Cardiovascular Circulation and Hepatic Perfusion of Pigs in 4-Dimensional Films Evaluated by 256-Slice Cone-Beam Computed Tomography

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Background In both cardiac and hepatic disorders it is desirable to accurately visualize the direction and scale of blood flow in the whole organ in pulsating 3-dimensional (D) images, which are known as 4-D images.

Methods and Results The present study used 256-slice cone-beam computed tomography (CT) (Athena, Sony-Toshiba) at one rotation per second and a section thickness of 0.5 mm to show the dynamics of cardiovascular circulation and hepatic perfusion by contrast injection in 4-D films of pigs. Four pigs (20 kg each) were anesthetized with isoflurane. The distal tips of the catheters were positioned in the inferior vena cava (IVC) (pigs 1–3) and in the proper hepatic artery (pig 4). Volumetric scanning and injection of contrast material were started simultaneously and continued for 25 s with image reconstruction at 1-s intervals. In pigs 1–3, 4-D filming revealed the dynamics of cardiovascular circulation, first in the IVC, followed by the right ventricle and pulmonary artery, then the left ventricle, left atrium, pulmonary vein, and finally, the right heart disappeared and only the left heart and aorta remained visible. In pig 4, the hepatic arterial trees, followed by the venous trees, could be easily visualized in turn on the 4-D images.

Conclusions This technology successfully demonstrated cardiovascular circulation and hepatic perfusion in 4-D and will have clinical applicability. (*Circ J* 2005; 69: 585–589)

Key Words: 4-D perfusion cardiovascular circulation; Hepatic perfusion; 256-slice cone beam computed tomography

In cardiovascular medicine, many subjects present with circulatory disorders, such as shunt flow in subjects with congenital shunt disease,¹ or disorders of blood inflow into the left atrial appendage (LAA) in subjects with chronic atrial fibrillation^{2,3} or left ventricular (LV) aneurysm seen in those with extensive anterior myocardial infarction,⁴ which may lead to thrombi in the LAA or LV aneurysm. Therefore, it is desirable to accurately visualize the direction and scale of the shunt flow or disorders of blood flow in the whole heart in pulsating 3-dimensional (D) images, which are known as 4-D images.

Similarly, in hepatic medicine, many subjects present with perfusion disorders such as liver cirrhosis or hepatocellular carcinomas and perfusion studies are performed to characterize the blood flow.^{5–7} Again, in such cases it is desirable to continuously visualize all the hepatic arterial, capillary and venous trees in 4-D images.

In the studies using a prototype high-speed cone-beam computed tomography (CT) apparatus employing 256-detector rows (Athena, Sony-Toshiba), an entire volume of

the thoracic part or liver can be imaged within a single gantry rotation (1 second per rotation) and a section thickness of 0.5 mm^{8–10}. Furthermore, maximum continuous 25 s scanning enables 4-D analysis. Although this CT technique does not involve electrocardiogram (ECG)-gated acquisition, the combination of its synchrony with volumetric data and reconstruction technique in which 1 scanning period is divided into a maximum of 100 phases, facilitates selection of the most static images and allows entire heart data acquisition without cardiac motion artifacts. In the present study we investigated the ability of this new technology to capture cardiovascular circulation and hepatic perfusion on 4-D dynamic volumetric images of pigs.

Methods

Four domestic pigs, weighing 20 kg each, were mechanically ventilated under isoflurane anesthesia. The distal tips of the catheters were positioned in the inferior vena cava (IVC) for the cardiovascular system (pigs 1–3) and in the proper hepatic artery (pig 4) for obtaining images of the hepatic perfusion. The heart rate of the pigs ranged from 70–80 beats/min. The experiments were approved by the Animal Welfare Committee of the Institute, and were performed in compliance with the guidelines for the care and use of laboratory animals as described by the National Institutes of Health.

Scan conditions for the 256-slice cone-beam CT were: 120 kV, 200 mA, 1.0 s exposure, 1.0 s gantry rotation time,

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Fig 1. Volume-rendered reconstruction images of a porcine heart using 256-slice cone beam computed tomography represent the vessel lumens and the heart cavity filled with contrast material, with the surrounding ribcage observed from the anterior view (A–D) and posterior view (E–H), acquired after injection of contrast at 2 s (A, E), 5 s (B, F), 12 s (C, G), and 17 s (D, H). At 2 s after injection of the contrast material, only the inferior vena cava (IVC) could be observed (A, E); at 5 s, the right ventricle (RV), pulmonary artery (PA) and IVC could be observed (B, F); at 12 s, in addition to the RV and PA, the left ventricle (LV) and pulmonary vein (PV) could be observed (C, G); but at 17 s, the right heart disappeared and only the LV, PV, ascending aorta (Ao) and the right and the left internal thoracic arteries (ITA) could be observed (D, H).

0.5 mm slice thickness, and 256×0.5 mm slice collimation.

To begin, 10 ml of the iodinated contrast material (300 mgI/ml) was diluted with 40 ml of saline and injected at a rate of 3 ml/s at the same time as scanning of the entire heart was begun. Scanning continued for 25 s and in that time the radiation dose was 100 mSV!¹¹

The temporal resolution of this new CT is 1 s and the spatial resolution is approximately 1.0 mm (transverse) and 1.3 mm (longitudinal). Image reconstruction was performed

at every 0.1-s interval and we selected the most static images around every 1-s interval after injection of contrast resulting in 25-phase volume data which were transferred to a workstation (Virtual Place Advance Plus, AZE, Japan).

Results

In pigs 1–3, at 2 s after injection, the volume-rendered images showed only the IVC (Fig 1A,E); at 5 s, the right

Fig 2. Volume-rendered reconstruction images of a porcine liver using 256-slice cone-beam computed tomography. (A, B) Hepatic arterial trees; (C, D) liver area supplied by blood capillaries within the hepatic arterial trees; (E, F) liver area supplied by blood capillaries beginning to disappear and the hepatic venous trees appearing.

heart, including the right ventricle, the pulmonary artery, and the IVC could be seen (Fig 1B,F); at 12 s, the LV, left atria (LA), including the LAA, and pulmonary vein (PV) could also be observed (Fig 1C,G). At 17 s, the right heart had disappeared and only the LV, LA and PV, ascending and descending aorta, and the right and left internal thoracic arteries were visible (Fig 1D,H). Finally the LAA images disappeared completely, followed by those of the LV and the dynamics of the cardiovascular circulation could be observed in 4-D filming (data not shown).

In pig 4, at 3 s after injection, the volume-rendered images revealed only the hepatic arterial tree (Fig 2B); at 8 s, the area supplied by capillaries could be observed (Fig 2D); at 15 s, the hepatic arterial tree disappeared and the hepatic venous tree appeared (Fig 2F). These sequences could be visualized in 4-D filming, which allowed the hepatic perfusion to be easily observed (data not shown).

Discussion

Echocardiography,^{12,13} a flow pattern study of magnetic

resonance imaging,¹⁴ electron-beam CT,^{5,16} conventional left ventriculography^{17,18} and aortography have all been used to evaluate of cardiovascular blood flow, but they all use pulsating 2-D images only, which make it difficult to observe the 3-D spatial relationships circulation.

The 3-D images using ECG-gated multislice CT (MSCT)¹⁹ or electron-beam CT²⁰⁻²³ are constructed by building up data from the same cardiac phase (R-to-R interval) but with a different cardiac beat. However, these 3-D images do not allow any evaluation of the dynamics of blood flow.

The new 256-slice cone-beam CT with its combination of reconstruction techniques can successfully demonstrate the dynamics of the cardiovascular circulation system on 4-D films in which the configuration of the heart continued to the through plane without any gaps. In other words, this new prototype CT has a unique ability, synchrony, for acquiring images of the pulsating heart. Compared with a conventional 16-slice CT scanner with 0.75 mm slices, with this new 256-slice cone-beam CT, image noise, uniformity, and high contrast detectability are independent of the z-axis.⁸ Furthermore, the scanning mechanism can accommo-

date a rotation speed of up to 0.5 s/rotation and ECG-gated acquisition will be possible in the next generation of scanner⁸

In the present MSCT, using retrospective ECG-gating acquisition or respiratory motion-gating acquisition^{24,25} which use helical scanning with simultaneous recording of an ECG or respiratory motion signal, following acquisition, it is possible to obtain any volume data of the heart or lung at any cardiac or respiratory phase desired. Furthermore, using this system, it is possible to obtain maximum 100 volumetric data points divided into maximum 100 serial segments of one cardiac or respiratory phase such as 0, 1, 2,...,97, 98 and 99% of the R-to-R interval of the ECG or respiratory motion. Using serial maximum 100 phase volumetric data, it is also possible to obtain 4-D images on a workstation in which the motion of the heart or thoracic parts can be evaluated. Furthermore, this 256-slice cone-beam CT could represent the dynamics of contrast material in 4-D images; although it is not possible with the present MSCT which so far has been developed as a 64-slice data acquisition system.

This new modality could have applications in the visualization of shunt flow and disorders of blood flow into the LAA and LV aneurysm, which in the latter case may lead to the formation of thrombi. It also may be able to provide visualization of myocardial blood flow when the temporal resolution improves. Gradation of the myocardial blood flow within the myocardium (ie, the difference in the blood flow in the endomyocardium and epicardium) may produce a large amount of information when myocardial ischemia develops.

In the present study, we also demonstrated hepatic perfusion combined with selective hepatic arterial injection and observed clear hepatic enhancement on the 4-D films. Some investigators have reported hepatic perfusion using 3–9 phases of volumetric data of the whole liver, or continuous acquisition for 30 s that covered parts of the liver in 4 slices with the use of time density curves.^{5–7} However, the former technique does not use a sequential perfusion study, but is an intermittent perfusion study, and the latter technique is not an entirely volumetric only a partial volumetric hepatic perfusion study. To obtain 4-D images using the 256-slice cone-beam CT such as presented in this study, 2 techniques can be envisaged for the future.

One approach is to perform the same procedure as performed in pig 4 in this study using a combination of a selective angiography system with the CT system in which the CT acquisition with selective hepatic artery injection can be achieved without any movement of the patient. In fact, such a system is already in use;²⁶ and it would be possible to obtain 4-D images of the same hepatic enhancement presented in this study. Therefore, if the physician wishes to determine the area of liver supplied by the proper hepatic artery, or needs to obtain quantitative blood flow information in subjects with liver cirrhosis, or intends to evaluate the feeding artery of hepatocellular carcinoma, this technique provides useful information for devising the appropriate treatment strategy. In this study, because we placed the catheter in the proper hepatic artery, we could not evaluate the perfusion of the artery or the portal vein originating from the superior mesenteric artery or the splenic artery.

The other approach is non-invasive image acquisition using the new 256-slice cone-beam CT combined with intravenous injection. Even though with this method seg-

mentation of liver enhancement cannot be performed, we can evaluate the 3-D perfusion of the whole liver non-invasively, which is not possible with 16-slice or even the latest 64-slice MSCT. Using this technique, continuous 25-s acquisitions can be performed, yielding quantitative hepatic perfusion information by using time density curves of the liver on 3-D images.

We describe here a novel prototype CT that has the advantage of whole heart and liver imaging in a single gantry rotation without ECG-gated acquisition. This technique may facilitate cardiovascular and liver diagnosis and may also find application with other organs such as the brain, kidney and peripheral vasculature.

One of the problems encountered with this new 256-slice cone-beam CT scanner is that in order to achieve a detailed 4-D analysis, the number of images that the workstation has to process is very large. For example, 1 volume data set has 256 images, which means that if an image is acquired from 10 phases per s over a total of 25 s, the workstation has to process 64,000 (256×10×25) images at one time in order to achieve a detailed 4-D analysis. At present even the most advanced workstation cannot process such a huge volume of images, but this problem may resolve within a few years as workstations become more sophisticated. Recently, increasing attention has been given to the dose of radiation received during in cardiac CT.²⁷ Specifically, the radiation dose for evaluating blood flow dynamics using the 256-slice cone-beam CT is estimated as 4 mSV/s. Although it is better to keep the radiation dose to a minimum, it may be justifiable to perform such a procedure despite the radiation dose.

There is another type of CT available, a prototype flat-panel CT system (VCT, GE Global Research), with a 200-mm detector panel and a cell pitch factor of 0.2 mm, which also allows an entire organ to be imaged within a single gantry rotation.²⁸ Thus, in the near future, these new imaging modalities will likely become new diagnostic tools.

Conclusion

We successfully demonstrated the cardiovascular circulation and hepatic perfusion in 4-D using 256-slice cone-beam CT. This imaging modality has clinical potential for the visualization and analysis of cardiovascular circulatory problems and hepatic perfusion disorders.

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