Coronary artery disease remains the most frequent cause of death and disability in the developed world and rates are increasing among developing nations. As the population at risk has increased, national health care systems are under financial pressure to deliver cost-effective diagnosis and risk stratification of symptomatic patients suspected of having coronary ischemia. Noninvasive multislice cardiac computed tomography angiography (CCTA) has emerged since 2000 as a new diagnostic test with the potential to efficiently address this challenge.

Multiple studies of the accuracy of CCTA compared with invasive coronary angiography in thousands of patients have documented sensitivities and negative predictive values in the range of 90%. This suggests that CCTA may definitively exclude the diagnosis of coronary artery disease in a substantial proportion of appropriately selected patients, allowing scarce

Context  Cardiac computed tomography angiography (CCTA) can accurately diagnose coronary artery disease, but radiation dose from this procedure is of concern.

Objectives  To determine whether a collaborative radiation dose–reduction program would be associated with reduced radiation dose in patients undergoing CCTA in a statewide registry over a 1-year period and to define its effect on image quality.

Design, Setting, and Patients  A prospective, controlled, nonrandomized study conducted during a control period (July-August 2007), an intervention period (September 2007-April 2008), and a follow-up period (May-June 2008) at 15 hospital imaging centers participating in the Advanced Cardiovascular Imaging Consortium in Michigan, which included small community hospitals and large academic medical centers. A total of 4995 sequential patients undergoing CCTA for suspected coronary artery disease were enrolled; 4862 patients (97.3%) had complete radiation data for analysis.

Intervention  A best-practice CCTA scan model was used, which included minimized scan range, heart rate reduction, electrocardiographic-gated tube current modulation, and reduced tube voltage in suitable patients.

Main Outcome Measures  Primary outcomes included dose-length product and effective radiation dose from all phases of the CCTA scan. Secondary outcomes were image quality assessed by a 4-point scale (1 indicated excellent; 2, good; 3, adequate; and 4, nondiagnostic) and frequency of diagnostic-quality scans.

Results  Compared with the control period, patients’ estimated median radiation dose in the follow-up period was reduced by 53.3% (dose-length product decreased from 1493 mGy/cm [interquartile range {IQR}, 855-1823 mGy/cm] to 697 mGy/cm [IQR, 407-1163 mGy/cm]; P = .001) and effective dose from 21 mSv (IQR, 12-26 mSv) to 10 mSv (IQR, 6-16 mSv) (P < .001). The greatest reduction in dose occurred at low-volume sites. There were no significant changes in median image quality assessment during the control period compared with the follow-up period (median image quality of 2 [images rated as good] vs median image quality of 2; P = .13) or frequency of diagnostic-quality scans (554/620 patients [89%] vs 769/835 patients [92%]; P = .07).

Conclusion  Consistent application of currently available dose-reduction techniques was associated with a marked reduction in estimated radiation doses in a statewide CCTA registry, without impairment of image quality.

Trial Registration  clinicaltrials.gov Identifier: NCT00640068
health care resources to be focused on those patients truly requiring long-term medical therapy or expensive invasive procedures.

The exposure of patients to ionizing radiation during CCTA is a barrier to wider implementation of this test. The concern about the potential carcinogenic effects of diagnostic levels of radiation has recently been heightened by reports suggesting that some patients may incur substantial cumulative radiation doses due to repeated CT scans, radio-nuclide testing, and/or fluoroscopy over the course of their lifetimes. Although the rate of occurrence of cancer induction from diagnostic radiation remains controversial, it is generally accepted that even very low radiation doses have some cancer-inducing potential. The technique of CCTA is particularly amenable to radiation dose reduction using hardware and acquisition protocols customized to patients’ characteristics. However, implementing these techniques is a practical challenge for physicians and technologists trying to achieve optimal diagnostic image quality.

The Advanced Cardiovascular Imaging Consortium (ACIC) is a multicenter, collaborative quality improvement program at hospitals and imaging practices providing CCTA in the state of Michigan. In July 2007, a radiation dose–reduction study was initiated at 15 ACIC participating sites. Its objectives were to determine whether implementation of a best-practice model for scan acquisition would be associated with a reduction in the estimated radiation dose from CCTA and to define the associated effects on image quality and the frequency of diagnostic-quality scans.

**METHODS**

The ACIC is a voluntary, collaborative quality improvement program that now has 40 participating hospitals and imaging sites providing CCTA in the state of Michigan. The ACIC was organized in 2006 with ongoing financial support from Blue Cross/Blue Shield of Michigan and the Blue Care Network, which supports similar programs in different subspecialties. The operational method of the ACIC is to identify areas of potential care improvement that will become consensus best-practice goals, with participating sites voluntarily effecting change within their own institutions.

Patient enrollment in the ACIC began in July 2007, at which time 15 participating hospitals began collecting radiation data. The sites range in type from small community hospitals to large university and community hospitals with more than 1000 beds. The data from the initial months (July and August 2007) constitute the control period. The trial was conducted over the course of 12 months between July 1, 2007, and June 30, 2008, and only the original 15 ACIC sites were included in our analyses (2 sites had >30 scans per month and 13 sites had ≤30 scans per month). During the study period, 5173 patients underwent CCTA scanning at these sites, of whom 4995 agreed to participate in the ACIC registry (96.6%). This study includes data on all of the enrolled patients who had complete radiation-related data (4862/4995 consecutive patients [97.3%]; Figure 1).

This study was compliant with the Health Insurance Portability and Accountability Act and received a waiver from the institutional review boards of all participating sites, including a waiver of informed consent. The ACIC is conducted under the auspices of the Human Investigation Committee of the Research Institute of William Beaumont Hospital, which approved this study. All patients receive a patient information sheet on the ACIC database before imaging and can voluntarily exclude all of their information from the ACIC; only patients agreeing to ACIC participation are included in this report.

**Study Design**

A nonrandomized, controlled, prospective, multicenter trial conducted over 1 year, this study included consecutive patients undergoing clinically indicated CCTA. Baseline characteristics of the patients, radiation doses, and image quality metrics were analyzed after the control period. Based on these data, a set of best-practice recommendations for radiation dose reduction during CCTA scan acquisition was developed and disseminated to each participating site during the subsequent 8 months (the intervention period; September 2007–April 2008) at scheduled consortium meetings, during on-site visits by coordinating center staff, and via personal communications. During the final 2-month period (the follow-up period), measurement data were collected without further interventions and compared with the control period data.

**ACIC Data Collection**

The data collected by the coordinating center of the ACIC included detailed information about the patient characteristics of height, weight, baseline heart rate, and preexisting medical conditions such as asthma that could influence the choice of imaging protocols. These data were obtained from structured patient interviews and medical records. Nurses or technologists provided information about medication use and resulting vital sign responses at the time of the procedure. A technologist information sheet included the scanner manufacturer and model, and protocol parameters including longitudinal scan range, scan duration, scan voltage in peak kilovolts, the use of electrocardiographic-gated tube current modulation, and the resulting radiation measurements and calculated...
doses, including CT dose–index volume, dose-length product, and calculated effective dose in millisieverts. Importantly, the study data analysis included the total radiation dose from all parts of the CCTA scan, including topogram, test bolus or monitoring scan, coronary angiography, and calcium score (if performed). The reporting of total dose is distinct from some studies of radiation dose in CCTA, which reported only estimated absorbed or effective dose from the coronary angiogram scan alone.10,17 A structured physician report provided anatomical and functional findings, as well as semiquantitative image quality scores. Additional variables included the extent of severe calcification, motion artifacts, image noise, or low-contrast intensity that significantly impaired image interpretation.

Study End Points
The primary end points of the study were total dose–length product and effective radiation dose. The secondary end points of the study were the image quality score using a semiquantitative scale and the percentage of imaging studies that were considered to be of diagnostic quality.

Estimation of Radiation Dose
Radiation doses were estimated by previously described methods.8,10,13-15 Each scanner provided a protocol summary containing the dose-length product for each image series, which integrated estimated absorbed radiation in the x-, y-, and z-directions based on the CT-dose–index volume. The effective radiation dose was derived from the summed dose-length product multiplied by the European Working Group for Guidelines on Quality Criteria in Computed Tomography conversion coefficient (k = 0.014 mSv/mGy × cm).10,16

Image Quality Assessment
Physicians rated the quality of each image on a per-patient basis on the ACIC data collection forms according to the following scale. Excellent (score = 1) was defined as complete absence of motion artifacts, excellent signal-to-noise ratio, and clear delineation of vessel walls, with the ability to assess luminal stenosis as well as plaque characteristics. Good (score = 2) was defined as nonlimiting motion artifacts, reduced signal-to-noise ratio and/or calcifications are present, with preserved ability to assess luminal stenosis as well as plaque characteristics. Adequate (score = 3) was defined as reduced image quality due to any combination of noise, motion, poor contrast enhancement, or calcium that significantly impairs ease of interpretation, but image quality is sufficient to rule out significant stenosis. Nondiagnostic (score = 4) was defined as reduced image quality that precludes adequate assessment of stenosis in the majority of vessels.

Radiation Dose–Reduction Program
A radiation consulting team was selected by the Consortium Executive Committee that included the physician program director (G.L.R.), a consulting radiologic technologist (R.E.G.), and a licensed medical physicist. This team created a best-practice model for CCTA acquisition designed to reduce radiation dose (Box). This model is based on previously published methods of radiation dose reduction and included minimizing longitudinal scan range; use of sufficient B-blockers to control heart rate and heart rate variability; maximizing use of electrocardiographic-gated tube current modulation; narrowing the acquisition window at low, stable heart rates; and decreasing scan voltage in normal-weight individuals.13,14,17 At the time of the first quarterly meeting of the ACIC, data from the consortium as a whole was provided for all of the participants as well as individual site data for comparison. During that meeting, lectures on scanner technology, patient preparation, and customization of protocols to patient characteristics were provided. Consultation was arranged with representatives of scanner manufacturers for individualized onsite instruction in scanner-specific techniques. Each participating site identified a physician and radiology technologist who would be responsible for implementing the best-practice program.

Statistical Analyses
Continuous variables are shown as mean and standard deviation where applicable, otherwise, medians and 25th and 75th percentiles (interquartile range [IQR]) are given. Age was normally distributed and examined using a t test while body mass index (calculated as weight in kilograms divided by height in meters squared), hazard ratio, and the remaining continuous variables were examined using nonparametric Wilcoxon rank sum tests because they were not normally distributed. The categorical variables were examined using 2-sided χ² tests and are shown as counts and percentage frequency. A P value of less than .05 was considered significant; all P values were 2-tailed.

Significant univariable predictors of the achievement of a target dose of less than 15 mSv, corresponding to a dose-length product below 1070 mGy × cm, were identified using binary logistic regression analysis. This target was based on an estimated effective dose of 11 to 12 mSv for the CCTA scan alone,14 plus 1 to 2 mSv for noncontrast calcium scoring, and 1 mSv for the topogram and monitoring scan or test bolus scan. It was assumed that 8% of patients would have a triple rule-out scan or bypass graft imaging, which would raise the group’s median dose by about 1 mSv. All significant univariable predictors were further tested in a multivariable binary logistic regression model for the prediction of the target radiation dose. A P value of less than .20 was considered a criterion for the inclusion of the variable in the final multivariable prediction model.18 Data analyses were performed using SPSS version 11.5 (SPSS Inc, Chicago, Illinois) and SAS version 9.1.3 (SAS Institute Inc, Cary, North Carolina). For the sample size calculation in this study, a minimal observed decrease in the dose-length product value was assumed to be at least 5% in the follow-up period compared with the control period. Based on this assumption, the
sample size of 935 patients in both groups (control and follow-up) was required to show significance at the overall 2-sided α level of .05 with power of at least 90%. Under the assumption that 3% (at most) of the participants would not have complete data available for the analyses, the sample size was inflated to 985 patients in each group.

**RESULTS**

During the study period from July 1, 2007, through June 30, 2008, 5173 patients underwent CCTA scanning at study sites, of whom 4995 (96.6%) agreed to participate in ACIC. Of these, 4862 (97.3%) had complete data and were included in this analysis (Figure 1 and Table 1). The majority of the study participants were overweight (mean [SD] body mass index of 29.4 [6.0]). Only 550 patients (9%) had extended-range (full thorax) scans; these were obtained either for bypass graft imaging and/or triple rule-out (combined coronary and aorta or pulmonary artery angiography) scanning. There were no significant differences in patient characteristics between the control period and the follow-up period. Compared with the control period, the proportion of CCTA examinations ordered with coronary artery calcium scoring was significantly reduced during the follow-up period (410/574 patients [71%] vs 233/835 patients [28%]; P < .001). As part of the radiation dose–reduction program, acquisition of coronary calcium scores was recommended only if specifically ordered by the referring physician.

**Estimated Radiation Doses and Associated Factors**

Compared with the control period, patients’ median estimated radiation dose in the follow-up period was reduced by 53.3% (dose-length product decreased from 1493 mGy × cm [IQR, 853-1823 mGy × cm] to 697 mGy × cm [IQR, 407-1163 mGy × cm]; P < .001) and effective dose from 21 mSv (IQR, 12-26 mSv) to 10 mSv (IQR, 6-16 mSv) (P < .001; Table 2). The most frequently received effective radiation dose range decreased from 25-29 mSv to 5-10 mSv (Figure 2). An increase in the number of patients receiving the target dose below 15 mSv (P < .001 compared with the control period) was achieved at all sites (Figure 3). The increase in the proportion of those reach-
RADIATION DOSE FOR CARDIAC CT AFTER DOSE-REDUCTION IMPLEMENTATION

The most powerful univariable factors associated with achievement of the target radiation dose were the use of lower tube voltage (from 120 kVp to 100 kVp), which increased from 13% to 43% of cases (odds ratio [OR], 63 [95% confidence interval [CI], 45-87]; P < .001) (Table 3), and a site study volume of more than 30 scans per month (OR, 11 [95% CI, 10-13]; P < .001) (Figure 3). Among patient-related variables, reduction in heart rate demonstrated a strong positive association with a decreased radiation dose (OR, 1.02 [95% CI, 1.016-1.027] for each 1 beat per minute reduction; P < .001). While narrowing of the acquisition window based on heart rate during electrocardiographic-gated tube current modulation was recommended in the best-practice model, the time window was not directly measured. The use of electrocardiographic-gated tube current modulation increased from 84% of cases to 95% (P < .001), but this change was not significant in the model, possibly because of its frequent use throughout the study. Longitudinal scan range was inversely correlated with achieving the target dose (OR, 0.90 per 1 cm [95% CI, 0.88-0.92 per 1 cm]; P < .001).

Table 3 presents the multivariable binary logistic model for the prediction of the target radiation dose in the study population; this model showed similar results. Reduced tube voltage, high-scan volume, and low heart rate continued to be important predictors of lower dose, while longer scan range and use of either triple rule-out scanning or bypass graft imaging had a strong inverse relationship with achieving the target dose (OR, 0.50 [95% CI, 0.37-0.69]; P < .001).

Other independent and incremental patient-related factors predicting lower radiation dose were lower body mass index, female sex, and younger age.

**COMMENT**

The results of this study demonstrate that implementation of a best-practice model for scan acquisition was associated with a marked reduction in CCTA radiation dose in a statewide quality improvement program, and that diagnostic image quality was not impaired. The greatest reduction in improvement occurred at sites with lower scan volume. Baseline data obtained in this study support the concern that CCTA testing may result in relatively high radiation doses, but the rapid improve-

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**Table 1. Patient Characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Control Period (n = 620)</th>
<th>Intervention Period (n = 3407)</th>
<th>Follow-up Period (n = 835)</th>
<th>Overall Population (N = 4862)</th>
<th>P Valuea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, mean (SD), y</td>
<td>57.5 (13.1)</td>
<td>56.5 (13.0)</td>
<td>57.0 (13.2)</td>
<td>56.7 (13.0)</td>
<td>.46</td>
</tr>
<tr>
<td>Male sex, No. (%)</td>
<td>330 (53)</td>
<td>1822 (53)</td>
<td>436 (62)</td>
<td>2588 (53)</td>
<td>.40</td>
</tr>
<tr>
<td>Body mass index, mean (SD)</td>
<td>29.2 (6.4)</td>
<td>29.5 (6.0)</td>
<td>29.2 (6.1)</td>
<td>29.4 (6.0)</td>
<td>&gt;.05</td>
</tr>
<tr>
<td>Hypertension, No./total (%)</td>
<td>327 (54)</td>
<td>1692 (51)</td>
<td>432 (52)</td>
<td>2451 (51)</td>
<td>.41</td>
</tr>
<tr>
<td>Hyperlipidemia, No./total (%)</td>
<td>354 (57)</td>
<td>1823 (56)</td>
<td>435 (54)</td>
<td>2612 (56)</td>
<td>.006</td>
</tr>
<tr>
<td>Diabetes mellitus, No./total (%)</td>
<td>29 (6)</td>
<td>169 (5)</td>
<td>432 (52)</td>
<td>2451 (51)</td>
<td>.42</td>
</tr>
<tr>
<td>Current smoking, No. (%)</td>
<td>86 (15)</td>
<td>506 (15)</td>
<td>139 (17)</td>
<td>739 (15)</td>
<td>.15</td>
</tr>
<tr>
<td>Coronary artery disease</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Family history, No./total (%)</td>
<td>250 (44)</td>
<td>1464 (45)</td>
<td>332 (41)</td>
<td>2046 (44)</td>
<td>.39</td>
</tr>
<tr>
<td>Diagnosed, No. (%)</td>
<td>88 (14)</td>
<td>453 (13)</td>
<td>116 (14)</td>
<td>657 (14)</td>
<td>.87</td>
</tr>
<tr>
<td>Type of testc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCTA only, No. (%)</td>
<td>165 (27)</td>
<td>1875 (55)</td>
<td>76 (59)</td>
<td>2516 (52)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>CCTA with coronary calcium scoring, No./total (%)</td>
<td>410 (71)</td>
<td>1030 (32)</td>
<td>233 (28)</td>
<td>1673 (36)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>CCTA with evaluation of graft patency, No./total (%)</td>
<td>40 (6.7)</td>
<td>186 (5.5)</td>
<td>48 (6.7)</td>
<td>274 (5.7)</td>
<td>.47</td>
</tr>
<tr>
<td>CCTA with stent patency, No./total (%)</td>
<td>38 (6.4)</td>
<td>205 (6.0)</td>
<td>51 (6.1)</td>
<td>294 (6.1)</td>
<td>.85</td>
</tr>
<tr>
<td>Triple rule-out scan, No./total (%)</td>
<td>33 (5.6)</td>
<td>247 (7.3)</td>
<td>56 (6.7)</td>
<td>336 (7.0)</td>
<td>.40</td>
</tr>
<tr>
<td>Presenting symptom, No./total (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chest pain</td>
<td>330 (57)</td>
<td>1854 (55)</td>
<td>469 (56)</td>
<td>2663 (55)</td>
<td>.04</td>
</tr>
<tr>
<td>Dyspnea</td>
<td>216 (37)</td>
<td>997 (30)</td>
<td>223 (27)</td>
<td>1346 (30)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Asymptomatic</td>
<td>153 (27)</td>
<td>876 (30)</td>
<td>200 (24)</td>
<td>1229 (26)</td>
<td>.23</td>
</tr>
</tbody>
</table>

Abbreviation: CCTA, cardiac computed tomography angiography.

aComparison is between the control period and the follow-up period.

bCalculated as weight in kilograms divided by height in meters squared.

cThe categories are not mutually exclusive so summed values exceed 100%.

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ment in radiation dose in the first 3 intervention months (a decrease of 48%) demonstrates how use of existing technology and technical methods is associated with dramatically reduced doses. The dose-reduction program involved an educational aspect at every level in the imaging process. Without a feedback loop of regular dose measurements and reports, similar monitoring of patient preparation, and appropriate imaging protocols and resultant image quality, there would neither be the opportunity to detect dose elevations nor the ability to improve practice.

Individual imaging center experiences are illustrative. At one site there was a substantial baseline variation from standard CCTA practice due to consistent use of higher acquisition voltage (135 kVp); this was quickly corrected. At another site, the problem was more complex; several scanners were involved in the acquisition of cardiac studies at this large institution. Even with an experienced physician and licensed medical physicist providing input, it took time to implement a process involving many technologists performing these examinations at multiple locations.

From our multivariable analysis, a reduction in scan voltage from 120 kVp to 100 kVp emerged as the strongest variable associated with achieving a target dose under 15 mSv, followed by the monthly volume of the imaging site and lower heart rates. Interestingly, the increased use of electrocardiographic-gated tube current modulation was not a significant multivariable predictor in the improvement observed, but it was used frequently (74%) at the initiation of the study and the increase that resulted (to 94%) may not have been large enough to influence the model.

### Table 2. Bimonthly Radiation Dose Estimates, Scan Parameters, and Image Quality Measurements

<table>
<thead>
<tr>
<th></th>
<th>Control Period (Jul-Aug 2007) (n = 620)</th>
<th>Intervention Period</th>
<th>Follow-up Period (May-Jun 2008) (n = 835)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n = 943)</td>
<td>(n = 804)</td>
<td>(n = 858)</td>
</tr>
<tr>
<td>Dose-length product, median (IQR), mGy × cm</td>
<td>1493 (855-1823)</td>
<td>998 (591-1663)</td>
<td>1074 (621-1639)</td>
</tr>
<tr>
<td>Effective dose, median (IQR), mSv</td>
<td>21 (12-26)</td>
<td>14 (8-23)</td>
<td>15 (8-23)</td>
</tr>
<tr>
<td>100 kV used, No. (%)</td>
<td>79 (13)</td>
<td>261 (28)</td>
<td>236 (29)</td>
</tr>
<tr>
<td>Electrocardiogram current modulation, No. (%)</td>
<td>460 (74)</td>
<td>706 (75)</td>
<td>695 (86)</td>
</tr>
<tr>
<td>Scan length, mean (SD)</td>
<td>14.4 (4.4)</td>
<td>14.3 (3.4)</td>
<td>14.7 (3.9)</td>
</tr>
<tr>
<td>Heart rate, mean (SD), beats/min</td>
<td>65 (11)</td>
<td>65 (11)</td>
<td>66 (11)</td>
</tr>
<tr>
<td>Diagnostic quality scan, No. (%)</td>
<td>554 (89)</td>
<td>822 (87)</td>
<td>726 (90)</td>
</tr>
<tr>
<td>Scan quality</td>
<td>Median (IQR)</td>
<td>(n = 580)</td>
<td>(n = 889)</td>
</tr>
<tr>
<td>Excellent, No. (%)</td>
<td>189 (30.5)</td>
<td>260 (27.6)</td>
<td>213 (26.5)</td>
</tr>
<tr>
<td>Good, No. (%)</td>
<td>231 (37.3)</td>
<td>366 (38.8)</td>
<td>361 (44.9)</td>
</tr>
<tr>
<td>Adequate, No. (%)</td>
<td>134 (21.6)</td>
<td>196 (20.8)</td>
<td>152 (18.9)</td>
</tr>
<tr>
<td>Poor or nondiagnostic, No. (%)</td>
<td>26 (4.2)</td>
<td>67 (7.1)</td>
<td>61 (7.6)</td>
</tr>
</tbody>
</table>

Abbreviation: IQR, interquartile range.

*Comparison is between July-August 2007 and May-June 2008.
*The P value reflects the median for the 4 categories of excellent, good, adequate, and poor or nondiagnostic.

### Figure 2. Distribution of Patients by Estimated Radiation Dose

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which was an independently important factor. One method of achieving the correct longitudinal scan position is to use the noncontrast calcium scoring scan to define the levels of the coronary arteries.\textsuperscript{19} The use of full thorax scans, including the triple rule-out protocol, was inversely associated with achieving the target radiation dose. Consequently, this procedure should be reserved for cases in which there is a high clinical suspicion of aortic dissection or pulmonary embolism. Reduction of heart rate with use of β-blockers was emphasized to avoid motion artifacts, to allow maximal use of electrocardiographic-gated tube current modulation, and to permit narrowing of the scan acquisition time window to the greatest extent. Our results confirm that heart rate reduction was strongly associated with decreased radiation dose.

The findings of this study support and extend prior studies demonstrating an improvement in health care outcomes resulting from voluntary, collaborative quality improvement programs.\textsuperscript{20,22} These results also support previous research describing the level of radiation dose observed in clinical CCTA practice, the effectiveness of radiation dose-reduction techniques, and the ability to preserve image quality with their use.\textsuperscript{10,13,17,23,24}

In the Prospective Multicenter Study On Radiation Dose Estimates Of Cardiac CT Angiography in Daily Practice I (PROTECTION I), Hausleiter et al\textsuperscript{10} surveyed all consecutive CCTA scans from 50 international study sites over a 1-month period. An important difference between the 2 studies was that Hausleiter et al\textsuperscript{10} reported only the radiation dose incurred from the CCTA scan only, while our study analyzed the total cumulative dose resulting from all phases of the examination including the topogram, calcium scoring scan, monitoring or test bolus scans, and the CCTA scan. With this difference in mind, it is noteworthy that the median dose Hausleiter et al\textsuperscript{10} reported was 885 mGy × cm, corresponding to an effective dose of 12 mSv; this was lower than the dose during the control period of our study but higher than the final dose after the intervention period. While the study by Hausleiter et al\textsuperscript{10} did not include an interventional phase, there was marked variation in radiation doses among their sites, ranging from a minimum of 331 mGy × cm to 2146 mGy × cm. Analyzing the sources of variation in radiation dose, Hausleiter et al also found that using 100 kVp and higher monthly scan volumes...
were important predictors of lower radiation dose, whereas increased scan length and body mass index were associated with an increased radiation dose. They additionally reported that a reduced radiation dose was associated with sequential scanning.

Sequential CCTA scanning, also called prospective-triggered scanning, enables radiation dose reductions beyond the range of this study—to the 2- to 5-mSv level in suitable patients.25-29 This technique was not installed at any of our participating sites. More recently, single heartbeat acquisitions using wide detector–array 320-slice and high-pitch dual source scanners have been reported to provide further dose reductions to the 1- to 2-mSv range, regardless of heart rate, arrhythmia, or body habitus.22,30,31 It is noteworthy that the greatest dose reductions occurred at lower volume sites. In most cases, these sites had initiated CCTA scanning relatively recently and hence had less experience in this technique.

Clinical Implications
Observations from accuracy studies and clinical trials of CCTA in the evaluation of chest pain suggest that this technique may represent a diagnostic alternative to stress imaging studies, with greater efficiency and cost-effectiveness in appropriately chosen populations.23 However, enthusiasm for the potential cost savings and convenience of this method has been tempered by significant concerns about the doses of radiation received by patients. The present study tends to support these concerns with respect to imaging sites that fail to monitor their doses or implement effective dose-reduction methods. To put these dose levels in perspective, the initial doses experienced by patients during the control period were in the range received during nuclear stress testing with 201Tl.8 Using the best-practice model for scan acquisition, the median dose of the consortium was reduced within 3 months to levels commonly received by patients undergoing stress imaging with 99mTc. Our study suggests that when electrocardiographic-gated tube current modulation is widely and appropriately used at an experienced high-volume center, decreased tube voltage is the strongest independent factor associated with lower dose levels, and that proper preparation of patients with β-blockers to reduce heart rate also is important.

The scope of the intervention used in this study raises questions about the practicality and cost of implementing such a program on a large scale. Recently, guidelines for the acquisition of CCTA from imaging specialty societies have become available.32-34 These provide concise recommendations that are a valuable resource to physicians and technologists. The importance of radiation-reduction techniques must be emphasized during physician and technologist training and physicians should demonstrate technical mastery of these methods before certification to oversee CCTA scanning. Finally, it is impossible to improve practice without monitoring radiation doses, and a dose recording and review process has been recommended in published guidelines.35

Study Limitations
It is important to consider the limitations pertinent to the methods of this study. Unlike a randomized controlled trial, our study design limits the conclusions that can be drawn about the causal relationship between the study intervention (the best-practice model) and the results. Additional factors extraneous to the study intervention also could have played a role. Because sites volunteered for this study, results may not generalize to sites that may be less eager to participate in this program; however, there seems to be general acceptance of this type of strategy to lower exposure to radiation.

The method of estimating radiation dose used depends on the accuracy of measurements of CTDI100 using an ionization chamber and standardized phantom on each scanner.14 A uniform supervised calibration was not performed by the study investigators at each site. However, because each site served as its own control, inaccuracies introduced by variations in calibration were likely minimized because these inaccuracies were likely of similar magnitude in the control, intervention, and follow-up periods. Comparison between the effective radiation doses in this study to other non-CT procedures such as single photon-emission CT are subject to the assumptions implicit in the European Commission conversion coefficient.

The collected data did not include measurement of the width of the acquisition window during electrocardiographic-gated tube current modulation. We therefore cannot assess the contribution made to radiation dose reduction, although we hypothesize that this is reflected in the effect of heart rate reduction.

This study did not incorporate the technique of prospectively triggered sequential scanning, which could have had a major additional effect in reducing radiation dose.25,26,36

CONCLUSIONS
The findings of this study demonstrate that consistent application of currently available radiation dose–reduction techniques was associated with a marked reduction in the radiation dose received by patients undergoing CCTA in a statewide registry, without impairment of diagnostic image quality. This accomplishment provides support for the use of collaborative, consortium-based quality improvement strategies for improving the quality of medical care. Additional multicenter studies are needed to assess the potential for further dose reductions from the use of technical advances such as prospectively triggered scanning and single-heartbeat acquisitions.

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RADIATION DOSE FOR CARDIAC CT AFTER DOSE-REDUCTION IMPLEMENTATION

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