Diagn Interv Radiol 2022; 28:98–102

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RADIOLOGY PHYSICS

ORIGINAL ARTICLE

CT dose management for neurologic events in patients with cardiac devices: Radiation exposure variation in patients with cardiac devices

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PURPOSE
We aimed to compare the inter-center cranial computed tomography (CT) acquisition rates, CT findings, CT-related radiation dose, and variability of CT acquisition parameters for neurologic events among patients with implantable cardioverter-defibrillator (ICD) or left ventricular assist device (LVAD).

METHODS
A total of 224 patients (ICD group, n=155; LVAD group, n=69) who had at least one cranial CT scan were enrolled from 3 medical centers (Centers A, B, and C). The variability and effect of the number, indication, and findings of cranial CT scans as well as CT acquisition parameters including tube potential (kV), tube current (mAs), tube rotation time, slice collimation, and spiral or sequential scanning techniques on CT dose index volume ($CTDI_{vol}$), and total dose length product (DLP) were analyzed.

RESULTS
The mean DLP value of Center A and the mean $CTDI_{vol}$ values of Centers A and C were significantly lower than those of Center B (P < .001). The mean $CTDI_{vol}$ and DLP values in the ICD group were substantially lower than in the LVAD group (P < .001). The most potent parameters causing the changes in $CTDI_{vol}$ and DLP were kV, mAs values, and the CT scanning technique (sequential or spiral), according to multivariate linear regression analysis.

CONCLUSION
Cranial CT acquisition parameters and radiation doses vary significantly between centers, which necessitates optimization of cranial CT protocols to overcome the cumulative radiation dose burden in patients with neurologic events.

Implantable cardioverter defibrillators (ICD) and left ventricular assist devices (LVAD) have significantly improved the quality of life and survival rate of patients with cardiac arrhythmias and heart failure.[1,2] However, life-threatening complications related to the device itself, surgical technique, and perioperative management (bleeding, thromboembolic events, and infection) may occur.[3,4] Neurological events may present as a devastating complication of cardiac devices, which are associated with increased morbidity and mortality. The incidence of acute neurological events was reported as 14% and 47% in patients with LVAD and ICD, respectively.[5,6] Diagnosis, management, and post-treatment follow-up of patients with acute cerebrovascular events, especially cerebral ischemia complicated with hemorrhage, need repetitive cranial imaging with computerized tomography (CT) or magnetic resonance imaging (MRI). However, not all ICDs or LVADs are compatible with MRI. Furthermore, repeated cranial CT scans enhance radiation exposure and related cancer risk.[7] Cumulative CT radiation exposure was reported to add progressively to malignancy risk in a previous report.[8]

Ionizing radiation dose depends on imaging acquisition parameters of the CT scanners, which usually vary between centers, resulting in variable dose levels for the same CT examinations. Radiation dose variability in the CT protocols of different centers may cause non-negligible cumulative dose exposure in patients who undergo repetitive CT scans. In this multicenter study, our goal was to compare the cranial CT acquisition rates, CT findings,

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Received: 21 August 2020; revision requested 12 October 2020; last revision received 8 January 2020; accepted 12 January 2021.

Published online 16 August 2021.

DOI 10.5152/DIR.2021.20673

You may cite this article as: Coban G, Parlak S, Onur MR, *et al*. CT dose management for neurologic events in patients with cardiac devices: Radiation exposure variation in patients with cardiac devices. *Diagn Interv Radiol*. 2022;28(1):98-102.

and CT-related radiation dose exposure and to predict a dose reduction plan in patients with ICD or LVAD from 3 medical centers.

Methods

Study population

Our institutional review board approved this retrospective multicenter (Centers A, B, and C) study (protocol number GO18/1033). Informed consent was obtained from participants before cranial CT imaging. A total of 224 patients who had at least one cranial CT scan between January 2014 and October 2018 were enrolled from 3 medical centers (ICD group from Center A, n=155; LVAD group from Centers B and C, n=69). Patients without detailed radiation dose reports were excluded from the study. Only cranial CT acquisition parameters were selected to homogenize the CT protocol group in this multicenter study.

CT technique and dose analysis

The study data were obtained from 3 different medical centers and radiology information systems (HIS and RIS, respectively) using a preformatted data form. The contents of the preformatted data form included demographic characteristics of patients (age, sex, type of cardiac device, diagnosis on CT, number of cranial CT scans, and cranial CT acquisition parameters including tube potential, tube current, tube rotation time (TI), slice collimation (cSL), CT scanning techniques (spiral or sequential), and CT dose products, namely computed tomography dose index volume ($CTDI_{vol}$) and total dose length product (DLP). Radiologists (blinded to the study) obtained the parameters relevant to radiation dose from the cranial CT scan protocols generated by 7 different CT systems: 2 GE Medical Systems (Discovery CT750 HD, Lightspeed 16), 5 Siemens (Emotion Duo, Somatom Sensation 16, Somatom Perspective 64, Force, Definition AS plus 64), 1 Toshiba Aquilion 64. Mean and cumulative radiation dose values of patients from cranial CT scans performed during the study inclusion period were calculated using $CTDI_{vol}$ and DLP. Dose values of patients with ICD and LVAD were compared; the variability of cranial CT acquisition parameters and effect of CT acquisition parameters on $CTDI_{vol}$ and DLP values in the ICD group were investigated.

Main points

- The repetitive CT imaging to diagnose neurologic complications increases the cumulative dose burden in patients with implantable cardioverter-defibrillator and left ventricular assist devices.
- Mean and cumulative number of CT scans per patient change over a wide range between different centers.
- In particular, kV, mAs values, and CT scanning techniques (sequential or spiral) are the parameters with the strongest impact on $CTDI_{vol}$ and DLP changes.

Statistical analysis

The Kolmogorov–Smirnov test was used to determine whether continuous variables were normally distributed. Levene test was used to test for the assumption of homogeneity of variance. Descriptive statistics of the data were presented with n (%) and were shown as median (25th-75th percentiles) for non-normalized variables; normally distributed data were shown as mean ± SD. The significance of the difference in terms of continuous variables in which parametric test assumptions were provided between the groups was evaluated by Student t test when the number of independent groups was 2, and by one-way analysis of variance (ANOVA) for more than 2 groups. The significance of the difference in terms of continuous variables in which parametric test assumptions were not provided between the groups was evaluated by the Mann–Whitney U test when the number of independent groups was 2, and by the Kruskal–Wallis test for more than 2 groups. If the results of one-way ANOVA or the Kruskal–Wallis test statistics were found to be significant, the cause(s) were detected using post hoc Tukey HSD or Dunn–Bonferroni multiple comparison test. Pearson's chi-square test was used for categorical data. When there was an expected value problem in 2 × 2 or R × C contingency tables to compare categorical variables, Fisher exact or likelihood ratio tests were used, where appropriate. Spearman rank correlation coefficients were calculated to determine the degrees of association between continuous variables. Multivariate linear regression analyses were used to determine the best significant factor(s) in predicting changes in $CTDI_{vol}$ and total DLP dose. All significant variables at univariate analysis $P < .05$ were included in linear regression models as candidate factors. The regression coefficient, 95% CI, and t statistics were also calculated for each variable. Since the data of $CTDI_{vol}$ and total DLP dose levels were not distributed normally, logarithmic transformation was applied in multivariate linear regression analysis. Data were analyzed using IBM SPSS Statistics 17.0 (IBM Corp.). Results were considered statistically significant for $P < .05$.

Results

The demographic features of patients, mean number of CT examinations, CT findings, and mean radiation dose values of CT examinations are presented in Table 1. The majority of patients included in the study were from Center A and constituted the ICD group (69.20%). Patients from Center B (8.04%) and Center C (22.76%) comprised the LVAD group. Overall, acute neurologic events consisting of ischemia and hemorrhage were encountered in 11.61% of patients in Center A, 27.82% of patients in Center B, and 66.67% of patients in Center C. The incidence of acute cerebral ischemia was most common in Center B (n = 4, 22.22%). In comparison, intracranial bleeding was most common in Center C (n = 28, 54.90%). The median and number of CT examinations per patient in Center A was significantly lower than in Centers B and C (1 vs. 2 and 15, ($P < .001$) (Table 1). Median $CTDI_{vol}$ values in Center A and Center C were significantly lower than in Center B ($P < .001$). The median DLP value in Center A was significantly lower than in Center B ($P = .008$) and Center C ($P < .001$) (Table 2).

The median $CTDI_{vol}$ and DLP values in the ICD group were significantly lower than in the LVAD group ($P = .006$ and $P < .001$) (Table 2). There was a significant difference between median cumulative $CTDI_{vol}$ (45.8 mGy, 39.9-65.6 mGy vs. 238.0 mGy, 93.3-580.2 mGy) and DLP values (687.0 mGy·cm, 642.0-1188.0 mGy·cm vs. 4551.0 mGy·cm, 1406.5-11199.0 mGy·cm) of patients with ICD and LVAD ($P < .001$). The range of CT acquisition parameters in Centers A, B, and C are presented in Table 3. Tube potential values were lower in Center A and Center C than in Center B, while the most moderate tube current was used in Center A.

The CT acquisition parameters, including mean kV, mAs, and TI values, were significantly associated with the $CTDI_{vol}$ and DLP values (Table 4). The cSL values correlated with $CTDI_{vol}$ of CT examinations but not with DLP values. Median (25th-75th percentiles) $CTDI_{vol}$ and DLP values of patients (n = 118, 76.13%) who

Table 1. The demographic features of patients and CT findings						
	Center A (n = 155) (ICD)	Center B (n = 18)	Center C (n = 51)	*P*	LVAD (n = 69) (Center B + C)	ICD vs. LVAD *P*
Age (years), mean ± SD	71.0 ± 13.4	52.9 ± 12.1[a]	55.6 ± 11.3[b]	<.001*	54.9 ± 11.5	<.001**
Gender, n (%)				0.003‡		.002‡‡
Male	99 (63.90)	14 (77.80)	45 (88.20)		59 (85.50)	
Female	56 (36.10)	4 (22.20)	6 (11.80)		10 (14.50)	
Number of CT examinations, median (25th-75th percentiles)	1 (1-2)	2 (1-4)[d]	15 (8-28)[b,e]	<.001#	10 (2-23)	<.001##
CT findings, n (%)						
Normal	83 (53.55)	0 (0.0)[a]	2 (3.92)[b]	<.001‡	2 (2.89)	<.001‡
Acute ischemia	7 (4.51)	4 (22.22)[f]	6 (11.77)	0.026§	10 (14.50)	.020‡‡
Chronic ischemia	54 (34.84)	13 (72.22)[g]	15 (29.41)[h]	0.004‡	28 (40.58)	.501‡‡
Bleeding	11 (7.10)	1 (5.56)	28 (54.90)[b,e]	<.001‡	29 (42.03)	<.001‡‡

CT, computed tomography; ICD, introverter cardiac defibrillator; LVAD, left ventricular assist device; SD, standard deviation.
*One-way ANOVA), ‡Pearson chi-square test, #Kruskal–Wallis test, § Likelihood ratio test, **Student t test, ‡‡ Continuity corrected chi-square test, ## Mann-Whitney U test.
a: Center A vs. B ($P < .001$), b: Center A vs. C ($P < .001$), c: Center A vs. C ($P = .002$), d: Center A vs. B ($P = .013$), e: Center B vs. C ($P < .001$), f: Center A vs. B ($P = .017$), g: Center A vs. B ($P = .005$), h: Center B vs. C ($P = .004$).

underwent sequential cranial CT in Center A were significantly higher than median $CTDI_{vol,}$ and DLP values of patients (n = 37, 23.87%) who underwent cranial CTs performed with spiral CT technique (CTDIvol, 43.6 mGy [41.6-45.8 mGy] vs. 35.5 mGy [33.6-38.9 mGy], $P < .001$; DLP, 687.0 mGy·cm [642.0-733.0 mGy·cm] vs. 584.5 mGy·cm [511.7-651.7 mGy·cm], $P < .001$). The most powerful parameters causing the changes in $CTDI_{vol}$ and DLP were kV, mAs values, and CT scanning technique (sequential or spiral), according to multivariate linear regression analysis ($P < .001$) (Table 5). An increase in kV, mAs, TI, and cSL values, and the use of sequential CT imaging resulted in increased $CTDI_{vol}$ (coefficient of determination and the significance level of regression model were found as $R^2 = 0.593$ and $P < .001$, respectively). Independent of other factors, an increase in kV, mAs, and TI values and sequential imaging caused increased DLP values (coefficient of determination and the significance level of regression model were found as $R^2 = 0.593$ and $P < .001$, respectively).

Table 2. The comparisons of median CTDI volumes and DLP values across centers and between ICD and LVAD groups		
	Median $CTDI_{vol}$	Median DLP
Center A	43.3 (39.2-45.8)	670.0 (618.9-726.4)
Center B	95.0 (80.0-103.6)[a]	1357.5 (508.5-1636.2)[a]
Center C	43.9 (40.5-46.3)[b]	767.7 (734.3-819.4)[c]
P	<.001	<.001
ICD	43.3 (39.2-45.8)	670.0 (618.9-726.4)
LVAD	44.6 (41.1-49.8)	776.6 (733.0-849.1)
P	.006	<.001

Data were presented as median (25th-75th percentiles.) Kruskal–Wallis test was used for between center comparisons. Mann–Whitney U test was used for between device comparisons.
[a]Center A vs. B ($P < .01$),
[b]Center B vs. C ($P < .001$),
[c]Center A vs. C ($P < .001$).

Table 3. The range of CT acquisition parameters in centers				
Centers	Tube potential (kV)	Tube current (reference mAs)	Tube rotation time (s)	Collimated slice thickness (mm)
Center A	110-130	200-250	0.5-2	1-5
Center B	120-140	250-300	N/A	N/A
Center C	110-130	200-300	0.6-1.5	1-5

Discussion

Our results indicate that cranial CT frequency and radiation dose are significantly higher in patients with LVAD than patients with ICD. Furthermore, radiation dose parameters varied significantly between centers due to the use of incompatible CT protocols, which should be standardized.

Patients with cardiac devices undergo repetitive CT scans due to neurological emergencies and are exposed to significant cumulative radiation dose burden. Standardization of CT acquisition parameters under the guidance of dose reduction techniques is crucial in these patient groups.

In this retrospective multicenter study, we compared the CT acquisition parameters and dose products between different centers and CT vendors. The CT acquisition parameters applied and the resultant dose values of the 3 centers were more varied more than expected, which denotes the importance of standardization of repetitive CT examinations that produce a cumulative dose.

In our study, intracranial hemorrhage was more common in patients with LVAD compared to those with ICD, which caused

Table 4. Correlation coefficients and significance levels between the age, number of CT examinations, CT acquisition parameters, and radiation dose values in patients with ICD

	$CTDI_{vol}$		DLP	
	r	*P*	r	*P*
Age	0.057	.494	0.016	.841
Number of CT examinations	−0.162	.050	−0.071	.383
Mean tube potential	0.282	<.001	0.366	<.001
Mean tube current	0.436	<.001	0.316	<.001
Mean rotation time	0.391	<.001	0.245	<.001
Mean collimated slice thickness	0.398	<.001	0.056	.493

r, Spearman rank correlation coefficient.

Table 5. Effect of CT acquisition parameters on $CTDI_{vol}$ and DLP values of CT examinations performed in patients with ICD

		95% CI			
	B	LL	UL	t	*P*
$CTDI_{vol}$					
Mean kV	0.011	0.008	0.014	6.467	<.001
Mean mAs	0.002	0.001	0.002	6.793	<.001
Mean TI	0.009	-0.026	0.043	0.500	.618
Mean cSL	0.010	0.003	0.017	2.835	.005
Sequential CT scanning	0.092	0.060	0.124	5.738	<.001
Total DLP					
Mean kV	0.013	0.007	0.018	4.834	<.001
Mean mAs	0.002	0.001	0.003	5.755	<.001
Mean TI	−0.031	−0.087	0.024	−1.123	0.263
Sequential CT scanning	0.107	0.055	0.158	4.102	<.001

B, coefficient of regression; CI, confidence interval; LL, lower limit; UL, upper limit.

a higher frequency of cranial CT examinations and higher cumulative radiation exposure in the LVAD group than the ICD group. However, bleeding can be detected in cranial CTs performed with low kV and mAs values. Increasing the gantry rotation speed and the slice collimation by changing detector configuration can decrease the radiation dose without significantly lowering the contrast resolution and yield acceptable CT image quality in the follow-up of intracranial hemorrhage.[9] Our results also showed a positive correlation between slice collimation and $CTDI_{vol}$, a finding which conflicts with previous studies.[10,11] In our opinion, this unexpected correlation would be due to the most frequent usage of sequential cranial CT (n = 118, 76.13%) in Center A.

Radiation exposure should always be managed with the ALARA (as low as reasonably achievable) principle. We can manipulate the CT acquisition parameters in patients who need repetitive CT examinations, by ongoing communication with the physicians. In patients with the suspicion of ischemia, visualization of early ischemic regions may necessitate high contrast and spatial resolution on CT images, which may be accomplished with increased tube current and decreased slice collimation, preserving the image quality.[10] Given the low percentage of patients with suspected acute ischemia (n = 17, 7.58%) in our patient cohort, CT protocol selection algorithm may have been inefficient in the radiology departments of these centers. Furthermore, MRI compatibility of devices could be questioned in more detail in patients with ICD, and diffusion-weighted imaging, could replace cranial CT scans, where applicable. We are not aware whether such detailed information about patients' intracardiac devices was available to radiology staff in the centers where we performed our study.

Our study also revealed a significant difference between cranial CT acquisition rates of imaging centers. The median number of CT acquisition per patient in Center C (15 [8-28]) was higher than in Center A (1 [1-2]), and Center B (2 [1-4]). Device types of the patients may be responsible for the difference in CT acquisition rates of Centers A and C as patients in Center C included only patients having LVAD.

The high frequency of abnormal findings in Centers B and C compared with Center A is not surprising, since patients with LVAD are more prone to neurologic complications than the ICD group.[12] The underlying pathophysiologic mechanism of increased intracranial hemorrhage risk in LVAD patients was attributed to the non-physiologic pump hemodynamics that places a shearing force on circulating blood components, causing platelet dysfunction. This increased intracranial hemorrhage risk.[13,14]

The present study emphasizes the need for optimization of cranial CT protocols because the ionizing radiation doses of cranial CTs from 3 CT scanners were significantly different. Comparison of CT radiation doses in terms of $CTDI_{vol}$ and DLP yielded markedly higher dose values of Center B than Center A and Center C. The higher $CTDI_{vol}$ and DLP values in Center B were the result of using high tube voltage and current in cranial CT scanning. Radiation dose reduction principles consist of appropriateness criteria for imaging examinations and optimization of imaging techniques. Although the CT acquisition rate of Center B was low, an increased radiation dose exposure in this center was incompatible with the ALARA principle, with unoptimized CT acquisition parameters.

Optimization of CT acquisition parameters is crucial, particularly in clinical circumstances that need repetitive CT scans, as in cases with cardiac device implantation. This study revealed that ionizing radiation dose exposure value of CT scans is correlated with kV, mAs, tube rotation time, and collimated section thickness values in CT protocols. Decreasing tube potential and current and increasing tube rotation time results in reduced radiation dose.

The CT scanning technique has been well known to have a role in emitted radiation dose of CT scanners. Sequential CT scanning has been reported to cause higher radiation dose exposure than spiral CT scanning.[15,16] Similarly, we found that CT examinations performed with sequential CT scanning resulted in increased radiation dose. Previous studies indicated that image quality between spiral and sequential CT scanning was similar for cranial studies.[17] Bahner et al. recommended a sequential CT technique only for assessment of small structures.[18] The authors of this study, therefore, believe that the use of spiral CT technique in the acquisition of repetitive cranial CT scans would cause a significant reduction in radiation doses without lowering image quality and detection rate of acute stroke. The optimization of the CT scan range in the *z*-axis also plays a critical role in radiation exposure. According to dose results (Table 2), although $CTDI_{vol}$ values of cranial CTs performed in Center A and Center C were similar, the median DLP value of Center A was significantly lower than Center C, which implies the importance of optimization of CT scan range in the *z*-axis.

Our study had several limitations. First, we were not able to find some of the CT acquisition parameters in the dose report of CT examinations, which limited the evaluation of the effects of each parameter on CT doses. The second limitation was the absence of information about the neuroimaging history of these patients in other centers, which in turn restricted full assessment of the cumulative dose of patients. The third limitation was the unavailability of different parameters such as tube filtration, iterative reconstruction technique, and detector configuration, all of which vary across vendors. Although we emphasized the importance of modifying CT acquisition parameters such as decreasing tube voltage or increasing tube rotation time to reduce radiation dose, we did not evaluate the effect of modification of these parameters on image quality. Absence of patient-specific organ dose and effective dose values could be considered as another limitation of this study. However, radiation effects on specific tissues were beyond the scope of our study.

In conclusion, cranial CT examinations are indispensable in neurological emergencies. In patients with a cardiac device, acute neurologic events may necessitate repetitive CT examinations, which result in a cumulative dose burden. Applying radiation dose reduction strategies such as decreasing tube potential, tube current, and tube rotation time values, and increasing tube collimation thickness value in this patient group can result in a "dampening" effect in patient dose.

Conflict of interest disclosure

The authors declared no conflicts of interest.

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