Since the inception of coronary computed tomography angiography (CTA), minimizing ionizing radiation exposure has posed a clinical challenge. In a 1984 paper chronicling their pioneering work with the dynamic spatial reconstructor (DSR), the first scanner used for coronary CTA, Block, Bove, and Ritman (1) wrote that “an adult patient can expect to receive approximately 0.9 rads/s of DSR scan time.” Translating the details (2) into current terminology, a study performed on this scanner could be associated with an effective dose (ED) of up to 20 mSv, equivalent to 7 years of background radiation.

The ED from coronary CTA decreased dramatically, to 1.5 to 2.0 mSv (3), with the advent of the electron beam scanner; however, electron beam computed tomography (CT) had limited spatial resolution and gave way to multidetector-row (MDCT) scanners. As performed with early 4-slice MDCT scanners, coronary CTA was again associated with higher EDs, typically 6 to 13 mSv (3). An important factor that contributed to the increased dose was longer x-ray exposure time from these scanners, whose x-ray tubes and detector arrays operated in a helical mode with considerable overlap. The potential radiation doses imparted by coronary CTA continued to increase as MDCT technology advanced from 4 to 64 slices. Subsequent scanners used greater numbers of rows of thinner detectors, to improve z-axis coverage and spatial resolution, but required lower pitch for coronary CTA (i.e., more overlap), which increased dose. Their more powerful x-ray tubes enabled operators to maintain or even decrease noise level despite the improved spatial resolution, thereby improving image quality (IQ), but at the cost of increased dose. Thus, at the beginning of the 64-slice era, just as coronary CTA became widely used, the ED reached high levels not found since the days of the DSR. It was in this context that initial estimates projected surprisingly high cancer risks from a single coronary CTA scan, particularly in younger female patients (4). Although these estimates were derived from radioepidemiological models based on cancers from other radiation exposure scenarios, not epidemiological studies of actual cancers in patients undergoing coronary CTA, they nevertheless appropriately raised awareness of the need for radiation dose reduction.

The first widespread characterization of radiation doses from cardiac CT in the 64-slice era occurred in the PROTECTION I (Prospective Multicenter Study on Radiation Dose Estimates of Cardiac CT Angiography in Daily Practice I) study, a cross-sectional, international, observational study by Hausleiter et al. (5) describing doses in 2007 to nearly 2,000 patients at 50 centers, selected on the basis of previous publications on coronary CTA and personal contacts (5). Its primary outcome measure, dose-length product (DLP), is a dosimetric quantity reported by CT scanners for each scan. Some early dose-reduction techniques were used in PROTECTION I. Nevertheless, mean DLP was 885 mGy·cm; with a standard, albeit controversial (6), conversion factor (0.014 mSv·mGy⁻¹·cm⁻¹), which may underestimate ED, this would translate to an ED of 12 mSv. Of note, median DLPs ranged 7-fold between sites. PROTECTION I established a baseline of early 64-slice coronary CTA practice in high-quality centers.
Numerous subsequent studies have evaluated the effect on IQ and radiation dose of newer dose-reducing technological advances. Each advance aims to reduce the time during which patients are exposed to x-rays, the tube potential (which determines the energies of x-rays), or the tube current (which determines the rate at which x-rays are released). This literature mostly consists of single-center observational studies. Uniquely, the PROTECTION program has sought to validate these novel dose-reduction methods in a series of multicenter, multivendor, international randomized trials. Following on the success of PROTECTION I, PROTECTION studies II through V (Table 1) have, respectively, compared earlier coronary CTA methodology with reduced-tube-potential scanning (7), prospectively triggered axial imaging (8), high-pitch helical scanning for dual-source CT (9), and now in this issue of iJACC, reduced tube current with iterative image reconstruction (IR) (10), a computationally more demanding but improved approach to the reconstruction of images from raw data. It has been observed in numerous single-center and single-vendor studies that with IR, x-ray tube current can be decreased while IQ is maintained. PROTECTION V thus compared standard reconstruction with filtered back-projection to IR with a 30% reduction in tube current in 400 patients at 8 centers, imaged with use of scanners and reconstruction algorithms from the 4 largest manufacturers of CT equipment. Site investigators were encouraged to use other dose-reducing techniques, such as reduced tube potential (validated in PROTECTION II) and axial imaging (validated in PROTECTION III), as clinically appropriate. The authors found IQ to be noninferior in the IR group, whereas mean DLP was 29% lower, which was not surprising because radiation dose is linearly related to tube current. The median DLP of 157 mGy-cm in the IR group would translate to an ED of 2 to 4 mSv, depending on the conversion factor used.

In fact, the investigators’ use of a 30% reduction in tube current was admittedly conservative, and it may well be possible with IR to reduce tube current more while preserving IQ and diagnostic accuracy. More advanced “model-based” IR algorithms that model optical system geometry and image noise, although not yet available for coronary CTA, are on the horizon and offer potential to further reduce tube current. Thus, using a combination of technological developments such as reduced tube potential in nonobese patients, reduced tube current with IR, and axial, volume, or high-pitch helical scanning, it is possible to perform coronary CTA with very low radiation doses. Indeed, multiple groups have published experience performing coronary CTA, in selected patients, with an ED of <1 mSv. Is radiation dose from coronary CTA, as some have suggested, no longer a significant issue we need to concern ourselves with?

I would contend that the answer to this question is a resounding “no.” The potential to use multiple dose-reduction methods, and their successful implementation in the context of clinical research conducted at expert centers, need not imply that this is the standard of care received by patients undergoing coronary CTA worldwide. PROTECTION I demonstrated great between-center and within-center variation in DLP. The introduction into practice, as well as validation in PROTECTION II through V, of newer dose-reduction strategies, does not automatically translate into their subsequent adoption wherever appropriate. Numerous centers still do not have technology available to perform axial (or prospectively triggered helical) imaging and iterative reconstruction; I have visited 2 such sites in the past year or so. These are costly upgrades to the first generation of 64-slice scanners, not offset by increased reimbursement. Other centers opt for routine helical scan protocols with high tube potential and current to minimize noise and optimize IQ; I recently visited 1 such site with a typical DLP around 2,000 mGy-cm. We need more current data as to real-world coronary

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**Table 1** The PROTECTION Randomized Controlled Trials

<table>
<thead>
<tr>
<th>Study</th>
<th>Centers</th>
<th>n</th>
<th>DR Strategy</th>
<th>Standard Strategy</th>
<th>IQ:DR</th>
<th>IQ:S</th>
<th>DLP:DR</th>
<th>DLP:S</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROTECTION II</td>
<td>8</td>
<td>400</td>
<td>100 kVp (nonobese)</td>
<td>120 kVp (nonobese)</td>
<td>3.30±0.67</td>
<td>3.28±0.68</td>
<td>599±255</td>
<td>868±317</td>
</tr>
<tr>
<td>PROTECTION III</td>
<td>9</td>
<td>400</td>
<td>Axial mode</td>
<td>Helical mode</td>
<td>3.36±0.59</td>
<td>3.37±0.59</td>
<td>252±147</td>
<td>802±419</td>
</tr>
<tr>
<td>PROTECTION IV</td>
<td>3</td>
<td>303</td>
<td>High-pitch helical first</td>
<td>Conventional first</td>
<td>3.81±0.35</td>
<td>3.83±0.37</td>
<td>140±169</td>
<td>333±344</td>
</tr>
<tr>
<td>PROTECTION V</td>
<td>8</td>
<td>400</td>
<td>IR, 30% lower TC</td>
<td>FBP, standard TC</td>
<td>3.5±3.04</td>
<td>3.4±2.84</td>
<td>157(114-239)</td>
<td>222(141-319)</td>
</tr>
</tbody>
</table>

Values are n, mean ± SD, or median (interquartile range). Image quality was graded on a 4-point scale ranging from 1 = nondiagnostic to 4 = excellent.

DLP = dose-length product (in mGy-cm); DR = dose reduction; FBP = filtered back-projection; IQ = image quality; IR = iterative image reconstruction; PROTECTION = Prospective Multicenter Study on Radiation Dose Estimates of Cardiac CT Angiography in Daily Practice; S = standard; TC = tube current.
CTA dosimetry. I suspect this would show improvement since PROTECTION I; however, undoubtedly there remain many patients who do not receive the low doses observed in PROTECTION V.

A useful analogy can be made to seatbelts, which reduce the risk of fatality from a motor vehicle accident by 45%. Although Congress mandated their installation in automobiles in 1966, and thus they are in virtually all cars on the road today, 2010 data from the Centers for Disease Control and Prevention found the prevalence of always wearing a seatbelt ranged from 62% to 94%, depending on the state, with a steady increase between 2002 and 2010 (11). The Centers for Disease Control and Prevention investigators concluded, on the basis of these data, that enactment of statewide primary seatbelt enforcement regulations and enhanced enforcement of seatbelt laws were 2 effective strategies to increase seatbelt use and reduce traffic fatalities. The existence of safety technology, even if ubiquitous, does not ensure its use. Implementation can remain a challenge and can vary depending on modifiable systems factors. A burgeoning new field of implementation science is beginning to address this important undertaking (12).

Hausleiter et al. (10) have done a great service by validating our box of dose-reduction tools, particularly now in providing evidence that validates IR, which can be used for virtually all patients. Our community’s next challenge is to develop additional methods and systems to ensure each patient receives an optimal patient-centered, indication-specific protocol using the right tools to ensure diagnostic-quality information while minimizing radiation exposure.

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REFERENCES

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