Automatic Exposure Control in Multidetector-Row Computed Tomography

7

Mannudeep K. Kalra

CONTENTS

"Confusion now hath made his masterpiece!"

William Shakespeare

"Confusion is a word we have invented for an order which is not yet understood."

Henry Miller

William Shakespeare might have accidentally explained the premise for development of automatic exposure control (AEC) techniques, although Henry Miller might have summarized the issues related to the heterogeneous nomenclature of these techniques!

This chapter attempts to explore the rationale behind development of AEC for multi-detector-row CT scanners and to describe the mechanisms, clinical evidence and pitfalls of AEC techniques for radiation dose reduction or optimization.

7.1
Definition

AEC techniques have been defined as automatic adjustment of tube current in the x–y plane (angular AEC), along the z-axis (z-axis AEC) or both (combined AEC), according to the size and attenuation characteristics of the body region being scanned in order to achieve constant computed tomography (CT) image quality with lower radiation dose (Kalra et al. 2004b,e). The temporal automatic tube current modulation or the electrocardiography (ECG)-controlled (pulsed) dose modulation is also a type of AEC technique used for cardiac and coronary CT angiography.

In simple terms, AEC techniques used for CT scanning behave like photo-timing used in conventional radiography (Kalra et al. 2005a,b). The photo-timing technique terminates exposure once it has been adequately achieved. In this way, photo-timing attempts to limit dose while making sure that adequate quality has been achieved, regardless of patient size and body region assessed. Thus, it allows longer exposure time for X-ray projection of a larger, thicker and denser body part or patient, and shorter exposure time for thinner, smaller and less dense portion. However, CT scanning requires continuous exposure to X-rays, so instead of terminating exposure, the AEC techniques change tube current (mA) for different X-ray projections to maintain constant image quality (generally noise). Thus, AEC will decrease tube current for projections through smaller, less dense body regions (such as anterior–posterior projection at the level of the shoulders or chest) and will increase it for projections through larger, denser regions (such as lateral projection at the shoulder or abdomen). The ultimate objective of both techniques, AEC and photo-timing, is to ensure that no more and no less exposure is given to patients in order to acquire images with constant quality (Kalra et al. 2004e).

M. K. Kalra, MD, DNB
Department of Radiology, Massachusetts General Hospital, 55 Fruit Street, Boston, MA 02114, USA

7.2
Rationale

Until recently, most CT studies were performed using a fixed tube current technique (Kalra et al. 2004b). These fixed tube current values may be selected by technologists based on their arbitrary judgment or as per department protocols set by technologists, radiologists and/or medical physicists based on patient age and size, or study indication (Kalra et al. 2002, 2003a). However, the fixed tube current technique for multi-detector CT scanning may be associated with the following limitations:

- Lower dose efficiency: tube potential determines the photon energy, and tube current influences the photon fluence or the number of photons. The proportion of X-rays used for image creation to the amount of incident X-rays determines dose efficiency of the scanner. In contrast to the situation with a fixed tube current, AEC techniques can improve dose efficiency while maintaining constant image quality by modulating tube current to apply required amount of photons during a single X-ray rotation (for different X-ray beam projections) and from one rotation to the next (for different z-axis or section locations) (Althen 2005; Terada 2005).
- Standardization issues: fixed tube current values have to be adjusted for different generations of multi-detector-row CT scanners. Given the fact that on any given modern multi-detector-row scanner there are several ways to perform scanning, manual selection of fixed tube current may be difficult. In such circumstances, AEC techniques can automatically modulate mA to the selected combination of scanning parameters to obtain CT images of required quality. In this context, the AEC techniques are being increasingly used for dose optimization with multi-detector CT (Miyazaki et al. 2005).
- ECG controlled dose modulation or ECG pulsing: in contrast to fixed tube current, ECG pulsing can reduce tube current during ventricular systole and increase tube current during the relevant diastolic phase.

7.3
Nomenclature and Types of AEC Techniques

There is some confusion over the most appropriate nomenclature for the AEC technique (Kalra et al. 2004e). Both automatic exposure control and automatic tube current modulation have been used to describe the same technique. Although automatic tube current modulation may actually represent the technique more accurately, AEC may be the more commonly accepted term for the technique.

Similarly, several terminologies have also been used to describe different subtypes of AEC techniques (Kalra et al. 2004e). In order to avoid confusion, the most commonly used or described terminologies have been specified and used in this chapter (Table 7.1). Based on the scanning plane or direction in which AEC techniques are used for dose or tube current modula-

Table 7.1. Summary of mechanism of use of different automatic exposure control (AEC) techniques

AEC techniques	Mechanism of use
Angular AEC	Specify
Smart mA	mA
DOM	mAs/slice
CARE dose	Effective mAs
Z-axis AEC (Auto mA)	Specify noise index as well as minimum and maximum mA thresholds for tube current modulation
Z-axis AEC (ZEC)	Specify quality reference mAs value (rarely used without angular AEC also)
Z-axis AEC (Real EC)	Choose from four levels of image noise based on diagnostic requirement
Combined AEC (Auto mA 3D)	Specify noise index, minimum and maximum mA thresholds
Combined AEC (CARE Dose 4D)	Specify quality reference mAs value (modulation strength: weak, average, or strong, for small and large patients can be preset)

tion, AEC techniques may be classified as angular, z-axis, or combined techniques (Kalra et al. 2004e). The angular AEC techniques adapt tube current during each gantry rotation around the patient (Greess et al. 1999, 2001, 2002, 2004; Kopka et al. 1995). Thus, more than one tube current (mA) may be used during each gantry rotation. The angular AEC may estimate tube current during the first 180 degree gantry rotation and use this information for adapting tube current for the subsequent 180 degree rotation. This has been labeled as real-time or online angular AEC (CARE Dose, Siemens Medical Solutions, Forchheim, Germany; DOM, Philips Medical Systems, Netherlands) (Kalra et al. 2004e). The other type of angular AEC technique (Smart mA, GE Healthcare Technologies, Waukesha, Wisconsin, USA) uses a single localizer radiograph (the lateral projection) to obtain information for tube current modulation during the entire 360 degree rotation of X-ray tube around the patient.

In z-axis AEC, the tube current is adapted to maintain a constant specified image quality over the scan length. Thus, z-axis AEC techniques [Auto mA, GE Healthcare Technologies; z-exposure control (ZEC), Siemens Medical Solutions; Real EC, Toshiba Medical Solutions] change tube current from one table position to the other, based on information derived from a single lateral localizer radiograph (Kalra et al. 2005a).

Lastly, the combined AEC techniques (Auto mA 3D, GE Healthcare Technologies; CARE Dose 4D, Siemens Medical Solutions) include tube current modulation in both z-axis (z-axis AEC) and x–y plane (angular AEC) (Kalra et al. 2005b).

The different types of available AEC techniques on current multi-detector CT scanners are summarized in Table 7.2 (Kalra et al. 2005a).

7.4
AEC Mechanisms

Before moving on to the mechanism of AEC, it may be helpful to understand some basic physics nomenclature regarding CT. The three axes of CT scanner in relation to the patients are explained in Figure 7.1. Within each section position, there are

Table 7.2. Different types of automatic exposure control (AEC) techniques available on current multi-detector computed tomography (CT) scanners [Z-DOM is a combination of Automatic Current Setting (ACS) and DOM techniques]

Technique	GE	Philips	Siemens	Toshiba
Angular AEC	Smart mA	DOM	CARE Dose	–
Z-axis AEC	Auto mA	–	ZEC	Real EC
Combined AEC	Auto mA 3D	Z-DOM*	CARE Dose 4D	–

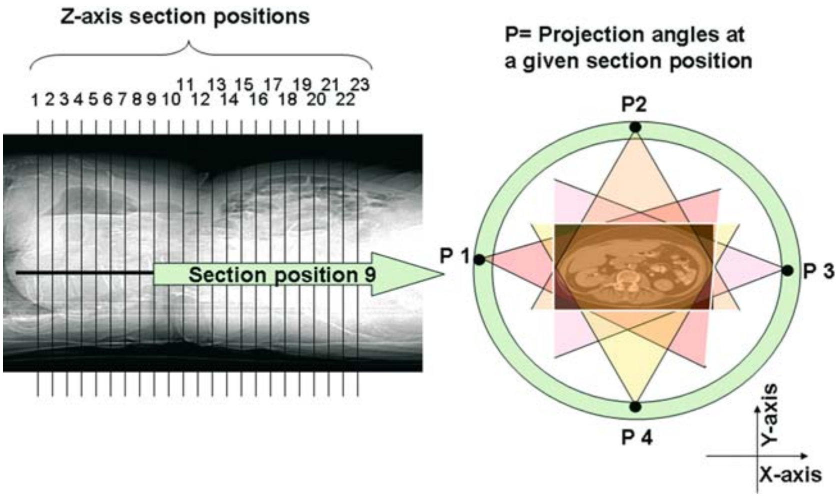

Fig. 7.1. The three axes of computed tomography (CT). The z-axis section position implies slice location or slice position. The x–y axes plane lies within each z-axis section position and represents the plane of X-ray beam projections during each gantry rotation

several hundred projection angles from which X-ray beams begin their journey from X-ray source to the detectors through the patient body. These projection angles lie in the x–y plane of the scanner. With table feed, there is change in the z-axis section position of the patient.

Image noise–mottle or graininess–an important determinant of image quality, depends on applied tube current and X-ray beam attenuation (Kalra et al. 2004b). The latter depends on patient size, shape and attenuation characteristics (profile) of the body region being scanned. An increase in the tube current results in lower noise, and a decrease in the tube current causes greater image noise. In general, an increase in attenuation profile results in greater image noise and vice-versa. Thus, in order to maintain constant image noise in the presence of changing attenuation profile, a region or projection with lower attenuation can be scanned with lower tube current than one with a high attenuation region or projection, which needs greater tube current. Although fixed tube current can be selected based on patient weight or size, use of fixed tube current does not allow adjustment of tube currents within a given study (Fig. 7.2) (Kalra et al. 2002, 2003a).

Angular AEC. The localizer radiograph-based angular AEC was the first AEC technique developed for radiation dose optimization in the early 1990s for single detector-row helical CT scanners (Kopka et al. 1995; Giacomuzzi et al. 1996; Lehmann et al. 1997). With the angular AEC technique, the tube current is modulated to decrease X-rays in projection angles (or in the x–y plane), which will have less beam attenuation and contribute less to the noise in the overall image (Kalra et al. 2004e). This is especially helpful in reducing radiation dose to the non-circular or asymmetric body regions, such as the shoulders, where "non-lateral" projections (such as anterior–posterior projections) have less X-ray beam attenuation than the lateral projection (which is typically the projection with greatest attenuation and noise contribution). Therefore, angular AEC will reduce mA and dose in the "non-lateral" projections without affecting overall image noise.

The Smart mA technique is a localizer radiograph-based, angular AEC technique, which determines the mA values from estimation of patient size, cross-sectional shape and regional attenuation information obtained from a single localizer radiograph (Fig. 7.3) (Kopka et al. 1995; Giacomuzzi et

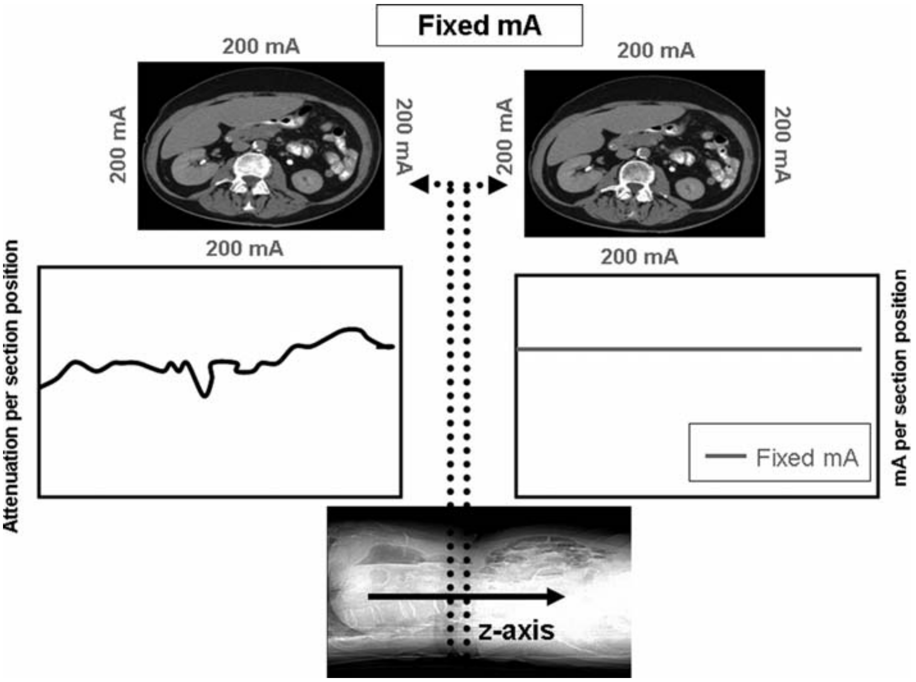

Fig. 7.2. With a fixed tube current, the scanner employs a single, specified mA value for all projections and section position for a given scan series acquisition. Although several computed tomography centers adapt this value with a fixed tube current technique based on patient size and study indication, this technique cannot take into account the variability of attenuation in a section at different beam projections and at different z-axis section positions

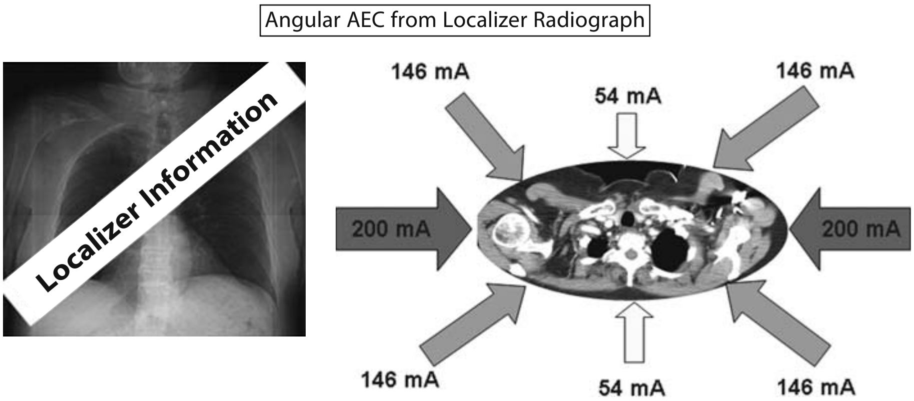

Fig. 7.3. Using a localizer radiograph-based angular automatic exposure control (AEC) technique, information about attenuation profile at different beam projections within each section position is collected from localizer radiograph. This information is used to modulate mA values at different beam projection angles during each X-ray tube revolution (the entire 360°). In an elliptical or asymmetric body cross-section, the technique will decrease mA values for beam projections in thinner portions or lower attenuation (such as in anterior–posterior or posterior–anterior projections) and increase them for those projections passing through regions with greater attenuation or thicker portion (such as lateral projections)

al. 1996; Lehmann et al. 1997). For this technique, the technologists specify a mA value and the software automatically adjusts tube current for different X-ray beam projection angles for the entire 360° tube rotation. The specified mA value provides information about the desired image noise for lateral projections and this information is then used to reduce mA for other "non-lateral" projections.

However, the CARE Dose technique is an on-line, angular AEC technique that adapts mA in real time or "on-the-fly" from projection data, which tails 180° behind the initial projection angles of X-rays and uses attenuation profile data from initial half rotation (180°) to modulate mA values in real time for the following half rotation (180°) (Fig. 7.4) (Greess et al. 1999, 2001, 2002, 2004; Kalra et al. 2004e). For this technique, the technologist selects an effective mAs value [product of tube current (mA) and gantry rotation time (s) divided by the pitch], and the scanner automatically adapts the tube current during each tube rotation while using a specified effective mAs value as a reference for desired image noise in the lateral projections of the first 180° rotation.

Regardless of its type, if used alone, all angular AEC techniques require specification of mA values and thus introduce an element of arbitrary or inappropriate selection of this initial value. For example, selection of a higher value for angular AEC will result in a higher dose than when selecting a lower value (Kalra et al. 2004e).

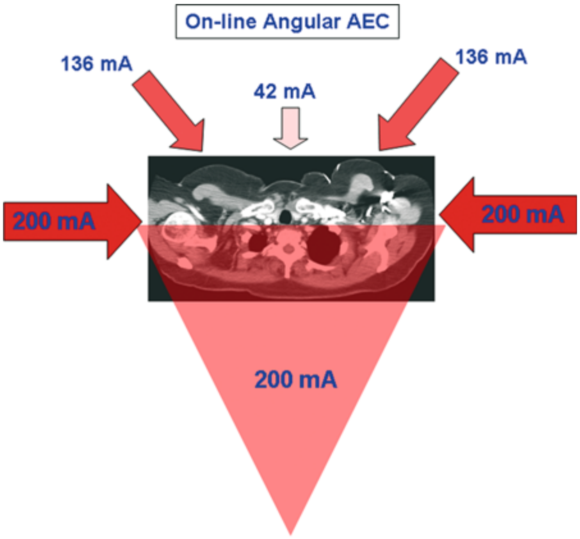

Fig. 7.4. Using an on-line, real-time angular automatic exposure control (AEC) technique, information about attenuation profile at different beam projections within each section position is collected during the first half rotation of X-ray tube around the patient. This technique assumes that the beam for subsequent half rotation is a mirror image of the first half rotation and modulates mA values for the second half according to attenuation data collected from the first half rotation. As a result, the on-line angular AEC modulates mA with a 180° lag. In an elliptical or asymmetrical body cross-section, the technique will use the same prescribed mA value (in present example 200 mA) in the first half rotation, and adapt the values for beam projections in the second half rotation based on beam attenuations

Z-axis AEC. The z-axis AEC techniques modulate mA for different z-axis section positions along the scanning direction based on the attenuation profile of the region being scanned (Fig. 7.5) (Kalra et al. 2004c,d; Campbell et al. 2005; Chapman et al. 2005; Namasivayam et al. in press). Contrary to the angular AEC, the z-axis AEC techniques adjust mA values to maintain image quality (noise index for Auto mA and quality reference mAs value for ZEC technique) specified by the user at all z-axis section positions and do not change tube current for different projections angles. Using a single localizer radiograph (generally the lateral radiograph), the software estimates mA values required to obtain images with a specified noise level (Kalra et al. 2005a).

For the Auto mA technique, the technologist selects a noise index (which approximates the image noise desired for the study) and an acceptable tube current range (minimum and maximum mA values, within which the technique will modulate the tube current) for the CT exam. Radiation dose with this technique depends on the specified noise index and patient size. A 5% decrease in noise index implies an approximate 10% increase in dose, whereas a 5% increment in noise index causes approximately 10% dose reduction (Kalra et al. 2005a). The minimum and maximum mA values also influence radiation dose associated with Auto mA by limiting the extent of decrease or increase in mA at any given noise index.

Although z-axis AEC represents a step forward from angular AEC techniques, as it requires technologists or radiologists to specify desired image quality rather than a tube current value, appropriate image quality requirements have not been completely defined. Furthermore, image quality requirements may differ for different studies and for different patients (small versus large). Thus, selection of high image quality can result in better image quality and higher dose exam that may not necessarily provide higher diagnostic yield. Conversely, lower image quality selection with z-axis AEC can cause inadvertently higher image noise

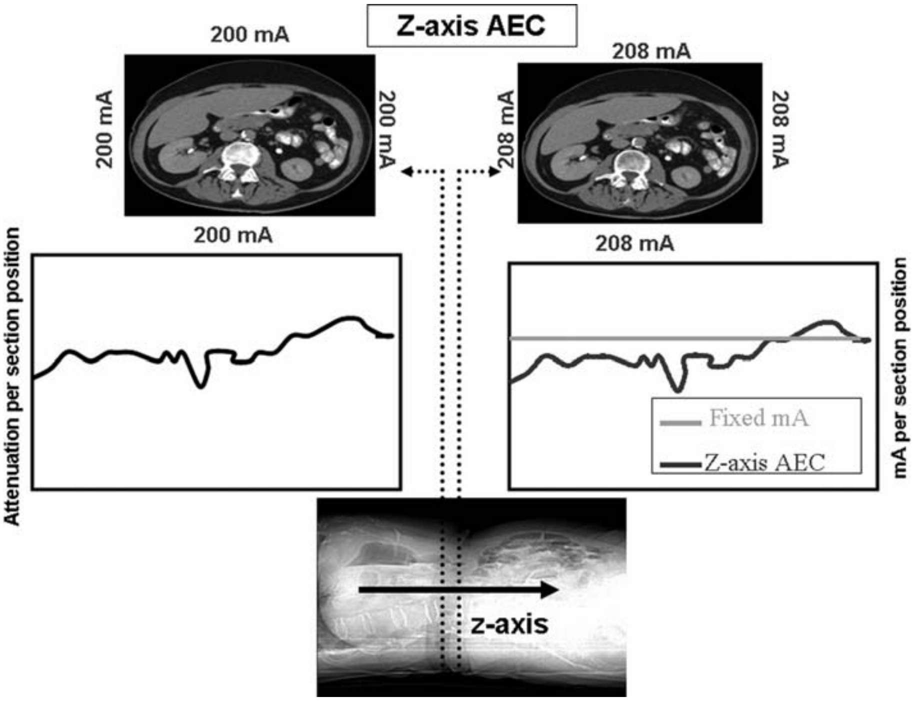

Fig. 7.5. Using a z-axis automatic exposure control (AEC) technique, attenuation for each z-axis section position is estimated from a single localizer radiograph. These data are used to estimate the mA value for each z-axis section position in order to generate images with specified image quality at all sections positions (as selected by the user in terms of quality reference mAs value or noise index). These values change from one section position to the other but not for different projection angles as in angular AEC techniques

and may compromise the diagnostic acceptability of the CT exam.

Combined AEC. These techniques modulate tube current for each z-axis section position (z-axis AEC component) and for different projection angles in each X-ray tube rotation (angular AEC component) (Fig. 7.6) (Kalra et al. 2005b; Rizzo et al. in press). The angular AEC component of the technique may be based on attenuation profile information obtained from the localizer radiograph or from online estimation of attenuation at different projection angles.

The Auto mA 3D technique uses a single localizer radiograph to derive information for modulating mA at each slice position (Auto mA) and for different projection angles (Smart mA). As required for the Auto mA technique, for this technique also, the user prescribes a noise index value with or without minimum and maximum mA limits (Kalra et al. 2004e).

CARE Dose 4D combines the on-line angular AEC (CARE Dose 4D) with the z-axis AEC technique (ZEC) (Rizzo et al. in press). This technique estimates size, shape and attenuation profile over the scan length (z-axis) in the direction of projection as well as in the perpendicular direction (in the x–y plane) using a mathematical algorithm. Axial mA values are determined by estimation of these attenuation profiles and are adapted, based on the patient size and attenuation profile. This adaptation is based on the user-specified quality reference mAs value for the z-axis AEC. Subsequently, these mA levels are used for on-line angular AEC according to the attenuation profile at different projection angles. The quality reference mAs values indicate the effective average for a "reference patient." The reference patient is defined as a "typical adult" weighing 70–80 kg (for adult CT studies) or as a "typical child" weighing 20 kg (for pediatric CT studies) (Rizzo et al. in press).

The diagnostic requirements of studies and radiologists' preferences determine the quality reference mAs value. Although the quality reference mAs value is not changed for patients of different size, for adjusting image quality or dose, the users can

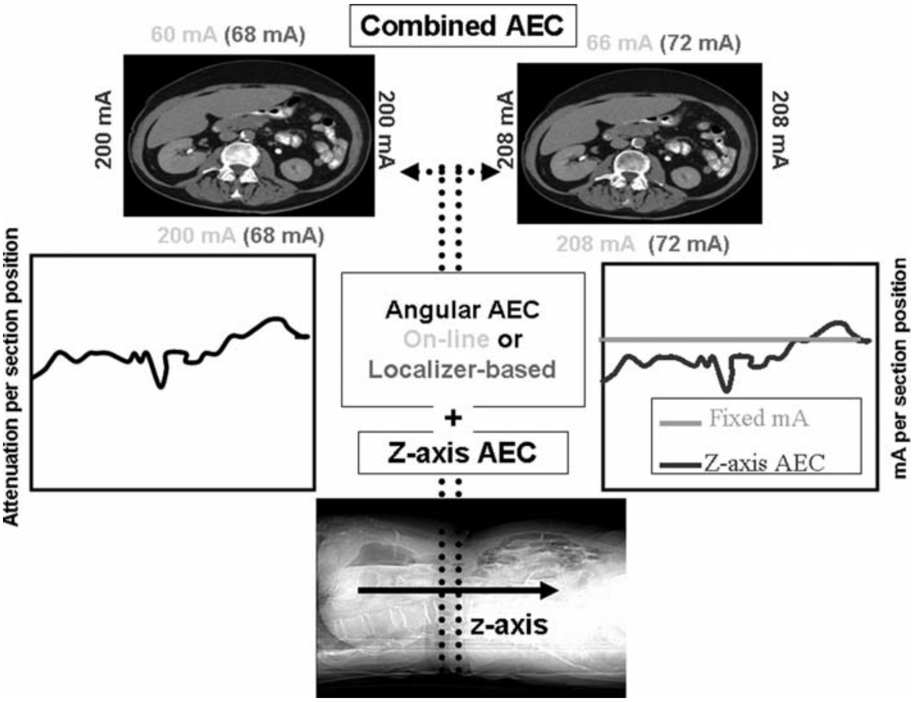

Fig. 7.6. The combined automatic exposure control (AEC) techniques initially use z-axis AEC to estimate mA values for each section position from a localizer radiograph. Subsequently, these values for angular AEC are also estimated based on mA values estimated from z-axis AEC and localizer radiograph (Auto mA 3D), or from z-axis AEC and on-line estimation of attenuation (CARE Dose 4D)

change the quality reference mAs value or strength of AEC. The technique classifies the patient as "slim" or "obese" from a single localizer radiograph and adapts the mA according to the user-specified modulation strength for "slim" or "obese." With CARE Dose 4D, effective mAs value is decreased for "slim" patients and increased for "obese" patients and the extent of mA modulation can be controlled using appropriate modulation strengths (weak, average or strong).

ECG dose modulation. For coronary CT angiography studies, most image data are reconstructed during ventricular diastole so that the influence of cardiac motion during systole can be reduced. The ECG pulsing decreases the tube current substantially during ventricular systole and increases it to the specified level during the diastolic phase, which is used for image reconstruction. This helps to reduce the overall dose to the patients. Thus, there will be no compromise in image quality in the diastolic phase reconstructed image data; whereas, during systole there will be more noise. With ECG pulsing, slower and regular heart rates allow greater and more precise dose modulation and reduction during ventricular systole, whereas faster and/or irregular heart rates will be associated with greater radiation dose to the patient.

7.5
Clinical Evidence for AEC Techniques

In the past 10 years, several clinical studies have shown a benefit of AEC techniques in managing radiation dose for single-detector row helical CT as well as multi-detector-row CT scanners (Kopka et al. 1995; Giacomuzzi et al. 1996; Lehmann et al. 1997; Greess et al. 1999, 2004; Tack et al. 2003; Kalra et al. 2004c,d; Mastora et al. 2004; Campbell et al. 2005; Chapman et al. 2005; Mulkens et al. 2005; Namasivayam et al. in press; Rizzo et al. in press). Compared with the fixed tube current technique, these techniques have been shown to reduce radiation dose for most patients without compromising diagnostic acceptability of CT studies and increase radiation dose in some large patients in order to maintain image quality at specified levels (Greess et al. 1999, 2001, 2002, 2004; Tack et al. 2003; Kalra et al. 2004c,d; Mastora et al. 2004; Campbell et al. 2005; Chapman et al. 2005; Mulkens et al. 2005; Namasivayam et al. in press; Rizzo et al. in press). The results of some clinical studies using AEC techniques are summarized in Table 7.3.

Several studies have shown benefits of ECG pulsing for cardiac CT studies (Poll et al. 2002). Phantom studies have shown that up to 37–44% dose reduction can be achieved using ECG pulsing, depending on the heart rate. A patient study indicated that, when compared with non-modulated coronary multidetector CT angiography, an average radiation dose reduction of 48% for males and of 45% for females can be achieved using ECG-controlled tube current modulation (Jakobs et al. 2002).

7.6
Trouble-shooting for AEC Techniques

- For all localizer radiograph-based AEC techniques (Smart mA, Auto mA, Auto mA 3D, Real EC, ZEC, CARE Dose 4D), the localizer radiograph must include the entire region being scanned with AEC. Beyond the localizer radiograph, these techniques will not adapt tube current appropriately.
- As some AEC techniques rely on localizer radiographs, it is important to avoid patient movement after acquisition of the first localizer radiograph (generally a single lateral localizer is used for most AEC techniques).
- AEC techniques will adapt tube current, taking into account all other relevant scanning parameters such as section profile, beam pitch, detector configuration, gantry rotation time and tube potential.
- Appropriate centering of patient in gantry isocenter, particularly in reference to table height, is extremely important in multi-detector CT scanners, as surface dose to the patient and image noise can increase with off-centering (Thomas L. Toth, GE Healthcare Technologies, personal communication).
- If arms are positioned by the side of the patient undergoing body CT, AEC techniques can increase the dose by as much as 30–35% (as they will compensate for increase in attenuation from arms) (Kalra et al. 2003). Thus, where possible, localizer radiographs must be acquired with appropriate positioning of the arms.

Table 7.3. Summary of reports on automatic exposure control techniques

Study	Technique	Region	Dose reduction
Greess et al. (1999)	CARE Dose	Shoulders	38%
Greess et al. (2001)	CARE Dose	Chest (pulmonary nodules)	21%
Greess et al. (2002)	CARE Dose	Neck	20%
		Chest	23%
		Abdomen	23%
Tack et al. (2003)	CARE Dose	Chest	17%
		Abdomen	20%
Mastora et al. (2004)	CARE Dose	Thoracic outlet	35%
Kalra et al. (2004c)	Auto mA	Abdomen	10–41%
Kalra et al. (2005b)	Auto mA	Chest	18–26%
Kalra et al. (2005a)	Auto mA	Abdomen (renal stones)	43–66%
Mulkens et al. (2005)	CARE Dose 4D	Chest	20%
		Abdomen-pelvis	32%
		Lumbar spine	37%
		Cervical spine	68%
Namasivayam et al. (*)	Auto mA	Neck	36%
Rizzo et al. (*)	CARE Dose 4D	Abdomen	41–43%

- Some AEC techniques ignore metallic implants when estimating attenuation profile and tube current (such as CARE Dose 4D) (Dalal et al. 2005), while others increase tube current in the region of metallic prosthesis as they cannot exclude the contribution of high attenuation from metallic prostheses (Rizzo et al. 2005). In the latter, a lower desired image quality should be set or the fixed tube current technique be used.
- Pediatric and adult settings for desired image quality usually differ and must be set as such (Kalra et al. 2004a,c).
- For a large patient, an increase in tube current with AEC techniques may be insufficient to obtain the desired or specified image quality (Kalra et al. 2004a,c). In such instances, the user must be attentive to other scanning parameters such as table feed, gantry rotation time and kVp.
- For low dose examinations, such as CT colonography and kidney stone CT, a lower "desired image quality" requirement for AEC techniques than with routine indications should be selected.
- CT dose index volume–CTDI vol displayed on the user interface of the scanner is the average CTDI vol over the scan length. This is crucial to understand as CTDI vol changes over the scan length and can be higher or lower at different section positions in the scan range. Thus, estimation of local or organ-based effective doses using these average values may not be accurate.
- Some AEC techniques may not be applicable or appropriate in all body regions, such as in head or extremities; therefore, user must inquire about applicability and accuracy of AEC techniques from their vendors.
- With ECG pulsing, image data during systolic phase will be noisy and may impair the cardiac cine or functional assessment as well as visualization of incidental extra-cardiac thoracic findings. In some cases, reconstructing these image data sets at thicker sections and/or smoother reconstruction kernel settings may help.

7.7
Pitfalls

Despite commendable advances and efforts of the vendors to optimize radiation dose associated with CT scanning, there are some issues associated with use of AEC techniques in routine clinical practice. Most importantly, there are substantial differences between nomenclature and dose modulation with AEC techniques from different vendors. This implies that the scanning method used with one AEC technique cannot be used on a similar technique using a scanner from a different vendor. Furthermore, presently, most vendors recommend use of an "empirical" desired image quality for scanning. It is important to understand that AEC techniques will work only as efficiently as the specified or desired image quality. If a higher image quality is specified (for example, higher quality reference mAs value for CARE Dose 4D or lower noise index for Auto mA), then the system will use a higher dose. Likewise, different desired image quality thresholds must be specified for different clinical indications; for example, a lower quality reference mAs value must be used for a kidney stone protocol than for routine abdominal CT protocols. Selection of inadvertently low image quality can lead to excessive dose reduction using AEC techniques and compromise diagnostic acceptability of the study. To facilitate appropriate use of AEC techniques, there is a need to define threshold levels of "desired image quality" for different clinical indications and patient ages.

Although AEC techniques can automatically increase tube current and dose to large patients, it is important to realize that, in a large patient, an increase in applied peak kilovoltage, gantry rotation time or scan field of view, or a decrease in beam pitch may also be necessary to obtain desired diagnostic information.

As with any new technique, there is a learning curve that radiologists and technologists must overcome in order to use these AEC techniques appropriately.

7.8
Summary

- Most modern multi-detector-row CT scanners allow use of AEC techniques
- AEC techniques can aid in optimizing radiation dose for different patient sizes and clinical indications
- Constant image quality at lower radiation dose can be achieved using AEC techniques in most patients
- For different clinical indications, users must modify the scanning parameters for AEC in order to attain desired dose reduction or image quality

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