Smart mA – Automatic Exposure Control (AEC): *Physics Principles and Practical Hints*

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Automatic Exposure Control (AEC) systems in CT

Why use AEC in CT?

The benefit from the use of ionizing radiation for medically appropriate imaging procedures far outweighs the small increase in risk. However, prudence demands that users and manufacturers take all reasonable steps to decrease the radiation dose to the patient, especially considering the continued increase in the use of medical imaging. One of the most important technologies used to reduce dose in CT is Automatic Exposure Control (AEC), which aims to automatically modulate the tube current to compensate for the variations in patient attenuation, both between different patients and within any given patient.

Within any given patient, there can be strong variations in x-ray attenuation as the tube rotates around the patient, particularly in anatomic regions that are particularly elliptical in shape, such as the shoulders and pelvis. The use of a constant tube current causes the x-ray projections through the most attenuating view angles to primarily determine the noise level in the reconstructed cross sectional image. The projections through less attenuated view angles contain radiation that contributes to the overall radiation dose, but does not further improve the quality of the final image. Angular tube current modulation allows the scanner to modify the current in real-time, based upon the attenuation at any given projection angle, such that similar noise can be maintained regardless of the projection angle. Angular tube current modulation can provide a dose reduction of up to 40-50% without compromising image quality.

The same concept can be used to adapt the tube current to different anatomic regions and to different patient sizes in order to produce consistent image quality at the lowest achievable dose. For smaller patients, less tube current, and therefore less dose, is needed to obtain the desired image quality. Larger patients require an increase in tube current to achieve diagnostic image quality, with a necessary increase in the delivered radiation dose. AEC has become a standard dose reduction and image quality tool and is offered in various forms by all major CT manufacturers.

Effective use of this important dose management tool requires an understanding of the AEC system implemented by the manufacturer. The four major AEC schemes are summarized in Table I, according to manufacturer.

Table I: Summary of the four most common AEC strategies

Manufacturer	AEC Trade name	Image Quality Reference	Goal
General Electric	Auto mA, Smart mA	Noise Index	Constant image noise regardless of attenuation level, using tube currents within prescribed minimum and maximum values.
Toshiba	SureExposure	Target Image Quality Level	
Siemens	CARE Dose4D	Quality Reference Effective mAs	Constant image quality regardless of attenuation level, with reference to a target mAs level for a standard-sized patient.
Philips	DoseRight	Reference Image	Keep the same image quality as in the reference image, regardless of attenuation level.

AEC Basic Principles

Automatic Exposure Control (AEC) is a generic name for any technique aimed at optimizing dose utilization by adjusting the tube current in real-time to accommodate differences in attenuation due to patient anatomy, shape, and size. The tube current may be modulated as a function of projection angle (Fig. 1a), longitudinal location along the patients (Fig. 1b), or both (Fig. 1c).

FIGURE 1a

Angular tube current modulation

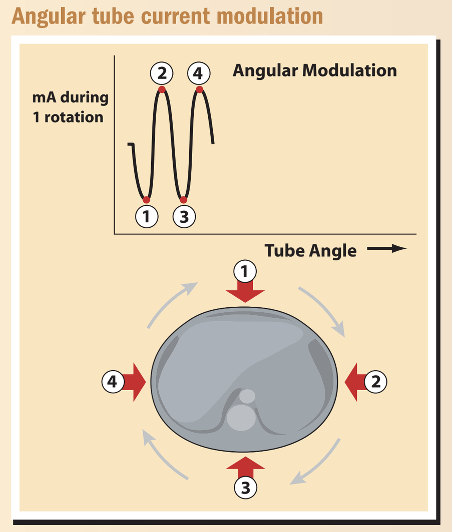


FIGURE 1b

Longitudinal tube current modulation

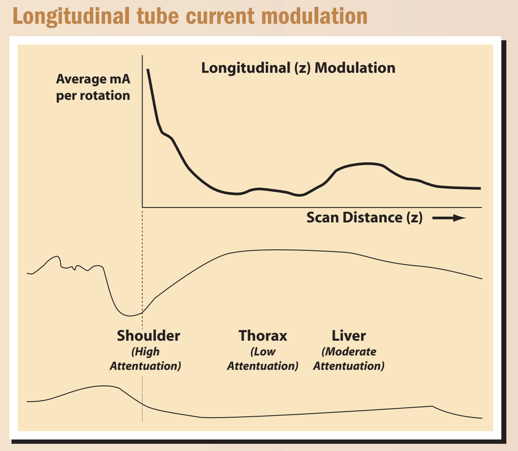
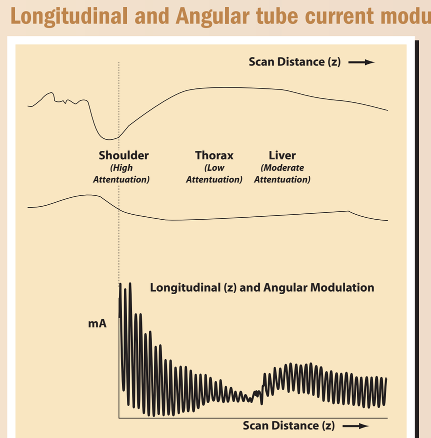


FIGURE 1c

Longitudinal and Angular tube current modulation



Purpose

The purpose of this exhibit is to expand this basic description of AEC, providing an explanation of the principles of operation for one specific system (Smart mA, General Electric Medical Systems). The objective is to equip CT operators with the information needed to use this system effectively in both routine and challenging clinical situations.

How Smart mA Works

Smart mA Terminology

Scout: The name used on General Electric's CT equipment for the scanned projection radiograph (SPR). This low dose, projection image is used to localize the start and end locations of a scan. In Smart mA, the scout is also used to determine the attenuation levels of the patient. Only one scout is required, either anterior-posterior (AP) or lateral; the perpendicular view is estimated using a mathematical model.

Noise Index: The technique parameter entered by the user to determine the desired noise level. The mA is automatically adjusted to compensate for variations in patient size and attenuation, thereby maintaining a user-selected noise level in the image independent of patient size and anatomy. A lower Noise Index indicates that a lower noise level in the image is desired and therefore the mA will be higher to achieve this goal.

Reference Noise Index: Default Noise Index for a given protocol, which can only be prescribed in protocol management.

Dose Steps: Each step of increase or decrease of Dose Steps will decrease or increase the Noise index by 5% of the reference Noise Index, respectively. When Dose Steps = 0, the prescribed Noise Index is exactly the reference Noise Index.

Manual mA: Disables the Smart mA feature and uses a constant mA for the scan.

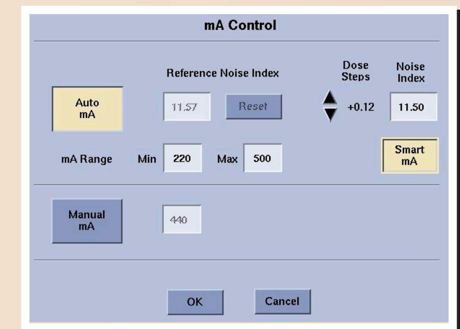
Auto mA: Enables the longitudinal tube current modulation. The tube current is adjusted along the z-direction. The magnitude is determined from the attenuation level at each z-location, which is estimated from the scout acquired just prior to the scan.

Smart mA: Enables both the longitudinal and angular tube current modulation. The tube current is adjusted during each rotation, reducing the magnitude for projection views with less attenuation and increasing the magnitude for projection views with more attenuation. For scan regions with significantly different attenuation along AP and lateral direction (shoulders), Smart mA can reduce the dose or improve the image quality. When Smart mA is enabled, Auto mA is automatically enabled.

mA Range: The Min and Max mA values specify the lowest and highest tube currents that can be used during the mA modulation.

FIGURE 2

Smart mA terminology and interface



Smart mA Principles

Smart mA automatically adjusts the tube-current along the angular and longitudinal directions based on patient size and attenuation level in order to maintain a user-selected noise level in the image.

Smart mA determines the tube current based on the scout image of the patient. It uses data measured by the manufacturer that describes noise values measured with a reference set of scan parameters on phantoms with various sizes and shapes. The reference technique is: User-selected tube potential for the exam (kVp), 2.5 mm slice thickness, 100 mAs, and an axial reconstruction using the "Standard" algorithm. For any given z-location, the system estimates the attenuation level and the oval ratio from the scout. The attenuation level reflects the density and size of the patient. The oval ratio reflects how circular or elliptical the patient is at that level and is estimated from brightness and width information in the scout image.

To determine the appropriate tube current, the system first estimates the noise that would be expected at any given z-location if the reference technique were used. This is done by interpolating between the generic data (measured at the factory) relating noise to attenuation level and oval ratio. Using the well-known relationships between image noise and mAs, slice thickness, and helical pitch, the mA required to achieve the prescribed noise index is calculated.

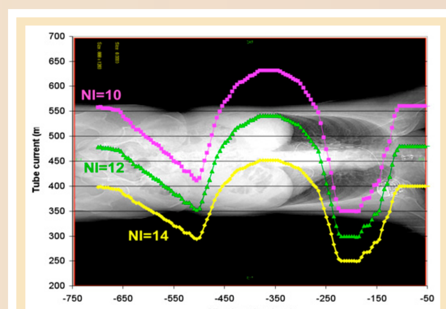
If the Smart mA feature is also enabled (in addition to Auto mA), the system will use the oval ratio of the patient at any z-location to calculate how the mA is to be varied as the tube rotates around the patient. This technique reduces the mA along the thinner direction (typically AP direction).

Noise Index

Smart mA uses the Noise Index as the measure of image quality. The user prescribes the desired image quality by selecting a certain Noise Index. For a given Noise Index, Smart mA automatically modulates the tube current to compensate for variations in patient size and attenuation in order to maintain a constant noise level in the image, independent of patient size and anatomy. The Noise Index value approximately equals the noise measured in the central region of the image for a uniform phantom and a standard reconstruction algorithm. A lower Noise Index indicates that higher image quality is requested by the user and a higher radiation dose is required to achieve the goal. A higher Noise Index indicates that lower image quality is requested by the user and a lower radiation dose is sufficient to achieve the goal (Figure 3).

FIGURE 3

Tube current modulation and Noise index



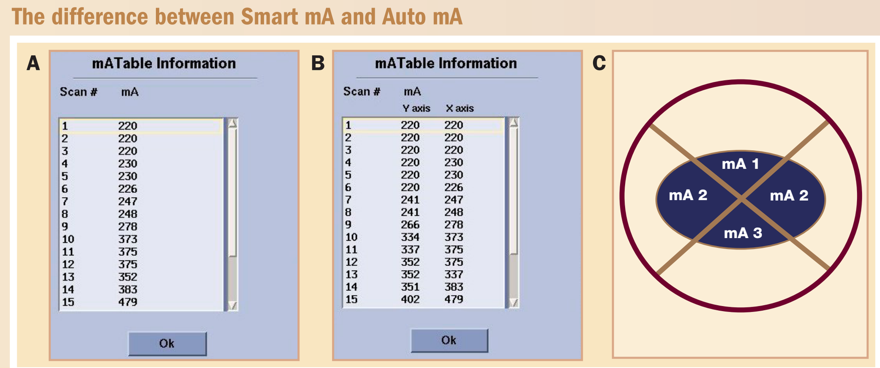
Demonstration of the variation in tube current along the z direction. A lower Noise Index (NI) requires higher tube current values, and vice versa.

Difference between Auto mA and Smart mA

Figure 4 shows the difference between Auto mA and Smart mA. Auto mA only enables the tube current modulation along the longitudinal (z) direction. Therefore, as shown in the representative mA table for Auto mA (Figure 4a), the tube current is kept constant during each rotation (referred to as scan) and only changes along the longitudinal direction. In contrast, Smart mA enables tube current modulation along both the longitudinal axis and angularly about the patient. Therefore, as shown in the example mA table for Smart mA (Figure 4b), there are two tube current values, one for the y-axis (AP) and the other for the x-axis (lateral) directions. The tube current is modulated (changed) four times for each rotation, as shown in Figure 4c. Since Smart mA reduces the mA along the axis with less attenuation (typically the AP direction), the radiation dose is reduced an additional amount relative to Auto mA. This can be accomplished without significantly reducing the image quality.

FIGURE 4

The difference between Smart mA and Auto mA



A — mATable Information

Scan #	mA
1	220
2	220
3	220
4	230
5	230
6	226
7	247
8	248
9	278
10	373
11	375
12	375
13	352
14	383
15	479

B — mATable Information

Scan #	mA Y axis	mA X axis
1	220	220
2	220	220
3	220	220
4	220	230
5	220	230
6	220	226
7	241	247
8	241	248
9	266	278
10	334	373
11	337	375
12	352	375
13	352	337
14	351	383
15	402	479

Using AEC to Prescribe the Desired Image Quality

AEC and Image Quality

- It is the user's responsibility to prescribe the desired level of image quality. It is then the AEC system's responsibility to determine the mA for each tube position in order to achieve the desired image quality. Higher image quality means lower noise and therefore requires higher radiation dose. Lower image quality means higher noise and therefore requires lower radiation dose.
- Different AEC systems use different methods to define the desired image quality. Here we compare Siemens' AEC system, CAREDose4D, to GE's AEC system, Smart mA.
  - GE: Smart mA uses Noise Index to prescribe image quality
  - Siemens: CAREDose4D uses Quality Reference mAs (QRM) to prescribe image quality
- Main Difference between goal of QRM and Noise Index
  - GE: For a given Noise Index, the system tries to maintain a constant noise level at all z locations for all the patient sizes
  - Siemens: For a given QRM, the system tries to maintain a constant level of overall diagnostic quality for all patient sizes. This requires that the targeted noise level change with the patient size

Smart mA - Constant Noise

- To maintain constant image noise, mA needs to be modulated dramatically with the change in patient size (see Figure 5), either doubling or halving the mA for every increase or decrease, respectively, of about 4 cm (soft tissue's half value layer)

CAREDose4D – Variable Noise

- QRM defines the reference level of image quality that is achieved using an effective mAs (mAs/pitch) of the same value as QRM on a reference patient size or attenuation level.
  - For smaller patient sizes or attenuation levels, lower noise is required in order to have the same diagnostic value since smaller patients have finer anatomical structures and lower inherent tissue contrast.
  - For larger patient sizes or attenuation levels, higher noise is accepted in order to have the same diagnostic value since larger patients usually have larger anatomical structures and higher inherent tissue contrast.

FIGURE 5

Adjusting the mA to maintain a constant noise level for all the patient sizes

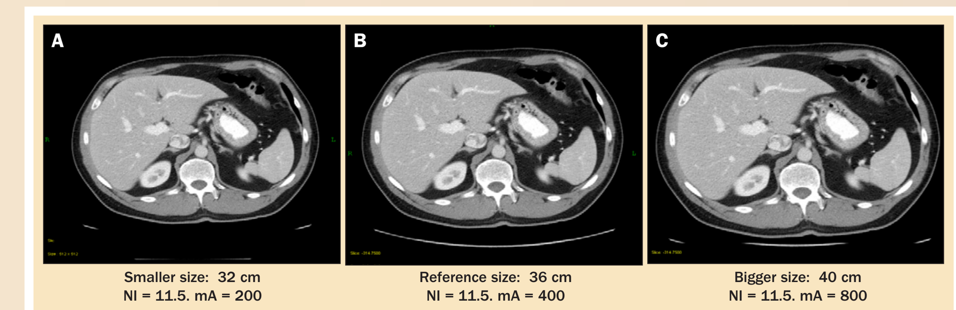
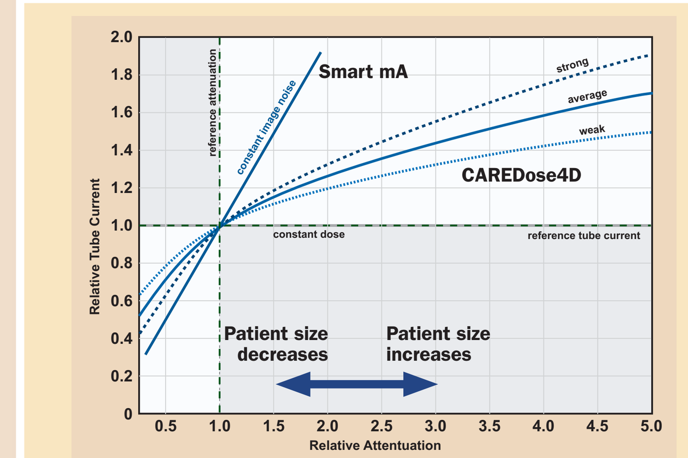


FIGURE 6

Graphical description of the principle of Smart mA in comparison with CAREDose4D



The horizontal axis represents the attenuation level relative to a reference attenuation level (1.0). The vertical axis represents the modulated tube current relative to a reference tube current. In Smart mA, image noise equal to the value of 1.0 corresponds to the tube current that is necessary to obtain the noise index for the reference attenuation level. In CAREDose4D, 1.0 corresponds to the tube current of the QRM prescribed by the operator. The four blue curves represent four modulation methods. The straight line yields constant image noise, which reaches the maximum allowable tube current for attenuation values that are only moderately larger that the reference — this method is used by Smart mA. The other three curves represent three different strengths of CAREDose4Dtube current modulation (strong, average, weak). The strength is an operator configurable parameter on the scanner.

Important Considerations in the Clinical Use of Smart mA

Scout

- The scout is used by Smart mA to determine the appropriate tube current for each location
- If a scout is unavailable, Smart mA cannot be enabled.
- If the scan length extends beyond the range included in the scout, Smart mA will use the value of the mA for the closest region included in the scout.
- Ideally, the kVp used to acquire the scan should match that used to acquire the scout. If the scan is acquired at a different kVp than the scout, the dose optimization may be slightly affected but the overall quality of the exam should not be jeopardized. There is no need to repeat a scout that was acquired at 120 kVp if the scan requires 140 kVp, or vice versa.
- Positioning the patient at isocenter is essential! Otherwise, the attenuation calculated based upon the off-centered scout will not be accurate. If a patient is centered too low (Fig. 7a), the patient appears wider on the scout than he/she actually is (Fig. 7b), thus misinforming the Smart mA algorithm regarding the patient width. Similarly, centering too high will misinform Smart mA as to the patient size (Fig. 7c). Note that the tube is positioned under the table in Figures 7a–c. This assumes a supine patient and decreases dose to radiation sensitive anterior structures, such as the breast.

FIGURE 7a

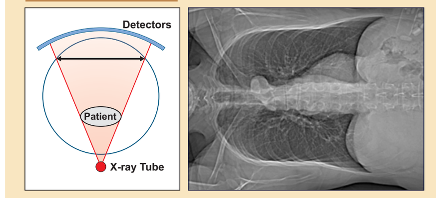


Figure 7a: Patient is centered too low in the scan field, making the patient appear wider than he/she actually is. The resultant exam may use more dose than is necessary.

FIGURE 7b

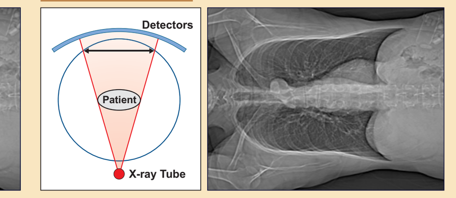


Figure 7b: Patient is properly centered in the scan field making the patient appear the same size that he/she actually is.

FIGURE 7c

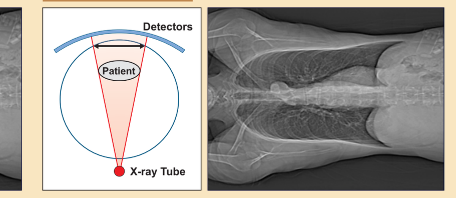


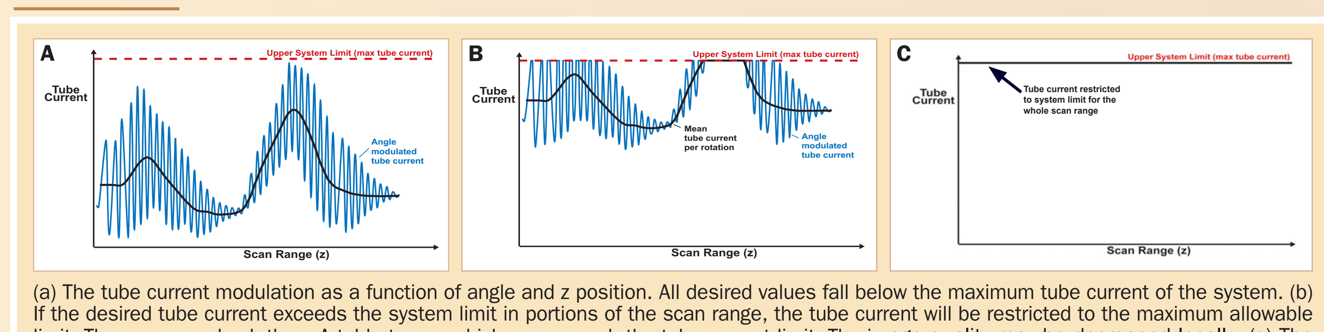
Figure 7c: Patient is centered too high in the scan field, making the patient appear narrower than he/she actually is. The resultant images may be too noisy.

Noise Index and Slice Thickness

Smart mA always uses the slice thickness of the first prospective reconstruction to estimate the tube current. Therefore, it is very important to understand the relationship between the noise index and slice thickness. Otherwise, the image quality and the radiation dose achieved using Smart mA could be very different from what is expected.

For example, when the slice thickness for the first prospective reconstruction is 5 mm, a noise index of 11.5 indicates that the desired noise level on the 5 mm images will be approximately 11.5. If the second prospective reconstruction job uses a 0.625 mm slice thickness with the same algorithm, then the noise level on the 0.625 mm image will be 11.5*sqrt(5/0.625)=32.5. However, when the slice thickness for the first prospective reconstruction is changed to 0.625 mm, Smart mA will calculate the mA based on a slice thickness of 0.625 mm. This implies that the noise index would have to be increased to 32.5 in order to maintain the same radiation dose (relative to the first prospective reconstruction using a 5 mm thickness). If a noise index of 11.5 is used with a first prospective reconstruction of 0.625 mm, then Smart mA will try to use 8 times the original radiation dose in order to achieve a noise level of 11.5 on a 0.625 mm image!

FIGURE 8a



(a) The tube current modulation as a function of angle and z position. All desired values fall below the maximum tube current of the system. (b) If the desired tube current exceeds the system limit in portions of the scan range, the tube current will be restricted to the maximum allowable limit. The user can check the mA table to see which scans reach the tube current limit. The image quality may be decreased locally. (c) The tube current is restricted to the maximum allowable limit for the whole scan range.

Tube Capacity and Large Patients

The maximum mA value achieved during current modulation is limited by the tube and generator capacity (Figure 8). Large-sized patients require a significant increase in tube current to achieve the prescribed noise index. The value may exceed the maximum tube current allowed for a given kVp and scan time combination for partial or full scanning range (Figure 8 b-c). The user has the option of continuing with the current settings, which may produce images with increased noise, or to modify the scan parameters such that the scan can proceed without any potential compromise.

Options for increasing the dose in spite of the system tube current limitation include:

- Increase the rotation time.
  - This will allow more photons per rotation. Scan times will be increased.
- Decrease the pitch
  - This will increase the dose level at each z location at the expense of increased scan time. For some systems, the image thickness will increase for pitch values > 1. The available number of pitches is limited.
- Change from 120 kVp to 140 kVp.
  - This improves x-ray penetration and tube output. Image contrast will be somewhat lower for materials such as bone and iodine and the tube current will need to be adjusted appropriately to compensate for the increase in kVp.
- Wait, if reasonable, for the tube or gantry to cool down (assuming recent use at a relatively high technique). While waiting, the maximum tube current limit increases as the tube and gantry become cool.

Implications of Smart mA's constant noise strategy

As described previously, Smart mA modulates the tube current to maintain a constant image noise, as prescribed by the noise index. The use of a constant noise index may cause the following problems:

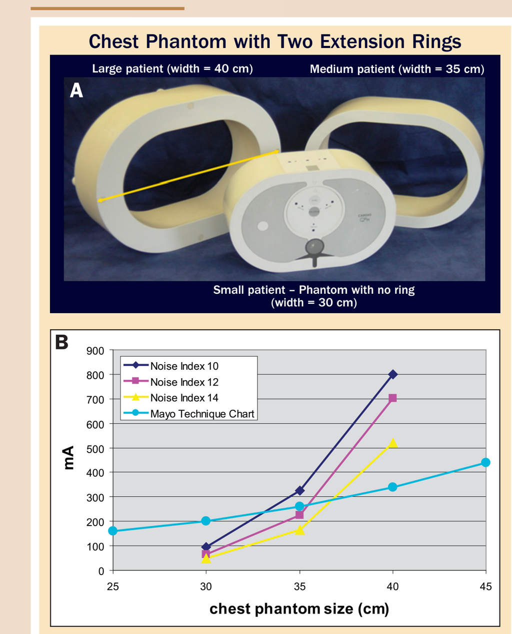
- For smaller patients, Smart mA drops the tube current too much, potentially leading to unacceptably high levels of image noise and the need for the exam to be repeated.
- For larger patients, Smart mA increases the tube current too much, leading to radiation doses that are higher than necessary for the diagnostic task and potentially tube heating problems.

To demonstrate this effect, we scanned three chest phantoms having lateral dimensions of 30, 35, and 40 cm (Figure 9a). Each phantom was scanned with a noise index of 10, 12, and 14. The average tube current used by Smart mA was compared to the tube current that has been in use, and accepted, by our clinical practice for more than six years (Figure 9b). The image quality obtained from our manual technique chart is considered acceptable over the full range of patient sizes (neonates to obese). The change of tube current required by Smart mA is much more drastic than our manual technique chart. The aggresive decrease of the tube current for smaller patients may potentially lead to unacceptably high noise. The much faster increase of the tube current for larger patients may lead to unacceptably high, and unnecessary, radiation doses and tube heating problems.

Pragmatic response – use of a Noise Index technique chart

To solve the problem described above, we use a noise index technique chart. Table 2 shows the noise index chart for our chest/abdomen/pelvis CT exams. Different noise index and mA range values are used for different patient sizes. For smaller patient sizes, a lower noise index is prescribed to avoid a big drop of the tube current and an unacceptable noise level. For larger patient sizes, a higher noise index is prescribed to avoid a big increase of the tube current. For each noise index, an appropriate mA range is also defined to avoid drastic changes of the tube current during the scan. In this way, the drawback of the constant noise paradigm is overcome while the potential benefit of AEC can be achieved.

FIGURE 9



Tube current as a function of phantom size at three noise index values. The horizontal axis corresponds to the lateral dimension of the thorax phantom. The vertical axis represents the average tube current for each scan. The light blue curve shows the Mayo manual technique chart (mA vs. patient size).

Table 2: Noise Index Chart

Lateral patient width (cm)	Noise Index (at 0.5s)	mA (min)	mA (max)
22.1 - 30	9	150	280
30.1 - 40	11.5	220	500
40.1 - 45	14.5	400	720
45.1 -	17 (0.7s)	450	770