Reducing radiation in cardiac SPECT, PET and CT: How Low Can We Go?

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Research support:
• American Heart Association
• Siemens Medical Solutions (CT)
Overview

• Radiation quantities and units
• Radiation dose calculation and dose reduction
  – Cardiac CT
  – PET and SPECT
• Comparative radiation doses: how low can we go?
• Summary

Background

• SPECT, PET, CT imaging uses ionizing radiation
• Keep radiation doses As Low As Reasonably Achievable (ALARA)
• We need to know
  – typical radiation dose
  – ways to minimize the radiation dose
With Rise in Radiation Exposure, Experts Urge Caution on Tests

Advances in radiology have radically transformed medical practice, with CT scans and nuclear medicine scans providing physicians with the ability to quickly pinpoint internal bleeding, diagnose kidney stones or confirm appendicitis, assess thyroid function and identify and open blockages in the blood vessels to the heart.

The downside is that Americans are being exposed to record amounts of ionizing radiation, the most common and potentially dangerous form of radiation.

According to a new study, the per-patient radiation from clinical imaging increased almost 60% percent in 2005, natural background radiation of human exposure; that has been imaging procedures, the authors

Radiation Quantities and Units
Radiation quantities and units

<table>
<thead>
<tr>
<th>Description</th>
<th>Traditional Unit</th>
<th>SI Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure</td>
<td>Ionization in air, entrance skin exposure</td>
<td>Roentgen (R)</td>
</tr>
<tr>
<td>Exposure, Activity - Radiation source output</td>
<td>radionuclides</td>
<td>1 mCi = 37 MBq</td>
</tr>
</tbody>
</table>

Absorbed Dose

- Energy deposited in tissue or organ
- Rad
- Gray (Gy)
  - 1 Gy = 100 rad
  - 1 rad = 10 mGy

Effective dose

- Risk-equivalent “whole-body” dose
- rem
- Sieverts mSv
  - 1 rem = 10 mSv

Tissue weighting factors

- International Commission for Radiation Protection (ICRP) tissue weighting factors based on mathematical model
- Reflects relative radiation sensitivity of each type of body tissue
- Effective dose can be calculated as weighted sum of absorbed dose for all tissues

McCollough et al AJR 2010; 194: 890
Effective Dose

• A single dose parameter which estimates total whole-body radiation risk

• Allows comparison of risk among different imaging protocols and modalities using ionizing radiation

<table>
<thead>
<tr>
<th>Description</th>
<th>Traditional Unit</th>
<th>SI Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective dose</td>
<td>Risk-equivalent “whole-body” dose</td>
<td>rem</td>
</tr>
</tbody>
</table>

Effective Dose: typical values

Avg Annual Background Radiation (U.S.) 3 mSv
PA and Lateral Chest X-ray 0.1 - 0.2 mSv
Screening mammography 0.3 – 0.6 mSv
Diagnostic Invasive Coronary Angiography 5 - 10 mSv
Chest CT 5 - 8 mSv
Cardiac CT
Myocardial Perfusion SPECT
Myocardial Perfusion PET

McCollough et al AJR 2010; 194: 890
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CT Hardware and cardiac CT scan modes
Electrons accelerated towards tungsten target

- X-rays produced when electrons strike target

- Number of x-rays
  - peak tube voltage (kVp)
  - tube current (mA)

- X-ray energies
  - peak tube voltage (kVp)

CT Acquisition

- Helical (Spiral)
  - continuous gantry rotation and table movement
  - continuous x-ray tube exposure

- Axial (Sequential)
  - “step-and-shoot”
  - x-ray tube on: prospectively ECG-triggering
Helical with retrospective ECG-gating

ECG-Pulsing or ECG-based tube current modulation

- 18 - 20 mSv
- 8 - 12 mSv
- 5 - 6 mSv

Helical CCTA with ECG-pulsing

Full tube current 70% phase only

- 60%
- 70% - Full tube current
- 80%

- 5 mSv
Axial with prospective ECG-triggering

1-3 mSv

Axial Prospectively ECG-triggered CCTA

100 kVp, Prospective
Radiation Dose 1.5 mSv

43-y/o woman, family history of CAD, Normal CCTA. HR 65 bpm
Pitch

- Helical acquisition
- Pitch = Table Feed per tube rotation (mm) / z-coverage per rotation (mm)

Reducing the number of Photons

Xray Tube: current and peak tube voltage: the difference?

Huda, Stone Review of Radiologic Physics 2003
**CT scan parameters and radiation reduction**

**mAs** - Tube current (mA) x Time (sec)
- Decreasing mAs decreases dose linearly

**kVp** – Decreasing kVp decreases dose
- Dose proportional to $(kVp)^{2.5-2.8}$

**Pitch** - Increasing pitch decreases dose
- Dose proportional to inverse pitch $(1/pitch)$

Hamberg et al Radiology 2003

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**Scanning with lower peak Voltage**

40% dose reduction possible. Up to BMI 30 or 85 kg

120 kVp
BMI 32

100 kVp
BMI 25
Predictors of Image Noise are patient thorax-shape specific

1. BMI
2. Weight and Height
3. Patient-specific outer thoracic tissue area* and thoracic cross-sectional area

$N = 165$ Prospective Axial and Retrospective Spiral

Schuhbaeck et al, JCCT 2013 in press

Non-contrast cardiac CT

- Non-contrast, gated
  
  Effective dose 0.2 - 3 mSv
  Prospective ECG-triggering recommended
Radiation Dose calculation in CT

Absorbed dose CT

CTDI – CT Dose Index
Measured with phantoms and ion chamber inserted
CT radiation dose

For each scan:

\( \text{CTDI}_{\text{vol}} \) – Average absorbed dose over x,y,z, at taking pitch into account (mGy)

- Independent of the length of the scan

Scan length (cm) –

---

CT radiation dose

For each scan:

\( \text{DLP} \) – Dose Length Product (mGy.cm)

Reflects total energy absorbed

\[ \text{Effective Dose (mSv)} = k \times \text{DLP} \]

\( k \) - constant (chest)

\( k = 0.014 \text{ mSv}/[\text{mGy.cm}] \)

Hausleiter et al JAMA 2009; 301:500
McCullough et al AJR 2010; 194: 890
Overview

• Radiation quantities and units
• Radiation dose calculation and dose reduction
  – Cardiac CT
  – PET and SPECT

Further Radiation Dose Reduction in medical imaging
- Area of intense, active research

• Summary

Radiation Dose-reduction implementation
Prospective controlled study at 15 hospital imaging centers

Radiation Dose From Cardiac Computed Tomography Before and After Implementation of Radiation Dose–Reduction Techniques

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 6,899 sequential patients undergoing CCTA for suspected coronary artery disease were enrolled; 6,862 patients (97.3%) had complete radiation data for analysis.

Raff et al JAMA 2009; 301: 2340
Dose reduction implementation: before & after

Best-practice scan model: Minimized scan range, HR reduction, ECG-gated tube modulation and reduced tube voltage

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

<table>
<thead>
<tr>
<th>Intervention Period</th>
<th>Control Period</th>
<th>Follow-up Period</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-Mar 2007 (n=542)</td>
<td>Jan-Mar 2008 (n=542)</td>
<td>Jan-Mar 2009 (n=542)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Dual-source, median (IQR)</td>
<td>1.9 (1.2)</td>
<td>1.3 (1.1)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Heart rate (bpm)</td>
<td>71 (10)</td>
<td>68 (11)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Coronary artery stenosis, No. (%)</td>
<td>0% (0%)</td>
<td>0% (0%)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Scan length, mm (IQR)</td>
<td>64.5 (11.5)</td>
<td>64.0 (11.5)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Effective dose, mSv (IQR)</td>
<td>0.66 (0.63)</td>
<td>0.62 (0.62)</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

High-pitch prospectively-triggered helical coronary CT Angiography

- “FLASH” mode: Prospectively-triggered high-pitch helical dual-source CT
- HR low and stable (< 60 bpm)

Achenbach et al EHJ 2009; 31: 340, Achenbach et al iJACC 2011; 4: 328
High-pitch prospectively-triggered helical CTA with Iterative Reconstruction

- 21 consecutive patients
- “FLASH” mode:
  Prospectively-triggered high-pitch helical dual-source CT
- low tube current 50 mAs
- HR low and stable (< 60 bpm)
- Body weight ≤ 75 kg

Effective dose: < 0.1 mSv

Schuhbaeck et al Eur Radiol 2012 in press

Patient-specific algorithm for dose reduction

- How to successfully combine multiple dose reduction strategies?
- No patient left behind

Calcium or Stent or BMI ≥ 30 or Weight ≥ 85 kg

YES

120 kVp

HR < 70, no Arrhythmia, Age < 65

120 kVp, FTC 70

NO

100 kVp

HR ≥ 70, Arrhythmia, Age ≥ 65

120 kVp, FTC 45-75

HR < 70, no Arrhythmia, Age < 65

100 kVp FTC 70

HR ≥ 70, Arrhythmia, Age ≥ 65

100 kVp FTC 45-75

Cedars-Sinai

Gutstein et al JCCT 2008; 3: 311

118 consecutive patients
### Patient-specific algorithm for dose reduction

<table>
<thead>
<tr>
<th>Effective Radiation Dose (mSv)</th>
<th>Overall population</th>
<th>FTC70 / 100 kVp</th>
<th>FTC70 / 120 kVp</th>
<th>FTC45-75 / 100 kVp</th>
<th>FTC45-75 / 120 kVp</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 mSv</td>
<td>2 mSv</td>
<td>5 mSv</td>
<td>7 mSv</td>
<td>7 mSv</td>
<td>13 mSv</td>
</tr>
</tbody>
</table>

Gutstein et al. JCCCT 2008; 2: 311; Dey et al. SCCT 2011; S25
Cedars-Sinai

### Iterative reconstruction

- 574 consecutive patients at 3 centers
- **Lowered tube current and iterative reconstruction** (ASIR)
  - 44% further reduction in radiation dose compared to previous standard protocol
- **Effective dose** 2.3 mSv (ASIR) compared to 4.1 mSv (FBP)

Leipsic et al. AJR 2010; 195: 655
Integration of dose reduction methods

Multicenter study: 449 patients undergoing CCTA before (n=247) vs after (n=202)
Standardized image acquisition protocol, including prospective gating, reduced tube voltage, lower tube current and reduced scan length

No differences in study interpretability before versus after protocol (96% vs. 96%, p=0.66)

Low radiation coronary calcium scanning

- Reduced mAs, based on patient body size

  Coronary Calcium Scoring by dual-source CT in 66 patients:

  Standard protocol followed by low-dose protocol with reduced tube-current
  - 85 mAs for BMI ≤ 30 or weight < 85 kg
  - 120 mAs otherwise

  Effective dose: 1.0 mSv at reduced mAs 1.7 mSv with standard scan
Low radiation coronary calcium scanning

• High-pitch prospectively-triggered scan: < 0.5 mSv

• Reduced x-ray tube kVp from 120 to 100 gives similar results:

  - Effective CT energy differs at each kVp setting: scanner calcium threshold, 130 HU for 120 kVp
  - Needs to be calibrated for 100 or 80 kVp

Nakazato et al JCCT 2009: 3: 294; Marwan et al JCCT 2010: S61

Summary I: CT

• Scan considering radiation dose:

  • ECG-pulsing should always be used with helical protocols

  • Lower heart rates: use prospective gating

  • Consider scanning at lower kVp

  • Lowered tube current with iterative reconstruction can further reduce radiation dose
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Radiation Dose calculation PET and SPECT
Radiation dosimetry in nuclear cardiology

- Activity in mCi or MBq
- Biokinetic model for distribution and metabolism of the radiopharmaceutical
  - animal models
  - human models
- Tissue or organ absorbed dose per MBq
- Effective dose


Effective Dose examples: SPECT and PET

<table>
<thead>
<tr>
<th>Tracer</th>
<th>Stress half-life</th>
<th>Stress (mCi)</th>
<th>Rest (mCi)</th>
<th>Effective dose (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{99m}$Tc sestamibi</td>
<td>6 hrs</td>
<td>27.5</td>
<td>10.0</td>
<td>11</td>
</tr>
<tr>
<td>Stress-rest SPECT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{99m}$Tc tetrofosmin</td>
<td>6 hrs</td>
<td>27.5</td>
<td>10.0</td>
<td>10</td>
</tr>
<tr>
<td>Stress-rest SPECT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{201}$TI Stress-rest and reinjection</td>
<td>73.1 hrs</td>
<td>3.0</td>
<td>1.5</td>
<td>31</td>
</tr>
<tr>
<td>$^{82}$Rb Stress-rest</td>
<td>1.27 min</td>
<td>40.0</td>
<td>40.0</td>
<td>3-4</td>
</tr>
<tr>
<td>PET</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{13}$N-ammonia Stress-rest PET</td>
<td>10 min</td>
<td>15.0</td>
<td>15.0</td>
<td>2-3</td>
</tr>
<tr>
<td>$^{18}$FDG PET</td>
<td>110 min</td>
<td>0</td>
<td>10.0</td>
<td>7</td>
</tr>
</tbody>
</table>

Radiation Dosimetry $^{82}$Rb PET

- Human in-vivo biokinetic measurements
- 10 healthy volunteers (5 male, 5 female)
- Dynamic PET/CT (6 table positions)
- Patient-specific organ time-activity curves

Senthamizhchelvan et al JNM 2010; 51: 1592

Radiation Dosimetry $^{82}$Rb PET

Organ biokinetics – time-activity curves

Peak activity 45 seconds or later after infusion
Absorbed organ doses from time-integrated activity coefficients and software
Effective dose from ICRP tissue-weighting factors

Senthamizhchelvan et al JNM 2010; 51:1592
Radiation Dosimetry $^{82}$Rb PET

- Organ doses to adrenals, thyroid and kidneys significantly lower than previous reports

- For a standard $^{82}$Rb injection $2 \times 1480 = 2940$ MBq ($2 \times 40 = 80$ mCi):
  - Mean effective dose of 3.7 mSv using ICRP 103 weighting factors
  - CT scan for attenuation correction - add 0.3 mSv
  - Reasonably low at 3-4 mSv for typical $^{82}$Rb stress-rest perfusion scan

Senthamizhchelvan et al JNM 2010; 51: 1592

Radiation Dose Reduction: SPECT

- Reduction of Thallium/dual-isotope imaging
- Stress-only scanning

16,854 patients

normal stress
SPECT
Stress-only 8034
Stress-rest 8820

- Patients with normal SPECT stress-only imaging have similar low mortality rate as stress-rest (p=0.89)
- With normal stress, additional rest imaging not required
- Stress-only injected dose (21.3 ± 10.7 mCi) 61% lower

Chang et al JACC 2010; 55: 221
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Further Radiation Dose Reduction in cardiac SPECT
Recent advances in myocardial perfusion SPECT

- Complete redesign of gamma camera collimator

**Detector:**
- Scintillation crystals with Photomultiplier Tubes replaced with solid state photon detectors
  - Cadmium Zinc Telluride (CZT) or Cesium Iodide (CsI)

Slomka et al, JNC 2009; 16: 255

Recent advances in myocardial perfusion SPECT

- DSPECT camera
- 9 detector/collimator columns
  - CZT crystals
  - Tungsten collimators (4x acceptance angle)
- Detector columns turn, focusing on the object of interest

Sharir et al, JACC Cardiovascular Imaging 2008; 1: 156
Improvement in system sensitivity

Sharir et al, JACC Cardiovascular Imaging 2008; 1: 156

Increased sensitivity: What comes next?

- Reduced acquisition times
  Increasing patient comfort and throughput

OR/AND

- Radiation dose reduction with lower injected doses with 10-15 minute acquisition time

- Effective MPI dose 4-7 mSv using new hardware using recent reports

Slomka et al, Cardiovascular Imaging reports 2012; 14: 208-216
<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Protocol</th>
<th>Injected Dose</th>
<th>Effective dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Husmann et al.</td>
<td>100</td>
<td>Stress only/Prosp gated CTA.</td>
<td>Stress only: 8.1 mCi</td>
<td>(5.4±0.8) mSv</td>
</tr>
<tr>
<td>Duvall et al.</td>
<td>209</td>
<td>Stress only 99mTc sestamibi</td>
<td>Stress only: 12.5 mCi</td>
<td>4.2 mSv</td>
</tr>
<tr>
<td>DePuey et al.</td>
<td>160</td>
<td>Tc-99m sestamibi</td>
<td>Rest: 5.8±0.6</td>
<td>6.8 mSv</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Stress: 17.5±2.5 mCi</td>
<td></td>
</tr>
<tr>
<td>Nkoulou et al.</td>
<td>50</td>
<td>1-day 99mTc tetrofosmin adenosine stress–rest</td>
<td>Stress/Rest 8.6/17.3 mCi 5min/5min</td>
<td>4.3 mSv</td>
</tr>
<tr>
<td>Duvall et al.</td>
<td>131</td>
<td>Tc-99m sestamibi</td>
<td>Rest 5 mCi</td>
<td>5.8 mSv</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Stress 15 mCi</td>
<td></td>
</tr>
<tr>
<td>Gimelli et al.</td>
<td>137</td>
<td>Tc99m tetrofosmin</td>
<td>Stress 5-6mCi Rest 10-12 mCi</td>
<td>5-10 mSv men 6-12 mSv (women)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Very Low-Dose Tc-99m Stress-Only High-efficiency MPI**

- 2 - 4 mCi Tc-99m injected, depending on BMI
- 10 min acquisition
- Effective dose ~ 1 mSv
Low-dose Tc-99m Protocol by High-Efficiency MPI

- Tc-99m MIBI low-dose resting scan with DSPECT compared to standard resting scan (ASPECT)

- Low-dose rest dose (3.5 mCi)
- Rest dose remainder (3.5-8 mCi)
- Standard Stress dose at peak stress

DSPECT Low-dose rest 9-15 min
ASPECT rest 20 min
Standard ASPECT stress

Effective dose Low-dose rest scan ~ 1 mSv

CSMC and other centers
How Low Can We Go?

Maintaining sufficient image quality for confident interpretation!

Effective Dose for cardiac imaging

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Effective Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Annual Background Radiation (U.S.)</td>
<td>3 mSv</td>
</tr>
<tr>
<td>Cardiac CT</td>
<td></td>
</tr>
<tr>
<td>Coronary Calcium Scoring</td>
<td>0.2 - 3 mSv</td>
</tr>
<tr>
<td>Coronary CT Angiography</td>
<td>0.1 - 18 mSv</td>
</tr>
<tr>
<td>SPECT</td>
<td></td>
</tr>
<tr>
<td>Perfusion $^{99m}$Tc Sestamibi Stress-rest</td>
<td>1 - 16 mSv</td>
</tr>
<tr>
<td>PET</td>
<td></td>
</tr>
<tr>
<td>cardiac $^{18}$FDG</td>
<td>7 mSv</td>
</tr>
<tr>
<td>Perfusion $^{82}$Rb Stress-rest</td>
<td>3 - 4 mSv</td>
</tr>
<tr>
<td>Perfusion $^{13}$N-ammonia Stress-rest</td>
<td>2 - 3 mSv</td>
</tr>
</tbody>
</table>
Cancer risk

Beir VII: Health Risks from Exposure to Low Levels of Ionizing Radiation

BEIR VII develops the most up-to-date and comprehensive risk estimates for cancer and other health effects from exposure to low-level ionizing radiation. It is among the first reports of its kind to include detailed estimates for cancer incidence in addition to cancer mortality. In general, BEIR VII supports previously reported risk estimates for cancer and leukemia, but the availability of new and more extensive data have strengthened confidence in these estimates. A comprehensive review of available biological and epidemiological data supports a "linear no-threshold" (LNT) risk model—that the risk of cancer proceeds in a linear fashion at lower doses without a threshold and that the smallest dose has the potential to cause a small increase in risk to leukemia.

The Linear No-Threshold Relationship Is Inconsistent with Radiation Biologic and Experimental Data

The linear no-threshold risk induced by low doses of ionizing radiation is controversial. It cannot be assessed with the current epidemiological methods alone because of low levels of radiation exposure and small numbers of cases. Data from biological experiments and other methods have shown that at least a small threshold exists below which the risk of radiation-induced cancer is negligible.

Gerber et al
AHA Writing Group
Circulation 2009; 119: 1056

| Estimated Risk of Fatal Malignancy or Lifetime Odds of Dying (per 1000 Individuals) |
| Exposure                                                                 |   |
| Effective radiation dose                                                |   |
| 1 mSv (non-ionizing radiation)                                          | 0.05 |
| 10 mSv (ionizing radiation)                                             | 0.5  |
| Invasive coronary angiography, radiation oncology, and nuclear medicine  | 2   |
| 0.1 mSv (very low radiation source, low exposure)                      | 5  |
| Natural fatal cancer                                                    | 212 |
| Passive smoking                                                        | 4  |
| Low exposure                                                            | 10 |
| High exposure, married to a smoker                                      | 3   |
| Radon in home                                                           | 21  |
| US average                                                              | 1  |
| High exposure (1% to 3%)                                                | 13  |
| Aesthetic in drinking water                                             | 1  |
| 2.5 µg/L (US estimated average)                                        | 11.9|
| 0.5 µg/L (acceptable limit before 2000s)                               | 1.8 |
| Motor vehicle accident                                                  | 0.9 |
| Pedestrian accidents                                                    | 0.2 |
| Drinking                                                               | 0.013|
| Walking smoking                                                        |   |
Summary

• Multiple steps and approximations in radiation dose estimates

For chest, $k = 0.014 \text{ mSv/[mGy.cm]}$

McCollough et al AJR 2010; 194: 890

Summary

• Every effort should be made to reduce patient dose while maintaining sufficient image quality for confident interpretation

• There is also a risk in not performing an imaging study when indicated

Gerber et al AHA Writing Group Circulation 2009; 119: 1056
Summary

• Patient age:
  – Relative risk is lowest in older patients due to decreased lifetime cancer risk

• When testing is limited to appropriate patients and indications, the benefit exceeds the harm

Shaw et al JACC Cardiovascular Imaging 2010; 3: 550

Thank you