A newly developed technique involving the optimization of flow velocity compensation for lower extremity CT angiography

ZHANG Lei[1*], XU Dong[1], LI KunCheng[2], JIN ErHu[3] & BARNES Bret[4]

[1] *Department of Cardiology, Capital Medical College Affiliated Beijing Xuanwu Hospital, Beijing 100053, China;*

[2] *Department of Radiology, Capital Medical College Affiliated Beijing Xuanwu Hospital, Beijing 100053, China;*

[3] *Department of Radiology, Capital Medical College Affiliated Beijing Friendship Hospital, Beijing 100069, China;*

[4] *Department of Radiology, Medical College of Wisconsin, 9200 W Wisconsin Ave, Milwaukee, WI 53226, USA*

Advanced computed tomography (CT) technology has allowed for faster and more robust imaging. However, it has been a technical challenge to correctly synchronize CT acquisition with adequate and uniform arterial enhancement in the entire peripheral arterial tree. In this summary, we introduce a method of injection/acquisition optimization strategy based on a velocity-compensated CT angiography technique for the peripheral artery system, which is currently used in the United States. We believe that this imaging technique will provide additional information for our daily CT services in China.

CT angiography, lower extremity artery disease, acquisition speed, test-bolus, bolus-tracking

Multidetector computed tomography (MDCT) was first introduced in 1998 [1–3] and represents a breakthrough in computed tomography (CT) technology. Compared with single-detector spiral CT, MDCT is more advanced in detector design, with increasing numbers of detector rows; this enables the scanning speed to be increased exponentially [3]. Currently, 64-detector row CT with faster scanning involving a gantry rotation time of 0.33 s [4], an increased beam width of 40 mm [4] and a thinner slice width detector configuration of 0.5 mm [4], has allowed wide-area coverage in combination with submillimeter isotropic spatial resolution and rapid acquisition. Significant advances in MDCT technology, along with powerful 3D volumetric data analysis and display, now offer new opportunities in CT angiography (CTA). Multidetector computed tomography angiography (MDCTA) has shown a great advantage in terms of the accurate mapping of disease for interventional planning using noninvasive techniques [4–8]. This modality is now widely used and has largely replaced catheter arteriography as a preintervention angiographic technique [9,10].

Advanced CT technology has allowed for faster and more robust imaging. However, because the scanning times have become shorter, if the injection/acquisition technique is not adapted to the new scanner capabilities it is possible to completely miss the bolus or the appropriate enhancement phase, which is a prerequisite for the accurate assessment of arteries. Contrast enhancement in CTA is affected by numerous interacting factors that can be categorized into three components, namely patient, contrast injection and image acquisition [11,12]. Among these factors, CT acquisition parameters, acquisition speed (table speed) in particular plays a critical role, as it determines the synchronization of CT acquisition with the propagation of the contrast bolus through the arteries. This synchronization is particularly challenging for lower extremity artery CT angiography, because of the considerable variability of the flow velocity from patient to patient [10].

In the current summarization, we introduce a method of

*Corresponding author (email: zleizhang@hotmail.com)

injection/acquisition optimization strategy based on a velocity-compensated CT angiography technique for the peripheral artery system, which is currently used in the United States.

1 Lower extremity CT angiography: Challenges, current technology and clinical use

It has been a technical challenge to correctly synchronize CT acquisition with adequate and uniform arterial enhancement in the entire peripheral arterial tree. If the scan is too fast, it will outrun the bolus. However, if the scan is too slow, that is, the imaging occurs after peak arterial enhancement, venous contamination can result [13–18]. An optimal examination protocol should ensure sufficient arterial enhancement throughout the entire arterial tree without under- or over-opacification of the vessel or significant venous enhancement [19,20]. To achieve optimal image quality, accurate circulation timing and an appropriate contrast bolus length are essential.

Many attempts have been made to optimize the arterial opacification of lower extremity arteries in MDCT. Nakaya et al. [13] presented their experience on using a test injection and monitoring scans at knee level, and Siriapisith et al. [15] reported on the use of pitch, which was selected according to the age of the patients, as a factor in the maximization of vessel opacification. Combination of bolus tracking with the monitoring scan at the level of abdominal aorta, which is used for determining the delay time, is a common and practical technique for routine use. This method is currently widely used in China. The advantage of this method includes the fact that it allows the CT technicians to easily perform CTA with a relatively simple standardized protocol, which is preferable in the setting of a busy CT unit; in addition, it allows a relatively low overall contrast volume, because an additional test bolus injection is not required. At most institutions, this method allows a contrast volume of 100 mL at 370 mg mL^{-1} for CT angiography of the lower extremities. However, it has been reported that by using this method, the CT scan may outpace the contrast agent flow rate and result in insufficient enhancement at a particular institution, in the case of patients with diffuse atherosclerosis and asymmetric arterial disease [13].

A 2-mini-bolus test injection is a sensitive and accurate method for calculating the flow velocity, which can differ widely among patients [6,13–18], as was first described by Fleischmann and Rubin in 2005 at Stanford University, USA. At around the same time, this method was successfully employed and developed at the Medical College of Wisconsin, USA [10,21]. It enables the alignment of the flow velocity and table speed, to prevent the table speed from outrunning the head of the contrast bolus. By combining "flow velocity-compensated CTA" with "delayed phase" CTA for the lower extremities, the performance and relia-

bility of CTA can be significantly improved and its clinical utility broadened. This more fully developed technique provides a significant uniform vascular enhancement through the entire period of image acquisition for the peripheral arterial tree, from the abdominal aorta to the pedal artery. This technique is particularly useful given the high incidence of patients with vascular disease including arteries with aneurysms, critical distal ischemia and asymmetric occlusive disease; these are conditions that truly test the potential applications of this technique, and also the capacity for the homogeneous opacification of these vessels in patients with significant but common diseases. The combination of "flow velocity-compensated CTA" with "delayed phase CTA" also ensures a lower contrast load and effective radiation dose without sacrificing image quality or diagnostic performance [10,21].

2 Optimization of flow velocity compensation for the lower extremity CT angiography technique

2.1 Image acquisition strategies

The central element of the technique is the predetermination of the flow velocity in the arterial circulation, by separately measuring the arrival times in the aortopopliteal arterial segments following preliminary mini-bolus injections. Aligning the flow velocity and table speed can achieve optimal synchronization of the acquisition with the propagation of the contrast bolus as it passes down through the arteries. The acquisition strategies used were developed based on the following principles. (1) The arterial flow velocity is predetermined by the measurement of the "arrival time" in the supraceliac aorta and popliteal artery segments. The arrival time is determined by using a test-bolus injection. The use of a test-bolus, the injection of a small amount of contrast medium (15 mL) at 5–6 mL s^{-1} while acquiring a time-attenuation curve, is a reliable and accurate means for determining the arrival time from the intravenous injection site to the arterial territory of interest. This is true even in patients with substantially altered hemodynamics secondary to cardiac disease [6,11,19,21–25]. The "arrival time" is taken as the time to the peak in the arterial time-attenuation curves. The time to the peak in the supraceliac aorta is subtracted from the time to the peak in the popliteal artery to provide a transit time. The cephalocaudal distance between these two points is measured directly from a scout digital radiograph obtained using the CT scanner. The cephalocaudal distance divided by the transit time provides a determination of the average flow velocity. (2) The table speed is adjusted to be equivalent to the measured arterial flow velocity between the supraceliac aorta and popliteal artery. The table speed is determined by the beam width, pitch and scan rotation speed. A wide beam width, high pitch value and high scan rotation speed result in fast table motion. Conversely, the table speed may be decelerated by choosing a slower scan

rotation speed, lower pitch value and narrower beam width [10]. The acquisition is set to begin at 6 s after the arrival of the contrast in the supraceliac aorta, followed by a saline flush. When the velocity is different for the bilateral arteries, typically the slower vessel is used, depending on the vascular territory of interest. Then, the second pass is started beginning at the popliteal artery and the coverage through the bottom of the feet immediately following the completion of the first pass is extended, and a faster table speed is chosen along with a higher scan rotation and higher pitch value.

The lower extremities, which are anatomically large, exhibit considerable variability in flow velocity among individuals, and arterial filling times can be delayed physiologically or pathologically. Bolus propagation in a diseased lower extremity arterial tree may be obviously delayed to varying degrees in different patients, and often even within the same patient secondary to asymmetric arterial disease. Additionally, the flow velocity of the below-the-knee arterial segment is usually slower than that of the aortopopliteal segment, due to either physiological phenomena or pathologies associated with inflow disease. All of these factors contribute to the risk of insufficient enhancement of the distal arteries in the lower extremities.

Using flow velocity compensation for lower extremity CTA, CT acquisition following the head of contrast propagation downstream during the first circulation can ensure adequate and uniform enhancement. Accounting for physiological and pathological factors, further combined with the use of the delayed phase approach for the below-the-knee arterial segment (which is intended to allow the time for the contrast agent to fill the distal arterial territory of interest and ensure that the CT scan matches the contrast bolus time) is effective in most patients.

2.2 Contrast medium injection strategies

Image quality depends on adequate intravenous contrast administration, which can be altered by changing the injection parameters, such as the injection duration, injection rate and contrast medium volume [1,6,11,26,27]. The contrast medium injection strategies used have been developed based on the following principles. (1) The duration of the contrast medium injection is set to equal the combination of the delay time following contrast arrival in the supraceliac aorta and the beginning of acquisition plus the acquisition interval, which is adjusted to be equivalent to the transit time. The delay time is set to 6 s. After aortic arrival the delay time allows for the buildup of a relative plateau of arterial enhancement. The duration of injection is longer than the acquisition time, and the delay time is longer than the transit time; this is aimed at a prolonged relatively homogeneous plateau of enhancement during acquisition and a more reliable filling of the distal vasculature. (2) The administered contrast volume is determined by the duration of injection multiplied by the rate of injection. With a preset injection rate, the contrast volume is mainly dependent on the acquisition time. A longer acquisition time, secondary to a slower flow velocity, requires a greater contrast volume. However, contrast volumes can also be adjusted by decreasing the injection rate in patients with slower flow velocities and longer acquisition times [10]. Because a longer injection (without lowering the injection rate) results in a larger volume of contrast medium entering the body (and thus proportionally increases the magnitude of vascular enhancement), proportionally decreasing the injection rate ensures adequate vascular enhancement within the vasculature of interest.

Using flow velocity to determine the contrast load may enable more efficient use of contrast medium, resulting in an average contrast volume of 100 mL containing 300–350 mg iodine mL^{-1} available to evaluate a wide range of pathology without sacrificing image quality [10,21]. In this context, the developed injection/acquisition technique offers the ability to control arterial enhancement, which is highly desirable for CTA and provides us with an opportunity to improve contrast enhancement and to use contrast more efficiently. This ability is particularly advantageous in elderly patients with diffuse atherosclerosis who more frequently have peripheral arterial disease (PAD); they are evaluated using lower extremity CTA because contrast-induced nephropathy (CIN) occurs more often in these patients and the amount of contrast medium is partially related to the development of CIN [28–31]. Smaller amounts of contrast medium may be preferable to reduce the higher risk of CIN in elderly patients.

3 Radiation dose optimization

Consideration of patient dose is important, particularly with regard to the public health concerns that have consequently arisen [32–37]. Using optimally adjusted photon kilovoltage peak (kVp) and milliamperes (mAs), the radiation exposure can be significantly reduced without sacrificing image quality or diagnostic performance [36–40]. These techniques that have been developed consider not only radiation dose, but also individualized radiation exposure.

A tube potential of 100–120 kVp is considered to be optimal [5]. At a low kVp setting, the mean photon energy of the polychromatic X-ray beam is closer to the K-edge of the iodine at 33.2 keV, resulting in a higher mean attenuation value; this may improve the visualization of the small peripheral arteries and the branch vessels.

SmartmA adjustments are based on patient thickness and density, and can be made in both the axial (x and y) and longitudinal (z) directions; they have been associated with a 20%–44% radiation dose reduction [40]. Currently, this approach is the most effective technical tool available for radiation dose reduction in CTA without loss of image quality. Furthermore, with optimal synchronization of the acquisi-

tion with the contrast propagation speed, patients do not receive unnecessary radiation exposure. These approaches offer the advantages that customization of the scan parameters according to patient characteristics ensures the lowest effective exposure during the CTA examination, and therefore the lowest acceptable risk.

4 Conclusion

The further developed 2-mini-bolus test technique described here has been significantly improved in terms of performance and reliability of diagnosis, and has proved effective in most patients with vascular disease at different institutions; these include elderly patients with diffuse atherosclerosis, asymmetric arterial disease or aneurysm, as well as patients with cardiac disease.

The advantages of this technique include the following. (1) Uniform and adequate vascular enhancement throughout the entire arterial tree. Performance and reliability of the below-the-knee arterial segment CTA are significantly improved. (2) Using flow velocity for determining the contrast load may enable more efficient use of contrast medium, which allows a relatively low average contrast medium volume of 100 mL. (3) The customization of scan parameters according to patient characteristics ensures an acceptable but effective radiation exposure during the CTA examination, and therefore the lowest acceptable risk.

A disadvantage of this technique is that it is time-consuming and requires at least 5 min between the 2 test bolus injections, as well as time for manual calculation of the aortopopliteal bolus transit time by the CT technician. This could be a potential limitation for routine use in the setting of a busy CT unit in China. However, in the case of elderly patients with diffuse atherosclerosis, asymmetric arterial disease or aneurysm, as well as in patients with cardiac disease, the use of this technique would be highly desirable for overcoming the high number of non-diagnostic below-the-knee arterial segments, bringing us an additional step forward in facing the challenges involving peripheral CTA.

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