Abstract: Computed tomographic (CT) angiography is important for imaging studies on cardiovascular structures, peripheral vessels, and solid organs. In practice, a CT angiography scan is triggered by the bolus arrival at a prespecified anatomical location, which is determined using CT fluoroscopy. In this article, we propose a projection-based method adapted from the Grangeat formula to detect the bolus arrival. Then, we evaluate our new method in numerical and animal studies. Our results indicate that this method allows significantly better temporal resolution and is computationally more efficient, as compared with the image-based methods.

Key Words: CT angiography, bolus arrival, CT fluoroscopy, Grangeat formula

Computed tomographic angiography (CTA) has become a popular alternative to catheter-based angiography because of its acquisition speed, tomographic nature, noninvasiveness, and cost-effectiveness.1,2 Before a CTA scan is obtained, a contrast material is first injected into an antecubital or large forearm vein, and then the change of the CT number in a vascular region of interest (ROI) is monitored in real time using CT fluoroscopy (CTF).3 When the contrast bolus reaches a preset threshold, the monitoring scan stops, and the CTA scan starts to produce images with an enhanced signal-to-noise ratio.4 Administration of a contrast material only provides a short temporal window to depict vessels, lesions, and tumors optimally.5,6 Scanning too early may result in compromised enhancement of vessels, whereas scanning too late may lead to overlapping venous structures.7 Various image-based systems are now used to initiate a CTA scan upon the bolus arrival.

These include the SmartPrep (General Electric Medical Systems, Milwaukee, Wis),8,9 the CARE Bolus (Siemens, Erlangen, Germany),8,9 and the SureStart (Toshiba America Medical Systems, Tustin, Calif). All these systems rely on the bolus intensity curve in an ROI.7 The problems with these image-based methods are poor image quality because of a reduced tube current and insufficient temporal resolution governed by the angular range of the projection data set needed for image reconstruction. About 20 years ago, the Chronogram method was proposed to study the bolus geometry after intravenous contrast injection.12,13 That method is also a projection-based method, but it only works in the 2-dimensional case, simply computes the average of fan-beam projections, and just gives approximate results.

In this article, we propose a projection-based method adapted from the Grangeat formula. Our method calculates the change of the bolus strength from any multislice/cone-beam projection and recovers the bolus intensity curve from these changes. Consequently, our method works with modern CT scanners that are in multislice/cone-beam geometry, detects the bolus arrival accurately and instantly without reconstructing images from a full/half scan data set, and does produce theoretically exact results. In the second section, we formulated our projection-based bolus detection method. In the third section, we evaluated our method in numerical and animal studies. In the last section, we discussed relevant issues and concluded the article.

BOLUS DETECTION FORMULA

First, let us describe how to extract the bolus intensity curve using the CTF image-based method. During a monitoring CTF scan, sequential images are reconstructed and displayed in real time. In the field of view, ROI images are compared with that in the baseline image in which no bolus is involved. The differences between the current and baselines images reveal the enhancement in Hounsfield unit (HU) due to the bolus material. Once the average of the differences reaches a preset threshold, such as 100 HU, for a given time interval, for example, 2 seconds, the monitoring scan is switched to the CTA scan.7,8 Let \( f_0(x,y) \) be a reconstructed image in the plane of interest at time \( t_0 \) without any involvement of the bolus; \( f_1(x,y) \), a reconstructed image at time \( t_1 \) with a contribution from the bolus; and \( A \), the ROIs; we define the total bolus change \( SB \) from \( t_0 \) to \( t_1 \) as follows:

\[
SB = \int \int f_1(x,y) - f_0(x,y) \, dx \, dy
\]  

Then, let us describe our projection-based method to compute the above quantity. Our method is formulated in...
the Grangeat framework, which is a relationship between a cone-beam projection and the first derivative of the 3-dimensional Radon transform, originally intended for exact cone-beam reconstruction.\textsuperscript{14} Because the half-scan mode shortens the data acquisition time, Lee and Wang\textsuperscript{15} developed Grangeat-type, half-scan, cone-beam image reconstruction algorithms in the circular and helical scanning cases.\textsuperscript{16} However, the Grangeat formula has never been used to extract clinical information directly from projections.

In our bolus-chasing CTA project, an x-ray source rotates along a circle in the transaxial plane of a patient where the bolus dynamics is monitored. Let us now apply the Grangeat framework, which is a relationship between a cone-beam projection and the first derivative of the 3-dimensional Radon transform, originally intended for exact cone-beam reconstruction.\textsuperscript{14} Because the half-scan mode shortens the data acquisition time, Lee and Wang\textsuperscript{15} developed Grangeat-type, half-scan, cone-beam image reconstruction algorithms in the circular and helical scanning cases.\textsuperscript{16} However, the Grangeat formula has never been used to extract clinical information directly from projections.

In our bolus-chasing CTA project, an x-ray source rotates along a circle in the transaxial plane of a patient where the bolus dynamics is monitored. Let us now apply the Grangeat formula\textsuperscript{14} in this plane. As shown in Figure 1, we then have

\[
Rf'(\vec{x}, \rho)|_{\rho=0} = \frac{\partial}{\partial \theta} \int_{-\infty}^{\infty} \frac{SO_{xy}}{\sqrt{u^2 + v^2 + SO^2}} Xf(S, u, v) du|_{v=0} \quad (2)
\]

In Figure 1, the source $S$ is placed on the origin of the Cartesian coordinates. Point $P(x, y, z)$ is an arbitrary point in the object. Point $B$ is the intersection of the $v$-axis and a detection line parallel to the $u$-axis. The $u$-$v$ plane is parallel to the $y$-$z$ plane and made to go through the object center $O$. $SA$ goes from the source $S$ through $P(x, y, z)$ to the point $A$ on the detection plane. $Xf(S, u, v)$ represents the line integral from $S$ through $A$. The unit directional vector $\vec{n}$ gives the normal direction of the plane $SBA$; $\rho$ is the distance from the point $O$ to the plane $SAB$. $Rf'(\vec{n}, \rho)$ denotes the partial derivative of $Rf(\vec{n}, \rho)$ with respect to $\rho$. Eq. (2) comes directly when the Grangeat formula\textsuperscript{14} is specialized by setting $\vec{n} = \vec{x}$.

Given multislice/cone-beam projections from time $t_0$ to $t_1$, we have the corresponding view angles from $O_0$ to $O_1$ that satisfy the following relationship:

$$\theta_1 - \theta_0 = \omega(t_1 - t_0)$$

where $\omega$ is the angular velocity of the x-ray source. Then, we immediately have

\[
S_B = \int_{t_0}^{t_1} Rf'(\vec{x}, t) dt = Rf(\vec{x}, t_1) - Rf(\vec{x}, t_0) \quad (3)
\]

where $Rf(\vec{x}, t_1)$ is the planar integral at time $t_1$ and $Rf(\vec{x}, t_0)$ is the planar integral at time $t_0$. Hence, the total bolus change $S_B$ is the planar integral change from time $t_0$ to $t_1$ and can be computed by the integral of $Rf'(\vec{x}, t_1)$ from time $t_0$ to $t_1$. We have the formula for the total bolus change (Appendix):

\[
S_B = \frac{SO}{\Delta v} \int_{\theta_0}^{\theta_1} \int_{-\infty}^{\infty} P_{\theta,v}(u)|_{v=-\Delta v/2}^{v=\Delta v/2} du d\theta \quad (4)
\]

**EXPERIMENTAL STUDIES**

To verify the correctness of our projection-based method for bolus arrival detection, we randomly selected a full-scan data set from a sheep lung CT study performed using a Siemens scanner (Siemens Medical Systems, SENSATION64) and reconstructed the image as the background. There are 1160 projections in the full scan and 672 ray sums in each projection slice. The distance between the x-ray source and the isocenter is 570 mm. The field-of-view diameter is 501 mm.

Within this sheep scan, we superimposed a mathematically exact bolus dynamics as the gold standard. Specifically, in the field of view, we numerically inserted an ellipsoid whose 3 half axes were set to $a = 25$ mm, $b = 25$ mm, and $c = 250$ mm. The ellipsoid was moved along the $z$-axis from 100 to 0 mm and added them to real projections in the full scan, as the first turn of our assumed monitoring scan. Furthermore, we repeated the process for $z$ values from 0 to 100 mm to obtain the second turn of the monitoring scan. In other words, we generated 2320 projections in total for our 2-turn monitoring scan.

The bolus strength was calculated using Eq. (4) and displayed in Figure 2. The bolus strength was also found

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\[
S_B = \pi abc(e^2 - z^2)\rho \quad (5)
\]

where $\rho$ is the density of the ellipsoid. Then, we digitally synthesized various projections at different $z$ values from −100 to 0 mm and added them to real projections in the full scan, as the first turn of our assumed monitoring scan. Furthermore, we repeated the process for $z$ values from 0 to 100 mm to obtain the second turn of the monitoring scan. In other words, we generated 2320 projections in total for our 2-turn monitoring scan.

The bolus strength was calculated using Eq. (4) and displayed in Figure 2. The bolus strength was also found
using Eq. (1), based on full-scan and half-scan reconstructions, respectively (Fig. 2). In Figure 2, it can be seen that the Grangeat method can detect the bolus change since the first projection, the half-scan method can detect the bolus change since the 381st projection, and the full-scan method cannot detect the bolus change until the 581st projection. The relative errors associated with these 3 bolus detection methods are plotted in Figure 3. Our results clearly indicate that whereas both the full-scan and half-scan reconstructions suffered from a time lag in picking up the bolus strength, our projection-based method captures the bolus dynamics precisely and instantaneously.

**DISCUSSIONS AND CONCLUSIONS**

There are 2 advantages of our adapted Grangeat method: (1) instant detection and accurate quantification of the moving bolus and (2) high efficiency in the involved computation as compared with the full-scan and half-scan reconstructions. The reason for the similar relative errors with our adapted Grangeat method at the beginning in Figure 3 is that the derivative of the planar bolus strength had a large value. Our proposed method may not only be applied for bolus detection but also extended for bolus analysis during the whole CTA scan. In contrast to the current CTA strategy that is based on a constant table speed, our team is actively developing a bolus-chasing spiral CTA approach by dynamically predicting bolus propagation and adaptively varying scanning pitch from the aortic arch to the feet. For that purpose, it is highly useful to extract the bolus behavior exactly and instantly as a primary feedback to our table speed control system. Clearly, it is an interesting and important topic how to use the Grangeat methodology during a bolus-chasing CTA scan. We are investigating this issue and will report the results in the future.

In fact, our Grangeat framework only uses projections measured from 2 adjacent detector rows to obtain the bolus dynamics, which does not work in fan-beam geometry. That is, our adapted Grangeat formula can be used as long as the projections are in multislice/cone-beam geometry. However, we can approximately compute the bolus changes in fan-beam geometry using a projection rebinning method, which is beyond the scope of this article. In conclusion, we have developed a novel projection-based method for bolus arrival detection. Our experimental results have demonstrated that this method allows significantly better temporal resolution and is computationally more efficient, as compared with the image-based methods. Further work is needed to extend this methodology for extraction of the bolus dynamics during the entire CTA scan.

**DERIVATION OF THE BOLUS CHANGE FORMULA**

Let $P_{x,v}(u)$ denote $\lambda(S, u, v)$, substituting Eq. (2) into Eq. (3), we have

$$S_B = \int_{t_0}^{t_1} \phi'_v(v)|_{v=0} dt, \quad \phi_v(v) = \int_{-\infty}^{v} \frac{SO \cdot P_{x,v}(u)}{u^2 + v^2 + SO^2} du \quad (A1)$$

In practice, we can compute the discrete derivative with respect to $v$ as follows:

$$\phi'_v(v) = \left[ \phi_v\left( v + \frac{\Delta v}{2} \right) - \phi_v\left( v - \frac{\Delta v}{2} \right) \right] / \Delta v \quad (A2)$$

where $\Delta v$ is the distance between the 2 adjacent detector rows. Let $v = 0$, then

$$\phi'_v(0) \approx \left[ \phi_v(\Delta v/2) - \phi_v(-\Delta v/2) \right] / \Delta v. \quad (A3)$$

Substituting Eq. (A3) into Eq. (A1), we finally have

$$S_B = \frac{SO}{\Delta v} \int_{t_0}^{t_1} \int_{-\infty}^{v} \frac{P_{x,v}(u)|_{v=\Delta v/2}}{\sqrt{u^2 + (\Delta v)^2/4 + SO^2}} du \theta. \quad (A4)$$

**REFERENCES**