abdominal aortic lesions involving visceral branches, conventional approaches require repeated imaging to confirm whether the placement of a stent or balloon affects key branches such as the renal artery, celiac trunk, or superior mesenteric artery. By contrast, CTA-X-ray image fusion enables clinicians to preoperatively mark branch openings that may be impacted by the stent, allowing for intuitive visualization of vascular morphology and branch locations. This reduces the need for repeated imaging, improves the accuracy of stent deployment, and ultimately enhances procedural efficiency while minimizing contrast exposure [6,19-30].
In endovascular repair of aortic arch lesions, a primary concern is the potential impact of interventional devices on the three major branches of the aortic arch—the brachiocephalic trunk, left common carotid artery, and left subclavian

artery—where inadvertent coverage could lead to severe complications. To mitigate these risks, techniques such as windowing and chimney stenting have been introduced; however, they still necessitate multiple imaging confirmations. CTA-X-ray image fusion technology provides real-time intraoperative visualization of the spatial relationship between interventional devices and the three major aortic arch branches, facilitating more precise device placement while reducing contrast agent use and procedure duration [31-35].

Overall, CTA-X-ray image fusion technology holds significant clinical value in the endovascular repair of complex aortic lesions. By integrating preoperative vascular mapping with intraoperative image overlay, this technique enables more accurate device placement, reduces reliance on traditional contrast-based confirmation, and enhances both the safety and efficiency of the procedure.

4.2 CTA-X-ray Image Fusion in Cardiac Diseases

In vascular endoluminal interventions involving valve replacement, precise anatomical localization is critical. For example, in transcatheter aortic valve replacement (TAVR), clinicians must accurately identify the axial positions of the left coronary sinus, right coronary sinus, and non-coronary sinus, as well as measure the diameter of the sinus orifice/annulus, the width of the aortic root, and the distance from the sinus floor to the left and right coronary arteries. Additionally, precise localization of the aortic valve is essential to ensure that the prosthetic valve displaces the diseased native valve while maintaining unobstructed flow through the coronary arteries. Beyond preoperative measurement accuracy, real-time intraoperative visualization of valve positioning and deployment is crucial for procedural success [36].

Currently, X-ray fluoroscopy remains the primary imaging modality used intraoperatively; however, its ability to provide detailed anatomical assessment is limited. CTA-X-ray image fusion technology enhances intraoperative guidance by integrating preoperative measurements into the live imaging environment. Clinicians can annotate preoperative assessments directly onto the image in the form of circular markers, allowing for intuitive real-time verification of prosthetic valve positioning. This approach reduces procedural complexity, shortens operative duration, and improves overall surgical success rates by facilitating more precise deployment of the prosthetic valve.

4.3 CTA-X-ray Image Fusion in Tumors

CTA-X-ray image fusion technology also holds significant clinical value in tumor interventional procedures. In the case of liver cancer, this technology enables precise preoperative localization and selection of tumor-feeding vessels, facilitating optimal interventional path planning. During the procedure, real-time fusion imaging provides accurate intraoperative guidance, allowing clinicians to efficiently identify and navigate to the target vessels for embolization. This approach enhances the precision of tumor interventions while significantly reducing procedural duration, improving both treatment efficacy and surgical efficiency [37,38].

5 DEVELOPMENT OF CTA-X-RAY IMAGE FUSION

CTA-X-ray image fusion technology has been widely adopted in vascular endoluminal interventions, offering enhanced visualization and procedural precision. Originally developed for geological analysis, image fusion techniques have been progressively integrated into vascular interventions with advancements in medical imaging [39]. While conventional angiographic contrast agents provide essential intraoperative imaging, their use is associated with potential risks to both patients and clinicians. To mitigate these challenges, CTA-X-ray image fusion has emerged as a viable alternative, aiming to minimize contrast agent usage while improving procedural accuracy and efficiency.

With the rapid evolution of image fusion technology, two primary system types have been developed. Hybrid operating room (OR)-based fusion systems, such as Siemens ARTIS icono, Philips VesselNavigator, and GE Allia IGS 7, are designed for seamless integration into specialized surgical environments. In contrast, flexible, OR-compatible systems, such as Cydar Imaging Guidance and THERENVA's Endonaut, offer deployment versatility across various clinical settings [1,40].

The Siemens ARTIS icono system enhances intraoperative guidance by processing and aligning CTA datasets in real time, enabling precise localization of the aortic vessel wall and branch vessels, thereby optimizing stent placement and reducing contrast media dependency. The Philips VesselNavigator system incorporates automated vessel segmentation and 3D modeling, overlaying real-time intraoperative X-ray fluoroscopy to streamline procedures and minimize contrast agent use. GE's Allia IGS 7 system features personalized user interfaces and real-time dose optimization, simplifying workflows while reducing radiation exposure. Meanwhile, Cydar Imaging Guidance and the Endonaut system leverage deep learning algorithms to generate and dynamically update 3D vascular pathways, offering real-time navigation that further improves surgical accuracy while reducing reliance on contrast agents [41,42].

Overall, image fusion technology represents a major advancement in vascular endoluminal interventions, significantly reducing contrast agent use, lowering radiation exposure, and enhancing procedural planning and execution. As these innovations continue to refine interventional techniques, image fusion is poised to transform traditional surgical approaches, improving both the safety and efficiency of endovascular procedures.

6 LIMITATIONS OF CTA-X-RAY IMAGE FUSION

Despite its clinical advantages, current CTA- X-ray image fusion technology has several limitations. Firstly, existing systems do not achieve fully dynamic real-time fusion, where the X-ray fluoroscopic image can automatically integrate with the corresponding CTA 3D reconstruction model at any angle and orientation. Instead, current techniques rely on preoperative planning, selecting optimal imaging angles for endovascular interventions. The fusion process is performed in advance using positional parameters obtained from imaging equipment, ensuring that clinicians have pre-prepared fused images for various procedural angles. Consequently, these systems do not offer true real-time fusion but rather rely on precomputed image overlays.

Secondly, most image fusion software requires access to positional parameters from imaging hardware, which are often proprietary and restricted by device manufacturers. As a result, many existing fusion technologies are dependent on specific company hardware and cannot function universally across different imaging platforms. This lack of interoperability limits their broader adoption in clinical practice.

Finally, the accuracy of CTA-X-ray image fusion remains a challenge, influenced by three primary factors. The first is vascular displacement due to respiratory motion. CTA data are typically acquired during breath-hold inspiration, which does not reflect the continuous low-tidal volume ventilation commonly used in general anesthesia. Studies have reported respiration-induced vascular misalignment, particularly at the level of the aortic arch and distal visceral branches. The second factor is vessel deformation caused by interventional devices. The introduction of stiff or rigid instruments into tortuous vessels, such as the iliac arteries or the distal horizontal segment of the descending aorta, can result in vessel straightening and anatomical distortion. As diagnostic CTA captures vessels in their natural state, such alterations introduce alignment discrepancies. The third factor is patient movement, which can further displace vascular structures. Manual calibration is necessary to correct misalignments when clinicians detect such discrepancies intraoperatively [34].

A study assessing the accuracy of fusion imaging during endovascular aortic repair (EVAR) reported an average misalignment error of 2 ± 2.5 mm (range: 0–7 mm) at the renal artery origin and 0.80 ± 1.66 mm (range: 0–5 mm) at the iliac bifurcation, highlighting the need for further refinement in fusion accuracy [43].

7 FUTURE TRENDS IN CTA-X-RAY IMAGE FUSION

The future development of CTA-X-ray image fusion should aim for a more real-time, widely applicable, and highly accurate system. Achieving this goal requires the integration of artificial intelligence (AI) with medical imaging technologies, particularly through deep learning approaches. AI-driven algorithms can enable automatic recognition of vascular and bony structures in CTA 3D reconstructions and X-ray fluoroscopic images, allowing for automated alignment and fusion without the need for preoperative manual adjustments. This advancement would enable true real-time image fusion, eliminating the dependence on precomputed overlays. Furthermore, deep learning-based AI can enhance alignment accuracy while reducing reliance on proprietary image localization parameters from different imaging devices. The ultimate objective of machine learning in this context is to allow systems to autonomously identify anatomical structures based on large-scale datasets, thereby facilitating broader adoption of image fusion technologies. Notably, companies such as CYDAR Medical (Cambridge, UK) and Endonaut (Rennes, France) have already made significant strides in developing hardware-independent image fusion systems, though further improvements are necessary to enhance their clinical utility [40,44-46].

Additionally, improving the accuracy of CTA-X-ray image fusion remains a critical challenge. Current misalignment errors primarily arise from respiratory motion and vascular deformation induced by rigid interventional devices. Respiration-related vascular discrepancies are most pronounced at the distal segments of the aortic arch and visceral branches, whereas rigid devices can cause significant vessel straightening, particularly in tortuous iliac arteries and the distal horizontal segment of the descending aorta. However, as long as the origin of the target vessel remains stable, these factors do not fundamentally limit the use of CTA-X-ray image fusion for procedural navigation. Future research on fusion accuracy should, therefore, prioritize optimizing alignment precision at the vessel origin to further enhance the reliability and applicability of this technology [2-3,34].

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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