Radiology

Cardioembolic Stroke: Dual-Energy Cardiac CT for Differentiation of Left Atrial Appendage Thrombus and Circulatory Stasis[1]

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Purpose: To assess the diagnostic performance of dual-energy cardiac computed tomography (CT) in the detection of left atrial appendage (LAA) thrombi and differentiation between thrombus and circulatory stasis in patients with stroke, by using transesophageal echocardiography (TEE) as the reference standard.

Materials and Methods: The institutional review board approved this study, and patients provided informed consent. Thirty-two patients with stroke who had atrial fibrillation (AF) and either thrombus or the spontaneous echo contrast (SEC) echo pattern at TEE were prospectively enrolled. For the control group, 31 patients who were planning to undergo AF ablation and who had no abnormalities at TEE were enrolled. All patients underwent dual-energy cardiac CT that was not electrocardiographically gated. For quantitative analysis, iodine concentration was measured on CT images. The statistical significance of differences in mean iodine concentration between thrombus and SEC as measured at CT was assessed by using the Student *t* test.

Results: Among the 63 patients, a total of 13 thrombi and 19 instances of SEC were detected at TEE. Using TEE as the reference standard, the overall sensitivity, specificity, positive predictive value, and negative predictive value of dual-energy cardiac CT in the detection of thrombi and SEC in the LAA were 97% (95% confidence interval [CI]: 82%, 100%), 100% (95% CI: 86%, 100%), 100%, and 97%, respectively. At CT, the mean iodine concentration was 1.23 mg/mL ± 0.34 (standard deviation) for thrombus and 3.61 mg/mL ± 1.01 for SEC (P = .001).

Conclusion: Dual-energy cardiac CT is a highly sensitive modality for detecting LAA thrombus and for differentiating thrombus from SEC in patients with stroke.

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Investigation of potential embolic sources is an important diagnostic step in treating patients with acute ischemic stroke or transient ischemic attack, especially when the mechanism is considered to be embolic. Cardiogenic embolism has been estimated to be the causative factor in 20%–40% of all cases of stroke (1–3). Atrial fibrillation (AF) is the most common cause of embolic sources from the heart, and AF-related strokes constitute about 60% of all cardioembolic strokes (4). Patients with stroke and AF frequently have concomitant potential cardiac sources of embolism and are at increased risk of recurrent embolism, despite anticoagulation (5,6). The detection of certain concomitant potential cardiac sources of embolism in patients with stroke and AF may thus help to identify a patient group with a high risk of recurrent stroke.

Thrombi of the left atrium (LA) and left atrial appendage (LAA) are common sources of stroke, and because they are treatable sources of embolism, their detection could markedly affect patient care. Currently, transesophageal echocardiography (TEE) is considered the reference standard for the detection of intracardiac thrombus. However, TEE requires special skills for proper performance and interpretation. Additionally, it is a relatively invasive test, usually performed with the patient conscious sedation (7,8).

Computed tomography (CT) has recently emerged as a very sensitive method with high diagnostic accuracy for the detection of intracardiac thrombus, which is seen as a filling defect (9–12). However, CT can result in false-positive findings, such as the echo pattern called spontaneous echo contrast (SEC), when an attenuation-based method is used, owing to the limited ability to discern tissue characteristics. The inability to visually distinguish all instances of SEC from definite thrombus at CT results in reduced specificity (9–11). Recently introduced dual-energy CT performed by using rapid kilovoltage switching has allowed simultaneous acquisition of low- and high-tube-voltage data sets. With this technique, it is possible to differentiate iodine from other materials by means of the material decomposition method (13). This is valuable for characterizing iodine-enhancing phenomena such as SEC from nonenhancing lesions such as thrombus.

The aim of this study was to assess the diagnostic performance of dual-energy cardiac CT in the detection of LAA thrombi and differentiation between thrombus and circulatory stasis in patients with stroke, by using TEE as the reference standard.

Materials and Methods

Patient Selection

Our institutional review board approved this study, and patients provided informed consent. From November 2010 to May 2011, 279 consecutive patients were admitted to our hospital because of a recent stroke (onset within the previous 7 days). Of these patients, 87 who had persistent or paroxysmal AF underwent TEE for suspected cardioembolic sources within 1 week of the initial stroke. TEE was not performed in nine patients: two patients with decreased consciousness, one patient with findings that indicated impending brain herniation, three patients with poor systemic condition, two patients with an inserted tracheal tube, and one patient in whom an esophageal transducer could not be introduced.

Of these patients, 37 who had either thrombus or SEC at TEE were prospectively enrolled to undergo dual-energy cardiac CT. Five patients who had contrast agent allergy (n = 1) or renal dysfunction (n = 1) or who did not provide informed consent (n = 3) were excluded. The remaining 32 patients with intracardiac thrombus or SEC were included in this study. All patients underwent brain CT or brain magnetic resonance imaging to confirm and characterize the stroke type and to exclude hemorrhage and other disease. Nineteen patients had acute infarction in the middle cerebral artery territory, 10 had acute infarction in the posterior cerebral artery territory, and three had multiple embolic infarctions in the cerebrum and cerebellum.

Advances in Knowledge

- Dual-energy cardiac CT is a noninvasive and sensitive modality for detecting left atrial appendage thrombus and for differentiating thrombus from circulatory stasis in patients with stroke.
- The mean iodine concentration was significantly different between thrombus and circulatory stasis (1.23 mg/mL ± 0.34 [standard deviation] vs 3.61 mg/mL ± 1.01; P = .001).

Implication for Patient Care

- Dual-energy cardiac CT may be clinically useful for detecting and ruling out intracardiac thrombus in patients at risk for cardioembolic stroke and could be an alternative diagnostic tool to transesophageal echocardiography.

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Abbreviations:
AA = ascending aorta
AF = atrial fibrillation
$CHADS_2$ = congestive heart failure, hypertension, age, diabetes mellitus, and prior stroke or transient ischemic attack
CI = confidence interval
LA = left atrium
LAA = LA appendage
ROC = receiver operating characteristic
ROI = region of interest
SEC = spontaneous echo contrast
TEE = transesophageal echocardiography

Author contributions:
Guarantors of integrity of entire study, J.H., H.Y.K., B.W.C.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; manuscript final version approval, all authors; literature research, J.H., Y.J.K., H.J.L., Y.J.H., H.Y.K., B.W.C.; clinical studies, all authors; statistical analysis, J.H., H.Y.K., B.W.C.; and manuscript editing, J.H., Y.J.K., H.Y.K., B.W.C.

Potential conflicts of interest are listed at the end of this article.

For the control group, we prospectively enrolled 31 patients who were planning to undergo AF ablation and who had no intracardiac abnormalities at TEE. All patients underwent TEE and dual-energy cardiac CT examinations within a 3-day period (mean, 2.3 days) to determine the cardioembolic source. Overall, the patients consisted of 49 men and 14 women, with age ranging from 38 to 88 years (mean age, 63.6 years). Baseline clinical characteristics, including information on systemic hypertension; hyperlipidemia; diabetes mellitus; smoking habits; and congestive heart failure, hypertension, age, diabetes mellitus, and prior stroke or transient ischemic attack ($CHADS_2$) score, were determined from medical records and on the basis of routine laboratory data (14).

Dual-Energy Cardiac CT Examination

Dual-energy CT studies were performed with a 64-row multidetector CT scanner (Discovery CT750 HD; GE Healthcare, Ind) in the craniocaudal direction during a single breath hold. Scanning was performed with the second injection of contrast agent, 180 seconds after injection of the first bolus of contrast agent.

No β-blockers were used for the regulation of heart rate, because CT was performed to evaluate the intracardiac structure and not the coronary arteries. The mean heart rate was 63.9 beats per minute ± 9 (standard deviation) (range, 45–89 beats per minute) during the CT examination.

A test-bolus technique was used before image acquisition in each patient. For test-bolus studies, 50 mL of the nonionic contrast agent iodixanol (Visipaque [320 milligrams of iodine per milliliter]; GE Healthcare, Cork, Ireland), was administered by using a power injector (Envision CT; Medrad, Wash) at a rate of 5 mL/sec and an 18-gauge needle placed into the right antecubital vein. After contrast agent administration, 50 mL of saline was administered at a flow rate of 5 mL/sec through the same venous access. A region of interest (ROI) was plotted inside the ascending aorta (AA), and a bolus geometry curve was acquired. Curve diagrams were analyzed immediately after acquisition, and the time to maximum enhancement was measured to determine the optimal scan delay.

By using gemstone spectral imaging mode (nonelectrocardiographically gated), scanning was started 180 seconds after the end of the test-bolus study (see Appendix E1 [online] for further detail). The second bolus, composed of 70 mL of iodixanol followed by 50 mL of saline solution, was administered intravenously at a rate of 5 mL/sec by using the power injector. We used the optimal scan delay time determined during the test-bolus study. The scanning parameters were as follows: 64 detector rows; section thickness, 0.625 mm; gantry rotation time, 0.5 second; tube voltage, 140 kV; tube current, 630 mAs; and pitch, 1.375:1. All images were reconstructed with a section thickness of 0.625 mm and a detail reconstruction kernel and were evaluated at an offline workstation (Volumeshare 4.4.5; GE Healthcare). Radiation exposure was estimated from the dose-length product. The calculated mean radiation dose was 3.98 mSv (dose-length product range, 154–313 mGy · cm), depending on the scan range and the patient's body weight.

TEE Examination

TEE was performed with a 5-MHz multiplane probe positioned at the appropriate level within the esophagus. For each patient, all images were recorded on digital video in real time for display and evaluation. Multiple standard tomographic planes were imaged, and LAA emptying velocity, the presence of LA or LAA thrombi, and the severity of SEC in the LA were determined. The severity of SEC was classified into one of four grades on the basis of appearance and density with a 5-MHz transducer as follows: none, mild (minimal echogenicity detectable only with optimal gain settings transiently during the cardiac cycle), moderate (a dense swirling pattern during the entire cardiac cycle), or severe (intense echodensity and very slow swirling patterns in the LAA, usually with a similar density in the main cavity).

Image Analysis

Two radiologists (J.H. and B.W.C., with 6 and 11 years of experience with cardiac CT, respectively), each of whom was blinded to the results of the other examinations and to the clinical data, prospectively and independently reviewed the CT images in the 63 patients. There was disagreement in one case between the two reviewers. In that case, consensus was achieved at a joint reading, and the final diagnosis was no filling defect.

At CT, the LAA was visually examined for any filling defects. If the entire LAA was not fully opacified with contrast media, it was deemed "underfilled."

For quantitative analysis, we measured the iodine concentration for filling defects on iodine maps provided by the workstation (see Appendix E1 [online] for further detail). On the workstation, monochromatic image pairs provided quantitative measurements (in milligrams per milliliters) of how live the material in the image was to each of the monochromatic pairs. The displayed iodine (water) image provided the quantitative value of iodine. For this purpose, ROIs of approximately 60 mm^2 (range, 15–208 mm^2) were placed inside the filling defect of the lesion seen on the iodine (water) images. In the control group, the ROI was also drawn to encompass as much of the LAA as possible on the iodine maps. Iodine concentration was independently measured at two selected points in milligrams per milliliter by the two radiologists (J.H. and B.W.C.), and the mean values were used for analysis.

For quantitative analysis, we also calculated the LAA-AA Hounsfield unit ratio for filling defects on CT images. ROIs were placed inside the filling defect in the LAA on CT images and in the AA of the same section to generate an LAA-AA Hounsfield unit ratio. CT attenuation was independently measured at two selected points in Hounsfield units by the two radiologists, and the mean LAA-AA Hounsfield unit ratio was used for analysis.

Receiver operating characteristic (ROC) curves were constructed by using

Table 1

Clinical Characteristics of 63 Patients

Characteristic	Patients with Stroke (n = 32)	Control Patients (n = 31)	P Value
Age (y)*	66.3 ± 10.9	61.2 ± 10.8	.077
Male sex	26 (81)	23 (74)	.713
AF	32 (100)	31 (100)	...
Hypertension	21 (66)	10 (32)	.003
Hyperlipidemia	4 (12)	3 (10)	.727
Diabetes mellitus	7 (22)	5 (16)	.753
Smoking	11 (34)	8 (26)	.866
History of CVA or TIA	11 (34)	5 (16)	.308
LV dysfunction or CHF	4 (12)	3 (10)	.727
$CHADS_2$ score*	3.24	1.16	.001

Note.—Unless otherwise specified, data are numbers of patients, with percentages in parentheses. CHF = congestive heart failure, CVA = cerebrovascular accident, LV = left ventricle, TIA = transient ischemic attack.

* Data are means (± standard deviation for Age).

Table 2

Comparison of CT and TEE in Detection of Filling Defects in 63 Patients

Finding	CT	TEE
Filling defect		
Thrombus	13	13
Circulatory stasis (SEC)	18	19
No abnormality	32	31

Note.—Data are numbers of findings.

the iodine concentration and LAA-AA Hounsfield unit ratio, and the best cutoff value was determined for the differentiation between thrombus and SEC. Retrospective analysis demonstrated that the best cutoff threshold values for separating thrombus from circulatory stasis was 1.74 mg/mL for iodine concentration and 0.19 HU for LAA-AA Hounsfield unit ratio.

Statistical Analysis

Categoric baseline characteristics were expressed as numbers and percentages and were compared between patients with and those without thrombus or SEC by using the χ^2 test. Continuous variables were expressed as means and standard deviations and were compared by using the Student t test for independent samples.

By using TEE as the reference standard, the sensitivity, specificity, positive predictive value, and negative predictive value of cardiac CT for detecting thrombus or SEC were calculated; 95% confidence intervals (CIs) were calculated by using the method of exact binomial tail areas (15). The statistical significance of differences in mean iodine concentration and LAA-AA Hounsfield unit ratio between thrombus and SEC as measured on CT was assessed by using the Student t test. The significance of differences in mean iodine concentration of thrombus and SEC according to different grades determined at TEE was assessed by using one-way analysis of variance with the Scheffe method. ROC curves were used to compare the performance of dual-energy cardiac CT with that of delayed contrast material–enhanced CT for the differentiation of thrombus and circulatory stasis. The correlation between iodine concentration and LAA emptying velocity determined at TEE was assessed. The correlation between iodine concentration and LAA-AA Hounsfield unit ratio was also assessed for thrombus and SEC. The Pearson correlation was used to determine the correlation of mean iodine concentration values and LAA-AA Hounsfield unit ratios between the two observers. $P < .05$ was considered to indicate a statistically significant difference. All statistical analyses were performed with statistical software (SPSS, version 18.0, SPSS, Chicago, Ill; and MedCalc, version 9.5, MedCalc, Mariakerke, Belgium).

Results

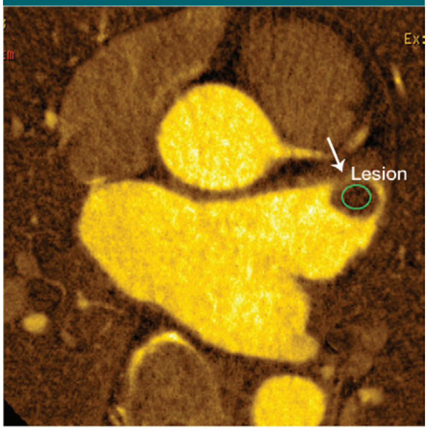
The clinical characteristics of the 63 patients are summarized in Table 1. The clinical characteristics were not significantly different between patients with stroke and patients in the control group, with the exception of patients with hypertension. We calculated the $CHADS_2$ score for each patient; mean $CHADS_2$ score was significantly higher in patients with stroke than in patients in the control group (3.24 vs 1.16, P = .001).

At TEE, there were a total of 13 thrombi and 19 instances of SEC (Table 2). All thrombi were located in the LAA. CT helped detect 31 filling defects in the LAA (Figs 1–3). One instance of mild SEC diagnosed at TEE was missed at CT. Using TEE as the reference standard, the overall sensitivity, specificity, positive predictive value, and negative predictive value of dual-energy cardiac CT for detecting thrombus and SEC were 97% (95% CI: 82%, 100%), 100% (95% CI: 86%, 100%), 100%, and 97%, respectively.

Table 3 shows the quantitative values measured at CT for the thrombus, circulatory stasis, and control groups. The mean iodine concentration was 1.23 mg/mL ± 0.34 (standard deviation) for the thrombus group, 3.61 mg/mL ± 1.01 for the circulatory stasis, and 15.47 mg/mL ± 3.06 for the control group. The mean iodine concentration was significantly different between thrombus and circulatory stasis (P = .001). At CT, the mean LAA-AA Hounsfield unit ratios were also significantly different between thrombus and circulatory stasis (0.18 vs 0.24 HU, P = .008).

ROC curve analysis of iodine concentration measurements at dual-energy cardiac CT defined 1.74 mg/mL as the best cutoff threshold for separating thrombus from circulatory stasis. By using the cutoff value of 1.74, the

Figure 1



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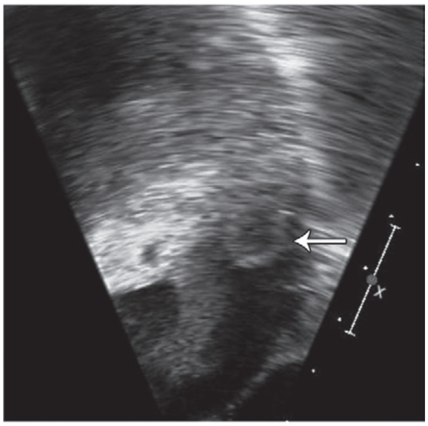
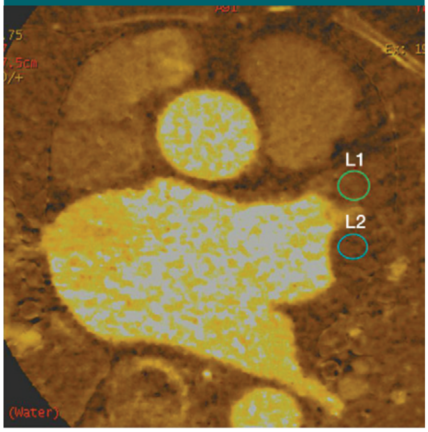


b.

Figure 1: Dual-energy cardiac CT and TEE images in 79-year-old man with stroke and an LAA thrombus. **(a)** Axial CT iodine map shows filling defect in LAA; the mean iodine concentration within the ROI was 1.34 mg/mL. **(b)** TEE image shows thrombus (arrow) in the LAA.

Figure 2



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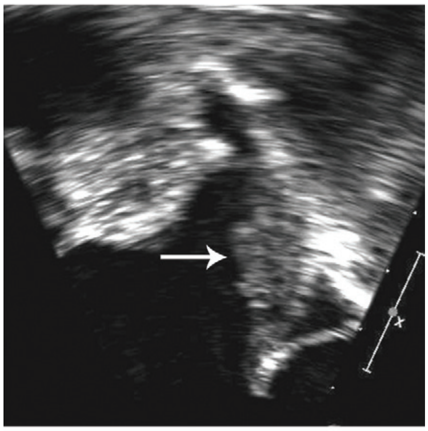
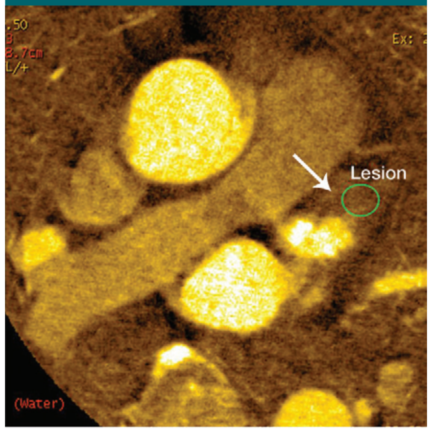


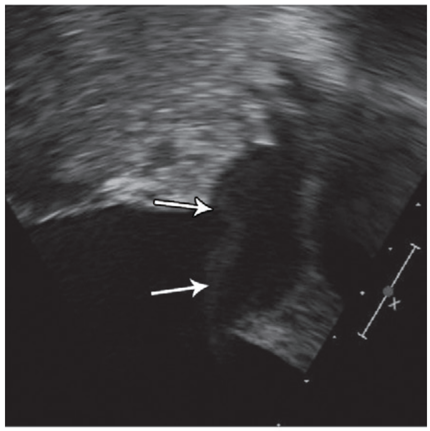
b.

Figure 2: Dual-energy cardiac CT and TEE images in 63-year-old woman with stroke, an LAA thrombus, and SEC. **(a)** Axial CT iodine map shows filling defect in the LAA; the mean iodine concentration was 3.34 mg/mL within the L1 ROI and 1.62 mg/mL within the L2 ROI. **(b)** TEE image shows fresh thrombus (arrow) with SEC in the LAA.

Figure 3



a.



b.

Figure 3: Dual-energy cardiac CT and TEE images in 69-year-old man with stroke and SEC. **(a)** Axial CT iodine map shows filling defect in the LAA; the mean iodine concentration within the ROI was 3.36 mg/mL. **(b)** TEE image obtained 1 day after CT shows SEC (arrows) without a thrombus in the LAA.

sensitivity, specificity, and area under the ROC curve were 100%, 100%, and 1.000 (95% CI: 0.887, 1.000), respectively. When we used Hounsfield unit ratios for differentiating thrombus from circulatory stasis, the best cutoff threshold was defined as 0.19 HU. Using the cutoff value of 0.19, the overall sensitivity, specificity, and area under the ROC curve were 82%, 67%, and 0.797 (95% CI: 0.607, 0.922), respectively. There were statistically significant differences in areas under the ROC curve in the differentiation between thrombus and circulatory stasis (1.000 vs 0.797, P = .014) (Fig 4).

Of the 18 filling defects diagnosed as circulatory stasis at quantitative analysis at CT, SEC was categorized as severe in eight cases, moderate in eight cases, and mild in two cases. However, the mean iodine concentration for severe SEC (3.41 mg/mL), moderate SEC (3.46 mg/mL), and mild SEC (4.54 mg/mL) did not vary significantly among SEC grades determined at TEE ($P > .05$).

At TEE, the mean LAA emptying velocities were 16.7 cm/sec ± 3.6 for thrombus, 22.8 cm/sec ± 7.2 for SEC, and 60.8 cm/sec ± 14.2 for the control group (no thrombus or SEC). The mean LAA emptying velocity was significantly different among the three groups ($P < .001$). However, the mean LAA emptying velocity was not significantly different between thrombus and SEC (P = .372). The LAA emptying velocity was positively correlated with the mean iodine concentrations at CT (r = 0.841). The mean iodine concentration for thrombus and SEC showed moderate correlation with LAA-AA Hounsfield

Table 3

Comparison of Quantitative Values for Thrombus, Circulatory Stasis, and Control Groups

Quantitative Value	Thrombus Group (*n* = 13)	Circulatory Stasis Group (*n* = 18)*	Control Group (*n* = 31)
Iodine concentration (mg/mL)	1.23 ± 0.34	3.61 ± 1.01	15.47 ± 3.06
LAA-AA Hounsfield unit ratio	0.18 ± 0.44	0.24 ± 0.72	0.89 ± 0.86

Note.—Data are means ± standard deviations.

* For quantitative analysis, one mild SEC that was missed at CT was excluded.

Figure 4

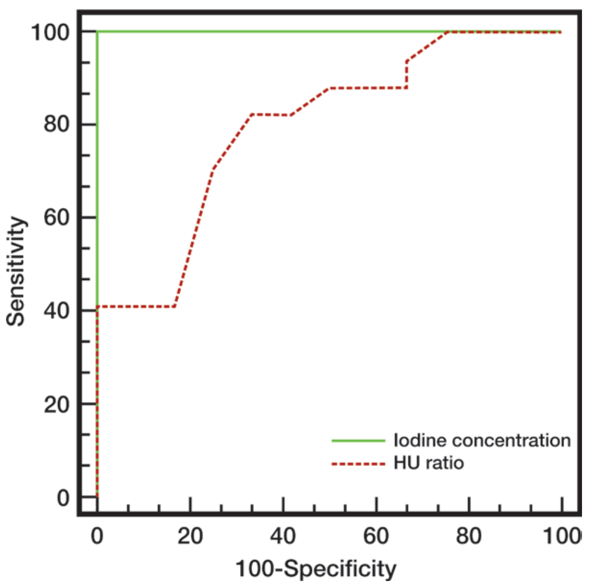


Figure 4: ROC curves of iodine concentration and Hounsfield unit ratio for distinguishing thrombus from circulatory stasis. The best cutoff values were 1.74 mg/mL for iodine concentration and 0.19 HU for LAA-AA Hounsfield unit ratio. The areas under the ROC curve were 1.000 and 0.797, respectively.

unit ratios at CT (*r* = 0.595). There was good interobserver agreement for mean iodine concentration and LAA-AA Hounsfield unit ratio (*r* = 0.897 and 0.884, respectively).

Discussion

This study was designed to examine the performance of dual-energy cardiac CT in comparison with TEE for the detection of thrombus and for differentiation between LAA thrombus and circulatory stasis in patients with stroke. We demonstrated that dual-energy cardiac CT is a noninvasive and sensitive modality for detecting LAA thrombus. Furthermore, using the dual-energy technique, it was possible to differentiate thrombus from circulatory stasis with an acceptable radiation dose.

AF is a major independent risk factor for stroke, and the risk increases when patients with AF have concomitant potential cardiac sources of embolism (4–6). Thus, accurate detection and diagnosis of high-risk embolic sources such as cardiac thrombi are important as they provide a substrate for embolic events and a rationale for anticoagulation therapy. In clinical practice, a noninvasive method with high reliability and accuracy comparable to those of TEE for the identification of intracardiac thrombus would be of substantial clinical value. Currently, CT can be used for the detection of intracardiac thrombus with high diagnostic accuracy (9–12). However, CT identifies intracardiac thrombus on the basis of its anatomic appearance. Therefore, it may be challenging to differentiate an LAA thrombus from circulatory stasis, which can appear as an apparent filling defect on CT images, thereby mimicking a thrombus. Comparing TEE and cardiac CT data in 223 patients with AF, Kim et al (10) reported that the sensitivity, specificity, positive predictive value, and negative predictive value for the detection of severe SEC and thrombus using cardiac CT were 93%, 85%, 31%, and 99%, respectively. This result suggests that CT can yield false-positive findings and is therefore incapable of allowing one to visually distinguish all instances of circulatory stasis from definite thrombus, thus resulting in reduced specificity. Further assessment with delayed imaging of the LAA after 1–2 minutes can improve the specificity for distinguishing circulatory stasis from thrombus (12). However, this two-phase protocol increases patient radiation exposure.

We used dual-energy CT for simultaneously detecting intracardiac thrombus and distinguishing thrombus from circulatory stasis. By using the dual-energy CT technique, it is possible to differentiate iodine from other high-attenuation materials by making use of the material decomposition theory (13,16,17). Materials can be differentiated by analyzing changes in the attenuation coefficient at two different x-ray energies. Because of the capability of dual-energy CT to help differentiate between iodine-enhancing lesions and nonenhancing lesions, we hypothesized that, using the dual-energy technique, it may be possible to differentiate thrombus from circulatory stasis. To achieve a sufficient attenuation difference between iodine-enhancing and nonenhancing lesions, we used 50 mL of the contrast agent for a test-bolus injection, and scanning was performed in a delayed phase, 180 seconds after provision of the test bolus.

We found that dual-energy cardiac CT showed both high sensitivity (97%) and high specificity (100%) in the detection of intracardiac filling defects in the LAA in patients with stroke, as compared with TEE. We had one false-negative finding on CT, which was diagnosed as mild SEC at TEE. Because of the time interval between the two modalities, the presence or severity of AF could have affected this result. However, 13 thrombi and moderate or severe instances of SEC were all correctly detected at CT. In addition, with the dual-energy technique, the mean iodine concentrations were significantly different between thrombus and circulatory stasis (P = .001).

In our study, the mean LAA-AA Hounsfield unit ratio was also significantly different between thrombus and circulatory stasis (0.18 vs 0.24, P = .008). Our previous study (18) demonstrated that delayed contrast-enhanced CT performed by using a double-injection protocol showed high sensitivity (96%) and specificity (100%) in thrombus and circulatory stasis detection. However, when the best cutoff value of a 0.2-HU ratio was determined by using ROC curves for separating thrombus from circulatory stasis, CT showed sensitivity of 85% and specificity of 94%. This result suggested that quantitative analysis with LAA-AA Hounsfield unit ratios is insufficient for accurate differentiation between thrombus and circulatory stasis.

In this study, when we used the best cutoff value of 1.74 mg/mL and calculated the overall sensitivity and specificity for the detection of thrombi, CT showed both high sensitivity (100%) and high specificity (100%). When we compared the diagnostic performance in the differentiation between thrombus and circulatory stasis using the quantitative values of LAA-AA ratios and iodine concentration, the AUC was significantly larger with the best cutoff value of iodine concentration than with the best cutoff value of Hounsfield unit ratio (1.000 vs 0.797, P = .014). These results suggest that dual-energy cardiac CT is more useful for differentiation between thrombus and circulatory stasis than conventional single-phase CT.

LAA dysfunction, which is often associated with AF, is also commonly accompanied by SEC (19,20). LA and LAA SEC is caused by local blood stasis, which is associated with a high incidence of thrombus formation and thromboembolic events (21,22). We evaluated whether any quantitative value at dual-energy CT can predict LAA function by measuring the mean iodine concentration on iodine map images. Our data revealed that the mean iodine concentration was strongly correlated with LAA emptying velocity as measured by using TEE (r = 0.841). However, our quantitative analysis showed that CT, as compared with TEE, could not help differentiate the severities of SEC. This finding suggests that iodine concentration can indirectly predict the function of the LA and LAA but is insufficient for accurate characterization of SEC severity in the LA and LAA.

TEE is not only the imaging method of choice for the detection of LAA thrombus or SEC but also can help detect cardioembolic sources of stroke such as patent foramen ovale, valvular vegetations, and mobile thrombi in the aorta. In addition, in contrast to CT, TEE can be performed in patients with renal dysfunction or an allergy to contrast media. However, TEE is a semi-invasive test. A recent report (23) indicated that multidetector CT is a useful noninvasive modality for the etiologic assessment of ischemic stroke. According to these data, multidetector CT facilitated correct etiologic classification in 38 (83%) of 46 patients.

In clinical practice, a less invasive modality that is capable of helping assess intracardiac thrombus in the setting of embolic stroke is desirable. We suggest that cardiac CT with the new dual-energy technique described in this study can be used as an alternative modality for detecting thrombus in selected patients with stroke because it has high diagnostic accuracy for the detection of intracardiac thrombus, it is capable of helping distinguish SEC from thrombus, and it is a noninvasive and reproducible modality.

We recognize that our study had several limitations. First, we did not perform dual-energy cardiac CT in all patients with stroke who underwent TEE. For CT, we selected patients with AF who had intracardiac thrombus or SEC confirmed at TEE. However, we prospectively enrolled 31 patients who were planning to undergo AF ablation and who had no intracardiac abnormalities at TEE as a control group and compared dual-energy CT and TEE findings. Second, we did not perform the two examinations on the same day. Rather, all examinations performed to evaluate patients for cardiac embolic sources of stroke were performed within a 3-day period. Third, because of the double injection of contrast agent, we used a total of 120 mL of contrast agent, which is much larger than the amount usually used for current cardiac CT protocols. However, we believe that this amount is acceptable for patients with normal renal function. In our study, the mean blood urea nitrogen and creatinine levels of the patients were 15.8 mg/dL (range, 9.8–23.8 mg/dL) and 1.01 mg/dL (range, 0.67–1.23 mg/dL [59.23–108.73 μmol/L]), respectively. Fourth, dual-energy cardiac CT was performed without electrocardiographic synchronization, because of the current technical limitations of the single-source CT with dual-energy option. Therefore, lack of synchronization with cardiac movements may have hindered visualization of small structures inside the LAA and created artifacts on images. A further limitation was radiation exposure. In our study, the calculated mean radiation dose was 3.98 mSv. Although a small amount of radiation exposure is inevitable, we believe that this technique provides a means of detecting and ruling out potential intracardiac thrombus in selected patients with stroke and has an acceptable radiation dose.

In conclusion, dual-energy cardiac CT is a noninvasive and sensitive modality for detecting LAA thrombus in patients with stroke. In addition, using the dual-energy technique, it is possible to differentiate between thrombus and circulatory stasis. Therefore, we believe that dual-energy cardiac CT may be clinically useful for detecting and ruling out intracardiac thrombus in patients at risk for cardioembolic stroke and that it could be an alternative diagnostic tool to TEE.

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