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Review

Subtraction Computed Tomographic Angiography and Ultra-high-resolution Computed Tomography: New Era of Vascular Imaging

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Computed tomographic angiography (CTA) is a widely used noninvasive imaging technique for visualizing and evaluating vascular diseases. For global anatomical evaluation of vascular diseases, CTA is superior to conventional catheter angiography because of its unlimited angulation in image projection. However, arterial calcification and/or vascular implants such as metallic stents could hinder the evaluation of lesions inside. Additionally, the spatial resolution of CT is not small enough to evaluate peripheral vascular structures. Recent technical developments in CT allowed several new image processing techniques. The areas of technical developments are image subtraction and/or energy subtraction, which are used to detect fine luminal images. Another area of technical development is ultra-high-resolution CT, which has four times finer in-plane spatial resolution than conventional CT. There are other developments in image quality improvement and/or radiation dose reduction. Thus, new techniques and environments of CT allow finer vascular and structural imaging without invasiveness. In this review, the details of these techniques are described, and future insights are discussed.

Keywords: CT, computed tomographic angiography (CTA), subtraction, ultra-high-resolution CT, energy subtraction

1. Introduction

CT is a widely used imaging modality for vascular imaging[1]. Essentially, CT images have fine objective details and reproducibility. Vascular steno-occlusive diseases are mostly based on arteriosclerosis, and vessel wall degeneration, which forms atheromatous plaque or wall calcification, causes luminal stenosis and organ ischemia. Direct luminal imaging is important in determining lesion severity and in developing a treatment strategy. However, typical radiopaque structures such as severe calcification and metallic implants could hinder luminal imaging.

Subtraction CT technique or imaging by ultra-high-resolution CT could be used to overcome the current limitations of CT imaging by uncovering the information in the datasets[2]. In this review, we aimed to clarify the difference between image subtraction and energy subtraction and to discuss the utility of ultra-high-resolution CT for vascular steno-occlusive diseases.

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2. Basic characteristics of current CT

The spatial resolution of current CT is at most 0.5 mm[3, 4], and its temporal resolution is 0.275 sec[5]. Improvements in spatial and temporal resolution are in parallel with the history of CT. The number of detector rows has also increased in the history of CT evolution. Currently, the number of detector rows in a general CT is ≥ 64.

The typical tube voltage is 120 kVp. For recent scanners, variable tube current is an essential choice. The traditional image reconstruction method of CT is filtered back-projection. Recently, the iterative reconstruction technique has been introduced for image reconstruction[6, 7].

3. Recent development in CT

3.1. Increased number of detector rows

Increasing the number of detector rows and improving the temporal resolution shorten scan time and enable a wide coverage of scanning. As a result, the quality of diagnostic images has improved; however, radiation exposure has also increased due to inadvertent application of CT and expansion of the scan range.

3.2. Iterative reconstruction

Iterative reconstruction is a type of model-based image reconstruction that uses mathematical (statistical) approximation of the image signal by repetition of data calculation. Reduction of image noise with iterative reconstruction contributes to the improvement of image quality[8–10]. With maintaining the same image quality between images reconstructed by traditional filtered back-projection and by iterative reconstruction, reduction of radiation dose is achievable with the iterative reconstruction technique.

3.3. Dual-energy imaging

Dual-energy imaging is a technique used to distinguish materials by detecting their difference in energy spectral absorption of X-ray[11, 12]. This difference can be calculated from two datasets that have different energy spectra. Typically, dual-energy imaging is used for distinguishing materials. It is possible to create different energy spectra of X-rays by changing the tube voltage.

For dual-energy imaging, there are three different systems:

- The traditional system is dual-source CT[13–15]. Dual-source CT has two image acquisition units set up in right angle. Each unit has an X-ray tube. To obtain dual-energy images, each unit has a different tube voltage. With dual-source CT, the helical data acquisition orbit of two datasets has a 90° deviation. This deviation results in a misregistration artifact.
- Another system is CT with fast kilovolt (kV) switching with single X-ray tube[16, 17]. A fast kV-switching system can minimize the difference between the helical data acquisition orbits of two datasets. However, the number of photon signals in each dataset is half of that obtained by conventional single scan. Reduction in photon signals can affect image quality.
- Another system is CT with dual-layer detector[18, 19]. With this detector, the spectrum of X-ray through the first detector layer will change. Therefore, datasets obtained in the first and second layers have different spectra of X-ray. With this system, reduction of photon signals in each detector layer can occur, but there is no deviation of the data acquisition orbit.

4. Subtraction CT imaging

4.1. Essentials of image subtraction

Image subtraction techniques such as digital subtraction angiography are widely used[2, 20–26]. The basic imaging concept of image subtraction is to obtain pixels or voxels with enhanced contrast and eliminate background structures without contrast enhancement. Subtraction methods are important, especially in vascular imaging, as they can show vascular lumens with enhanced contrast.

One of the major causes of vascular disease is arteriosclerosis. Arteriosclerosis, including atherosclerosis, is a degenerative disease of the blood vessel wall[27]. Arteriosclerotic plaque narrows the lumen of arteries and blocks blood flow to distant organs, causing organ ischemia. Thus, while detection of luminal stenosis is an essential diagnostic imaging atherosclerotic plaques often contain calcifications, which interferes with the visualization of the arterial lumen. Calcified plaque is not enhanced because calcification usually does not involve blood vessels. The subtraction technique effectively removes the calcified plaque, and the arterial lumen can be better visualized (Fig. 1).

4.2. Side effect of image subtraction

Because two datasets such as pre- and post-contrast image are used, anatomical inconsistencies due to patient movement between the two datasets can result in a misregistration artifact. To minimize the occurrence of a misregistration artifact, it is important to reduce patient movement and minimize the time between data acquisition of the two datasets. However, to obtain sufficient contrast enhancement, a certain interval is required between the administration of the contrast agent and the scanning of the contrast-enhanced image, which depends on the blood flow velocity of the patient.

Controlling patient movement with external fixation is another way to reduce misregistration artifact. Patient

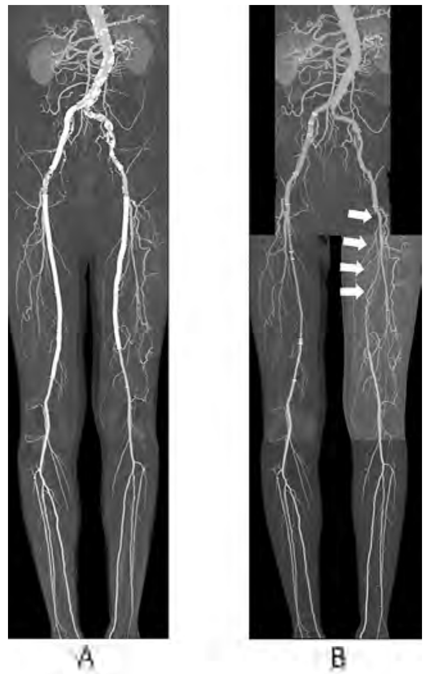

Fig. 1. Subtraction CTA for peripheral arterial occlusive disease. The maximum intensity projection (MIP) image of conventional CTA shows heavily calcified arteries and implanted metallic stents; however, the lesions inside are not visible (A). The MIP image of subtraction CT shows patent arteries of the right side and occluded left superficial femoral artery (arrow) (B).

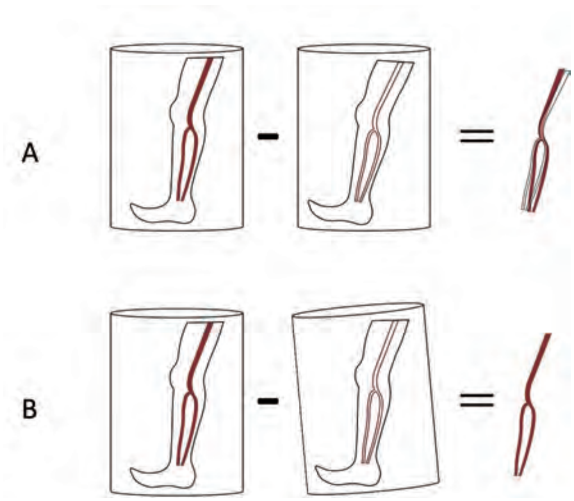

Fig. 2. Subtraction technique with rigid position matching. Simple volume subtraction of the datasets (cylinders) leads to a misregistration artifact (A). However, if the structural data inside the datasets were simply displaced, rigid position matching eliminates the misregistration artifact (B).

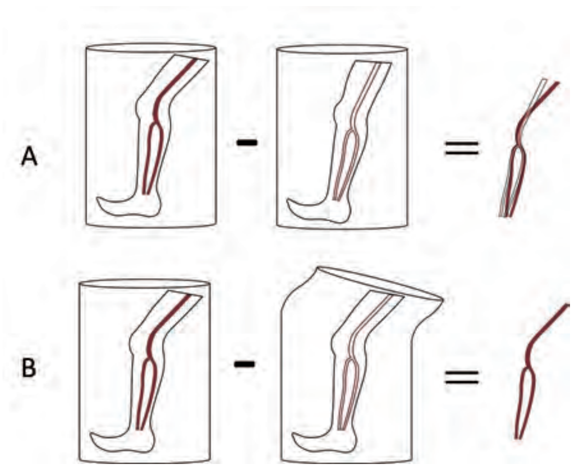

Fig. 3. Subtraction technique with nonrigid position matching. During the CT scanning, the anatomical structure can be distorted. Simple subtraction leads to misregistration (A). Nonrigid position matching technique coincides the structures and no misregistration will occur.

fixation systems, used primarily for patient fixation in radiation therapy, are devices that serve this purpose.

4.3. Supportive imaging technique for image subtraction

Despite some physical methods, the anatomical mismatch between the two datasets remains. Several postprocessing methods have been developed to minimize anatomical mismatches and reduce artifacts.

Rigid or nonrigid registration of image data is used to minimize anatomical mismatches[28] (Figs. 2 and 3). If image data acquisition is performed in a single rotation of the gantry, there is almost no misregistration artifact of the image dataset and precise alignment is possible. However, when image data acquisition is performed in multiple gantry rotations, nonrigid registration is used to compensate for deviations, as patient movement during data acquisition can cause irregular deviations of the structural organ position in the image dataset. Using such registration technology, accurate subtraction can be achieved (Fig. 3).

4.4. Essential of energy subtraction

The X-ray energy absorption of the material is different and unique. Although ordinary X-ray detectors can measure the intensity of X-rays, they cannot analyze the energy distribution. If a material is imaged twice or more using X-rays with different energy distributions, the energy absorption characteristics of the material can be analyzed from the difference in X-ray intensities[29]. Energy subtraction imaging can distinguish materials that are only recognized as high absorbers on a single x-ray. The identification of calcified and contrasted vessel lumens is the basis of dual-energy subtraction in CTA.

4.5. Side effect of energy subtraction

Since there is no single human tissue composed of a single material with the same density and the composition and concentration of substances vary, it is sometimes difficult to clearly characterize human tissues based on their energy distribution. Therefore, even energy subtraction can produce false images. Additionally, since the number of photons in each data is small, it may be difficult to depict detailed structures due to deterioration of image quality[30].

4.6. Supportive analyzing technique for energy subtraction

The disadvantage of dual-energy imaging is the small number of photons in each spectral data. Therefore, simple energy subtraction is not sufficient for detailed structural investigations. Several additional techniques are used to improve the image quality of dual-energy imaging.

Fusion imaging of subtracted energy images and conventional CT images is one of the options for better tissue analysis[31, 32]. Conventional CT images can be reconstructed from the entire data obtained by dual-energy imaging. Because the entire volume data are merged from different energy data, the image signal in the data increases, but the spectral information is lost. The fusion image adds spectral information to this conventional image reconstructed from the merged data. This technique is useful for detecting typical tumors, such as PET-CT; however, it is not suitable for luminal imaging, such as angiography, because high-density structures such as calcification and metallic stent remain.

4.7. Negative tradeoff of the subtraction technique

As we have already shown, image quality degradation due to subtraction is one of the drawbacks, but image quality can be maintained by recent improvements in image reconstruction technique, such as iterative reconstruction, and the environment in which subtraction technology can be used has expanded. Meanwhile, problems unique to subtraction, such as misregistration artifacts, have not been completely solved yet, and postprocessing is complicated and time-consuming.

Although increase in exposure has been cited as one of the problems[22], it is possible to obtain subtraction images with the same level of exposure, or even lower, than that of conventional CT[33, 34] by using the successive approximation reconstruction method.

5. Ultra-high-resolution CT

Ultra-high-resolution CT has two times higher spatial resolution in one axis than conventional CT. Therefore, its data size is 8 times bigger than that of conventional CT. The typical voxel length on each side is 0.25 mm. The image matrix size can be selected in conventional 512 × 512, 1,024 × 1,024, and 2,048 × 2,048 matrices. To obtain fine spatial resolution, the focus size of the X-ray tube is also improved by decreasing it to as small as 0.4 × 0.5 mm[2].

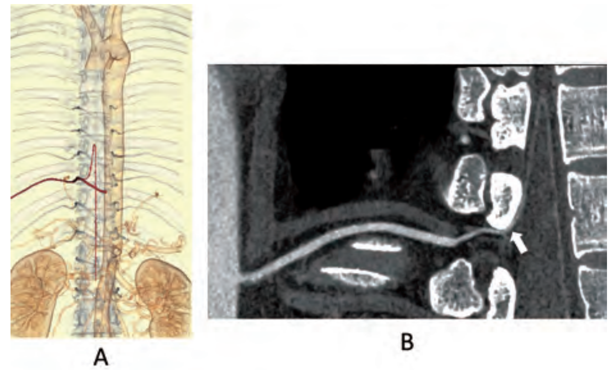

Fig. 4. Ultra-high-resolution CT of the artery of Adamkiewicz. The volume rendering image by ultra-high-resolution CT shows the artery of Adamkiewicz in detail (A). Curved planar reformation shows the fine continuation from the intercostal artery to the artery of Adamkiewicz (B).

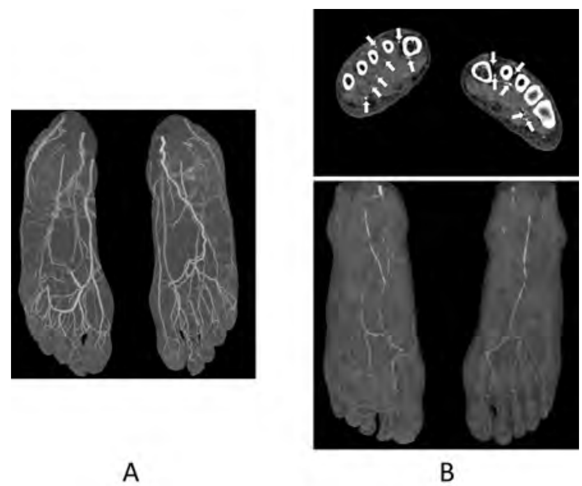

Fig. 5. Ultra-high-resolution CT of the digital artery of the foot. The maximum intensity projection (MIP) image without arterial stenosis of the feet shows fine visualization of the digital arteries and pedal arch (A). Axial plain CT image of the feet of a patient undergoing hemodialysis shows severely calcified digital arteries (B, top). The MIP image of this patient shows multiple stenosis or occlusion of the pedal arch and digital arteries (B, bottom).

To maintain image quality, the gantry rotation time is limited to 0.35 sec and its temporal resolution is lower than that of other cutting-edge CT; furthermore, radiation exposure slightly higher than that of conventional CT was required at initial ultra-high-resolution CT to achieve fine image quality. However, a recent update on the image reconstruction technique succeeded to maintain image quality with less radiation exposure. Currently, ultra-high-resolution CT has the potential of conventional use in daily practice.

For vascular diseases, ultra-high-resolution CT has great potential to improve the visualization of small vessels such as the artery of Adamkiewicz (Fig. 4), collateral pathways[35], and digital arteries[2]. In combination with the subtraction technique, ultra-high-resolution CT enables detailed evaluation in such small arteries despite severe calcifications (Fig. 5). These small arteries are important structures for planning strategies of invasive treatment and predicting outcome of organ ischemia.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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