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Abbreviations:

ACS = automatic current setting
ATCM = automatic tube current modulation

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Techniques and Applications of Automatic Tube Current Modulation for CT¹

Introduction of slip-ring technology with subsequent development of single- and multi-detector row helical computed tomographic (CT) scanners have expanded the applications of CT, leading to a substantial increase in the number of CT examinations being performed. Owing to concerns about the resultant increase in associated radiation dose, many technical innovations have been introduced. One such innovation is automatic tube current modulation. The purpose of automatic tube current modulation is to maintain constant image quality regardless of patient attenuation characteristics, thus allowing radiation dose to patients to be reduced. This review discusses the principles, clinical use, and limitations of different automatic tube current modulation techniques.

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Tube current (measured in milliamperes) is an important determinant of radiation dose and image quality in x-ray-based examinations. Recent advances in computed tomographic (CT) technology, including implementation of automatic tube current modulation (ATCM), allow reduction in radiation exposure during CT examinations (1–6). ATCM may be defined as a set of techniques that enable automatic adjustment of the tube current in the x-y plane (angular modulation) or along the z-axis (z-axis modulation) according to the size and attenuation characteristics of the body part being scanned and achieve constant CT image quality with lower radiation exposure. Hence, ATCM techniques are analogous to the automatic exposure-control or photograph-timing techniques used in conventional radiography.

Amid growing concerns about CT radiation exposure, the adoption of ATCM techniques should permit overall reduction in radiation exposure in CT examinations. Unfortunately, owing to rapid technologic advances, different vendors have developed different ATCM techniques and use proprietary nomenclature.

Nevertheless, the introduction of ATCM techniques in modern CT scanners represents an important step toward standardization of tube current protocols, with elimination of arbitrary selection by radiologists and technologists. This article will describe the principles of ATCM techniques, their clinical use, and the advantages and disadvantages of application in diagnostic CT scanning.

PRINCIPLES OF ATCM TECHNIQUES

Unlike in conventional radiography, during CT scanning the x-ray tube continuously rotates around the patient, emitting x-rays that traverse through a cross section of the body to generate attenuation profiles (image raw data) at the detectors. Thus, incident x-ray beam projections from multiple directions around the region of interest are used to reconstruct each cross-sectional CT image. Scanning parameters such as tube current and tube potential determine photon fluence and incident beam energy, which affect image quality and absorbed radiation dose. With other scanning parameters held constant, a reduction in tube current decreases radiation exposure but increases image noise or mottle, a principle determinant of image quality. Likewise, an increase in tube current leads to an increase in radiation exposure and a decrease in image noise. On a scale of diagnostic acceptability, image noise and radiation exposure represent conflicting factors, and disproportionate emphasis on either factor may have an adverse effect on image quality or radiation dose. Whereas images with lower noise (increased radiation exposure) may not

ESSENTIALS

- *Automatic tube current modulation techniques are based on the fact that image noise is determined by x-ray quantum noise in the transmitted beam projections.*
 - *These techniques adjust tube current in an effort to maintain constant image quality at the lowest dose.*
 - *Automatic tube current modulation represents an exciting recent technological innovation to enable radiation dose optimization.*
-

reveal additional diagnostic information, images with higher noise may obscure lesions that might have been visible in lower-noise images (7–9).

Authors of previous clinical and experimental studies have reported that satisfactory image quality can be obtained with a reduction of tube current on the basis of weight and cross-sectional dimensions of patients undergoing CT scanning (10–12). Results of these studies may be explained on the basis of variable attenuation of the incident beam traversing a particular cross-sectional dimension at a particular projection angle (1,2). The resultant attenuation determines image noise and is affected by scanning parameters, particularly tube current. For example, greater beam attenuation in a particular dimension or projection will result in greater noise and will require higher tube current than that needed by a beam undergoing less attenuation in another projection.

Manual adjustment of tube current based on patient weight or dimensions can aid in establishing an appropriate balance between image noise and radiation exposure (10,12). However, these adjustments do not guarantee constant image quality throughout the entire examination. For example, in CT scanning of chest, the choice of a fixed tube current does not account for differences in beam attenuation between the shoulder region and midchest region or between anteroposterior and lateral cross-sectional dimensions. ATCM techniques allow maintenance of constant image quality at a required radiation exposure level because ATCM rapidly responds to large variations in beam attenuation. ATCM is based on

the fact that image noise is determined by x-ray quantum noise in the transmitted beam projections. This technique aims to modulate tube current on the basis of regional body anatomy for adjustment of x-ray quantum noise to maintain constant image noise with improved dose efficiency.

Currently, two distinct techniques are available for ATCM: angular (x-y) modulation and z-axis modulation. Both techniques modulate tube current in an effort to maintain constant image quality at the lowest dose while simultaneously reducing tube loading (heating) and minimizing streak artifacts caused by a minimal number of photons.

Angular Modulation

The angular-modulation technique was introduced in 1994 for a single-detector row helical CT scanner (Smart-Scan; GE Medical Systems, Waukesha, Wis) (13–15). This software-based technique modulated tube current on the basis of the measured density of regional structures and the absorption values of the object of interest. This information was obtained by measuring local x-ray beam absorption in 100 central channels on two localizer radiographs (lateral and anteroposterior views). Preprogrammed sinusoidal modulation of tube current was achieved during 360° rotation for equalization of local differences in beam absorption to obtain relatively constant noise content and reduce radiation exposure. A radiation dose reduction of up to 20%, depending on patient geometry (asymmetry), has been reported (14). A recent refinement of the angular-modulation approach is an online, real-time, anatomy-adapted, attenuation-based tube current modulation technique (CARE Dose; Siemens Medical Solutions, Forchheim, Germany) that does not need the information of radiographic localizer images to achieve ATCM (1–3,16–20).

Angular-modulation techniques automatically adjust the tube current for each projection angle to the attenuation of the patient to minimize x-rays in projection angles (eg, anteroposterior or posteroanterior angles are less important than are lateral projections because the former cause less beam attenuation and hence are associated with less noise) that are less important with regard to reducing the overall noise content (Fig 1). In phantom studies in which an online angular-modulation technique was compared with the previous angular-modulation technique, a substantially greater radia-

tion reduction (up to 50%) with the online modulation technique was documented (1).

In patients with circular cross-sectional geometry, beam attenuation is constant in all projections (x-ray beam projection angles). However, in a noncircular cross-sectional geometry, attenuation varies strongly in different projections, sometimes by more than three orders of magnitude. In these settings, image noise in high-attenuation projection angles determines the overall image noise content. Thus, at angular projections with a small patient diameter or body region being imaged (eg, greater tube current reduction occurs in chest than in abdomen), corresponding to a relatively lower attenuation, the tube current can be reduced substantially without a measurable increase in the overall noise content of the image. Without angular modulation, tube current is held constant over the 360° rotation, regardless of the patient attenuation profile. The angular-modulation technique reduces tube current as a function of projection angles for low-attenuation projections (anteroposterior vs lateral projections). This technique calculates the modulation function (an objective image quality parameter) from the online attenuation profile of the patient. The modulation function data are processed and sent to the generator control for tube current modulation with a delay of 180° from the x-ray generation angle. In regions with marked asymmetry, such as the shoulders in CT scanning of chest, where attenuation is substantially less in the anteroposterior direction than in the lateral direction, a reduction in radiation dose of up to 90% can be achieved in the anteroposterior or posteroanterior direction by using the angular-modulation technique (20). In summary, the technique of angular modulation aids in improving dose efficiency in the x-y axis by reducing radiation exposure in a particular scanning plane.

The Dose-Right Dose Modulation, or DOM, technique (Philips Medical Systems, Eindhoven, the Netherlands) of angular modulation also adjusts tube current in asymmetric anatomic regions. This technique is based on the premise that tube current should be modulated according to the square root of the measured attenuation for that projection (1). The DOM technique modulates the current within a 360° tube rotation according to the square root of the attenuation measured from the similar and previous 180° or 360° views. In other words, the attenuation measured at an angular view

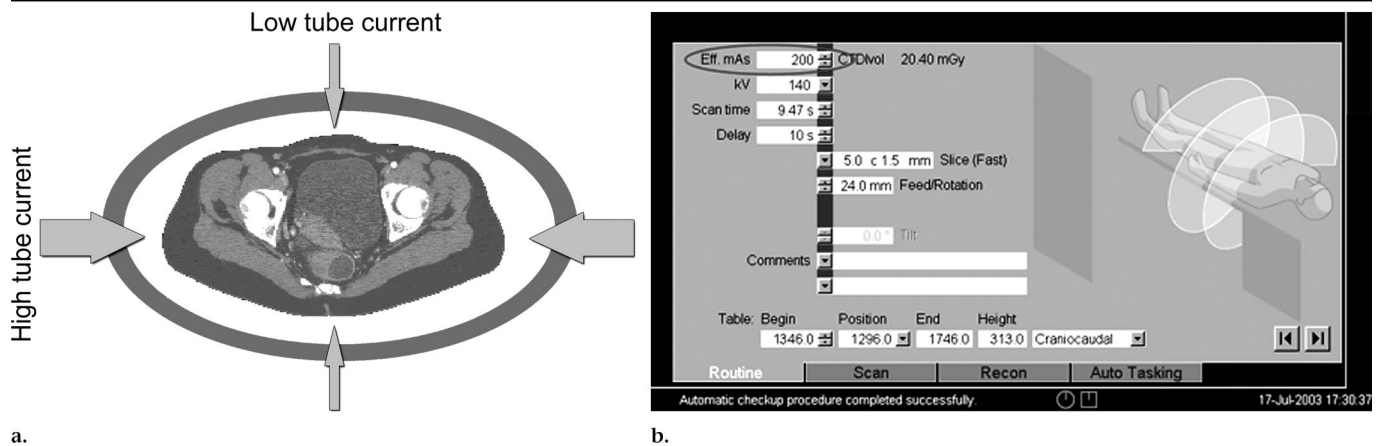


Figure 1. Angular modulation with CARE Dose (Siemens Medical Solutions) ATCM technique. (a) Online modulation of tube current is performed at different projections in the x-y plane within each 360° x-ray tube rotation. Thin arrows indicate reduction of tube current relative to higher tube current (thick arrows). (b) Users specify an effective tube current value in milliamperes (circled) to perform scanning with this technique.

(projection angle) is used to optimize the tube current later for a similar angular view.

Z-Axis Modulation

The z-axis-modulation (AutomA, GE Medical Systems; Real E.C., Toshiba Medical, Tokyo, Japan) technique functions somewhat differently than does angular modulation (21). The AutomA technique adjusts the tube current automatically to maintain a user-specified quantum noise level in the image data. It provides a noise index to allow users to select the amount of x-ray noise that will be present in the reconstructed images. Using a localizer radiograph, the scanner computes the tube current needed to obtain images with a selected noise level. Hence, z-axis modulation attempts to make all images have a similar noise irrespective of patient size and anatomy. The noise index value is approximately equal to the image noise (standard deviation) in the central region of an image of a uniform phantom.

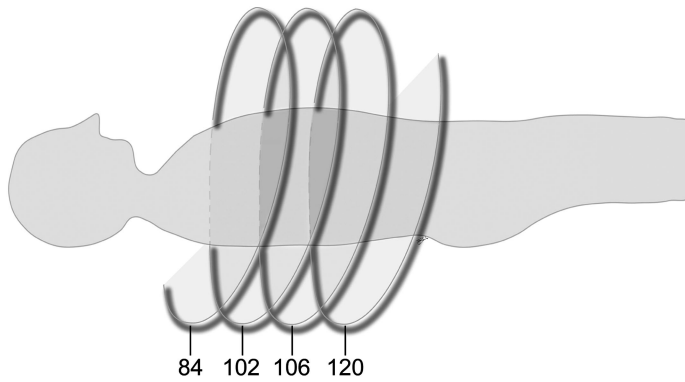
In the z-axis-modulation technique, the system determines the tube current by using the patient's localizer radiograph projection data and a set of empirically determined noise prediction coefficients by using the reference technique (Fig 2). The reference technique comprises an arbitrary 2.5-mm-thick section obtained at the selected peak voltage and 100 mAs for transverse reconstruction with a standard reconstruction algorithm. The projection data from a single localizer radiograph can be used to determine the density, size, and shape information of the patient (4,5). The total projection attenua-

tion data of a single localizer radiograph contain the patient's density and size information about the projection area, whereas the amplitude and area of the projection contain the patient's shape information, which gives an estimate of the patient's elliptic asymmetry expressed as an oval ratio at a given z-axis position. The oval ratio is the ratio of the a and b parameters (lengths of the long and short axes) of an ellipse. The ellipse parameters can be determined for the patient by using the equation for the area of an ellipse. The measured projection area and amplitude from the localizer radiograph give the area and the length of one axis, a , of the ellipse, allowing the length of the other axis, b , to be calculated. These characteristics of the localizer radiograph predict the amount of x-rays that will reach the detector for a specified technique and, hence, determine the image standard deviation due to x-ray noise for a given reconstruction algorithm. The predicted x-ray noise at a given z-axis position for the reference technique (ie, reference noise) is calculated from the projection area and oval ratio from the localizer radiograph by using the polynomial coefficients that were determined from the noise measurements in a set of phantoms representing a wide range of patient sizes and shapes.

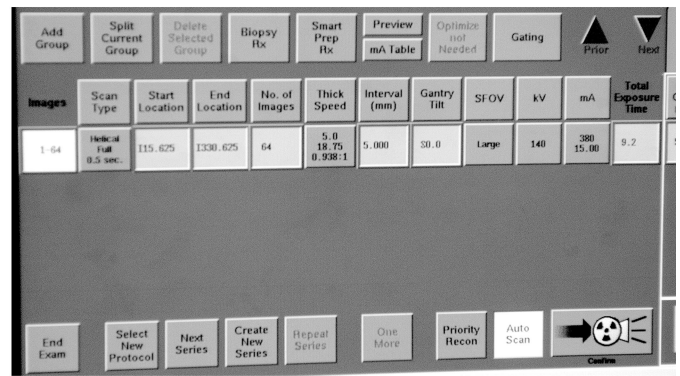
With knowledge of the reference noise and the difference between the reference technique and the selected technique data, the tube current required to obtain a prescribed noise index is easily calculated by using known x-ray physics equations, which state that noise is inversely related to the square root of the number of photons and that the number of pho-

tons is proportional to section thickness, section acquisition time, and tube current. In the currently available version of z-axis modulation of tube current, an adjustment factor for different helical pitches is incorporated in the calculation to account for noise differences between helical selections and the transverse reference technique data. Recent data (4–6) from clinical evaluations of z-axis modulation suggest that the radiation dose reduction with this technique is expected to be greater than that with fixed-tube-current methods, since the tube current is automatically reduced for smaller patients and specific anatomic regions.

Often, the actual noise measured on the image by drawing a region of interest will differ from the noise index selected for scanning. This is due to the fact that noise index settings only adjust the tube current, whereas the standard deviation is also affected by other parameters, including the reconstruction algorithm, the reconstructed section thickness (if different from the prospective thickness), the use of image space filters, variations in patient anatomy and patient motion, and the presence of beam-hardening artifacts. Substantial differences between the selected noise index and the standard deviation can also occur in very large patients owing to insufficient signal strength at the detector and superimposition of electronic noise, which can be minimized by using a higher peak voltage. Likewise, improper centering of patients in the scan field of view can result in noisier images owing to inappropriate beam attenuation by the bow-tie filter (5). As bow-tie filter attenuation



a.



b.

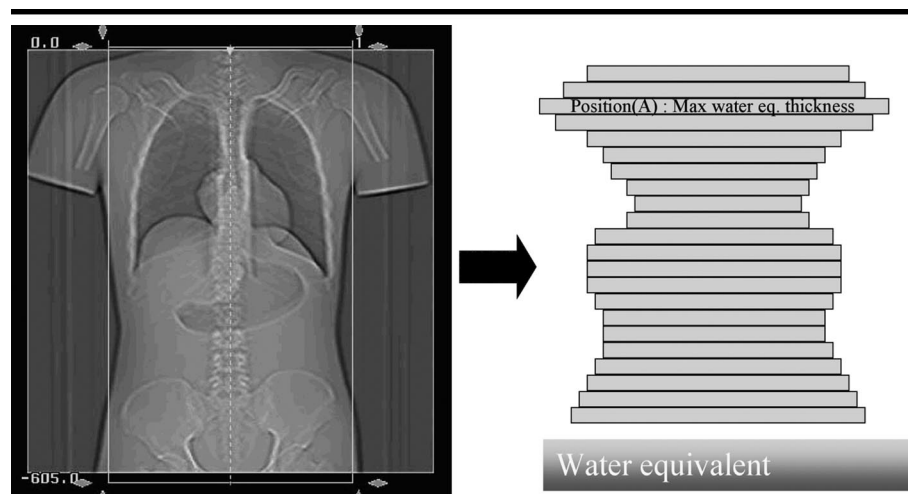
mATable Information

Scan #	mA
7	75
8	75
9	75
10	75
11	75
12	89
13	125
14	134
15	142
16	142
17	128
18	107
19	91
20	75
21	75

Ok

c.

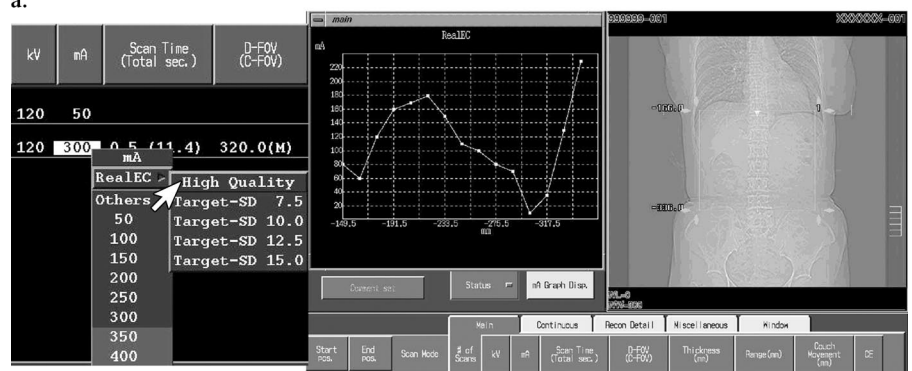
Figure 2. Z-axis modulation with AutomA (GE Medical Systems) ACTM technique. (a) Automatic modulation of tube current from one section location to others in the scanning direction is performed. (b) User selects noise index or enters value for desired noise index and sets minimum and maximum current values. (c) Tube current values (in milliamperes) can be previewed prior to scanning.



a.

increases with distance from isocenter, the thickest part of the patient should be approximately centered in the scan field of view to prevent inappropriate attenuation compensation by the bowtie filter due to incorrect patient positioning.

The Real E.C. technique implemented on Toshiba CT scanners is a z-axis-modulation technique that is also based on patient attenuation measurements acquired from a single localizer radiograph. Evolving from its original form, which provided operators with several options in the choice of nominal tube current to modulate on the basis of patient attenuation data, Real E.C. now offers four levels of image noise to match the diagnostic needs of the examination. The scanner software enables this by calculating the “water-equivalent” thickness of each section from the localizer radiograph (Figs 3, 4). The appropriate tube current is applied at the thickest section in the z-axis direction to achieve the selected



b.

Figure 3. Z-axis modulation with Real E.C. technique (Toshiba Medical). (a) Attenuation is measured on a digital radiograph (left) and is converted to water-equivalent thickness (right), allowing user to specify image quality by choosing different noise levels. (b) After user selects tube current or, more appropriately, desired noise level for the examination (left), the software displays the automatic modulation of tube current that will be used to achieve selected image quality.

standard deviation (noise level). Tube current is then modulated to maintain

the selected noise level throughout the entire scan.

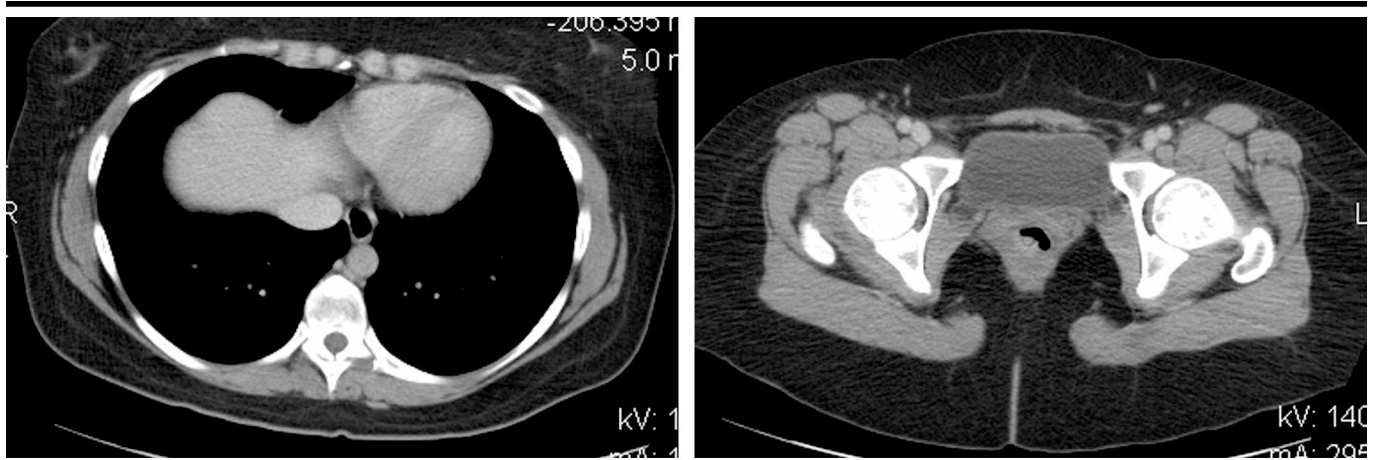


Figure 4. Transverse CT scans obtained with AutomA technique (noise index, 15 HU; 75–380 mA; 140 kVp; gantry rotation time, 0.5 second) in a 32-year-old woman with treated lymphoma. **(a)** Chest image obtained at 136 mA shows satisfactory image quality with soft-tissue algorithm. **(b)** Pelvic image obtained at 295 mA shows that noise in soft tissue is similar to that in **a**.

Automatic current setting (ACS) is a component of the Dose-Right technique (Philips Medical Systems). ACS suggests a tube current–time product level for individual patient examinations to achieve a preselected quantitative image noise level measured in the central region of a stored reference image from a prior examination performed to generate this image with a desired noise content for a specific protocol. ACS is calibrated on a protocol-by-protocol basis at the clinical site by storing reference images that achieve the clinical site’s desired image quality (ie, signal-to-noise ratio) for that protocol. In practice, a protocol is selected, the ACS is chosen, the localizer radiograph associated with the protocol is obtained, and the system host computer compares the localizer radiograph data with the protocol’s reference localizer radiograph data and calculates patient-specific calibration factor and tube current–time product for the CT scan. The suggested tube current–time product for the study will produce CT images with image noise (image quality) similar to that in the site’s prestored reference CT images. The system displays the volume CT dose index (radiation dose reduction with ACS prior to scanning) by calculating the dose difference between scans obtained with and scans obtained without the ACS technique. The volume CT dose index represents the average dose within a scan volume (relative to that of a standardized CT phantom) and is now required to be displayed on the user interface of the CT scanner. The CT dose index is given in milligrays. While it is not the dose to any specific patient, it is

a standardized index of the average dose delivered from the scan series. Thus, the user can select the suggested tube current–time product or individual settings at his or her discretion.

CLINICAL USE OF ATCM TECHNIQUES

From a practical standpoint, bringing ATCM techniques into everyday CT scanning means that most currently used scanning protocols, which involve manual selection of tube current for radiation dose optimization and image quality, need to be modified. Basic differences in ATCM techniques necessitate separate protocols for each technique. In this section, we shall discuss the protocols for routine CT scanning with individual ATCM techniques.

Z-Axis Modulation

The AutomA z-axis–modulation technique is offered with recently available multi-detector row CT scanners (LightSpeed; GE Medical Systems). Although angular modulation has been compared with fixed-tube-current techniques, to date there are no studies of which we are aware in which angular modulation has been compared with z-axis modulation in terms of image quality or radiation dose efficiency (18–20).

In scanners with the AutomA feature, the operator can use either a fixed-tube-current technique or a z-axis–modulation technique. In fixed-tube-current scanning protocols, the technologist selects a suitable tube current for all examinations

on the basis of his or her judgment or departmental guidelines. With this z-axis–modulation technique, instead of selecting a fixed tube current the technologist selects a noise index and a range of acceptable tube current (minimum and maximum milliamperere) settings. As described in the preceding section, the noise index determines image quality. No unit of measure has been assigned to the noise index, but because it approximates the standard deviation (in Hounsfield units) on CT images of a phantom, the noise index can be expressed in Hounsfield units. From a practical standpoint, the technologist selects the noise index and the acceptable range of tube current settings for the scan (Fig 2b). A 5% decrease in noise index (in Hounsfield units) typically increases radiation exposure by 10% and vice versa.

Determination of the range of tube current values can sometimes be influenced by patient habitus. Because noise index and tube current range affect image quality and radiation exposure to the patient, these two parameters must be judiciously selected. A very low noise index may provide higher image quality but will also result in higher than necessary radiation exposure to the patient. Conversely, a higher noise index will result in radiation dose reduction at the price of noisier images. Thus, with the AutomA technique, radiation exposure depends on the selected noise index and patient size. Higher radiation exposure can be avoided by selecting a higher noise index or by setting the maximum tube current parameter to the same level used with fixed-tube-current protocols.

Although image noise will increase in regions where the required tube current is limited by the maximum tube current, overall image quality would be similar to that with fixed-tube-current scanning. The vendor prescribes a noise index of 11–12 HU for routine abdominal and pelvic examinations and 10–11 HU for chest examinations, with a minimum tube current of 60–80 mA.

The protocol used at our institution for routine chest, abdominal, and pelvic CT examinations with a 16–detector row CT scanner and the AutomA technique of z-axis modulation is summarized in Table 1. Once the user has determined the desired parameter adjustments (including noise index), the parameters can be stored in the computer memory and recalled without need for modification in similar clinical cases.

Although the scanner automatically modulates tube current for a selected noise index, the user should be aware of some important implications of the technique. In patients with large cross-sectional dimensions, the scanner may not provide images with the selected noise index because the maximum tube current parameter may be less than the tube current required to generate images with that noise index. In this situation, the user should prospectively preview the amperage table on the console monitor before initiating scanning to determine whether the maximum tube current limit has been reached (Fig 2). If the maximum tube current limit is reached with a 0.5-second rotation, the user can increase the gantry rotation time or use higher peak kilovoltage (140 instead of 120 kVp).

Conversely, with small patients, particularly when not correctly positioned, ATCM techniques can result in excessive reduction in tube current and very noisy images. Instructions to technologists about the necessity of proper centering of patients in the gantry isocenter and increasing the limit for the minimum tube current parameter usually help limit the probability that noisy images will be obtained in small patients. Selecting a lower noise index for small patients while capping the maximum tube current parameter to avoid higher than necessary radiation exposure can also help improve image quality (5).

Authors of a recent study (4) found that the AutomA technique for pelvic and abdominal CT resulted in a mean reduction in tube current–time product of 33% (range, 1%–91%), compared with manual selection of tube current, in 87% (54 of 62) of patients. Compared with

TABLE 1
Protocol for AutomA Technique of Z-Axis Modulation for Routine Chest, Abdominal, and Pelvic CT

Parameter	Value
Noise index	15*
Tube current (mA)	75–380
Gantry rotation time (sec)	0.5 [†]
Voltage (kVp)	140
Beam pitch	0.94
Table speed (mm per rotation)	18.75
Detector configuration	16 rows, 1.25-mm-thick sections [‡]
Reconstructed section thickness (mm)	5

* Noise index of 20 used for unenhanced phase of CT and for assessment of kidney stones; index of 55, for CT colonography; and index of 12, for liver transplants.

[†] Time increased in 0.1-second steps to prevent maximum tube current limit.

[‡] LightSpeed 4.X; GE Medical Systems.

TABLE 2
Protocol for CARE Dose Technique of Angular Modulation for Routine Abdominal and Pelvic CT

Parameter	Value
Tube current (effective mA)	200
Gantry rotation time (sec)	0.5
Voltage (kVp)	140
CT pitch factor	1
Table speed (mm per rotation)	24
Detector configuration	16 rows, 1.25-mm-thick sections*
Reconstructed section thickness (mm)	5

* Senstation 16; Siemens Medical Solutions.

manual selection of a fixed tube current, CT examinations of abdomen and pelvis performed with the z-axis–modulation technique provided images with similar noise, diagnostic acceptability, and lesion detectability. In a study of 153 patients who underwent abdominal-pelvic CT with the AutomA technique (5), a greater reduction in mean radiation dose was noted in smaller patients (mean weight = 72 kg ± 17 [standard deviation], mean anteroposterior abdominal diameter = 23.2 cm ± 3.5, mean transverse diameter = 30.9 cm ± 3.8) than in larger patients (weight = 82 kg ± 16, anteroposterior diameter = 26.9 cm ± 3.9, transverse diameter = 34 cm ± 3.4). Findings from a recent phantom study (6) showed that kidney stones smaller than 5 mm can be adequately evaluated by using AutomA technique, with 56%–77% reduction in radiation dose relative to the dose from a fixed-tube-current technique. In addition, the authors of that study reported that patients with kidney stones can be adequately scanned with a noise index of 20 HU.

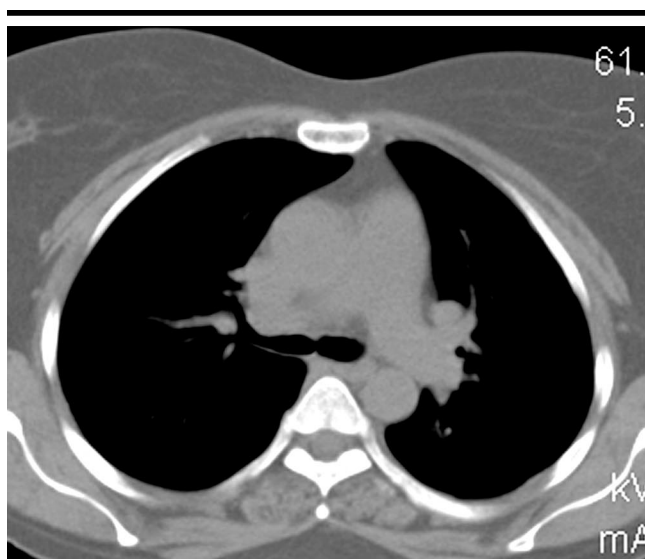
With the Real E.C. technique of z-axis modulation, the noise level can be incorporated into the examination protocol,

thus relieving the operator of any need to apply the technique to individual examinations. Should any protocol need adjustment to suit the needs of individual patients, the Real E.C. technique automatically evaluates the effects on the noise level of parameters such as peak voltage, section thickness, helical pitch, and reconstruction algorithm and selects the required tube current to deliver the desired standard deviation.

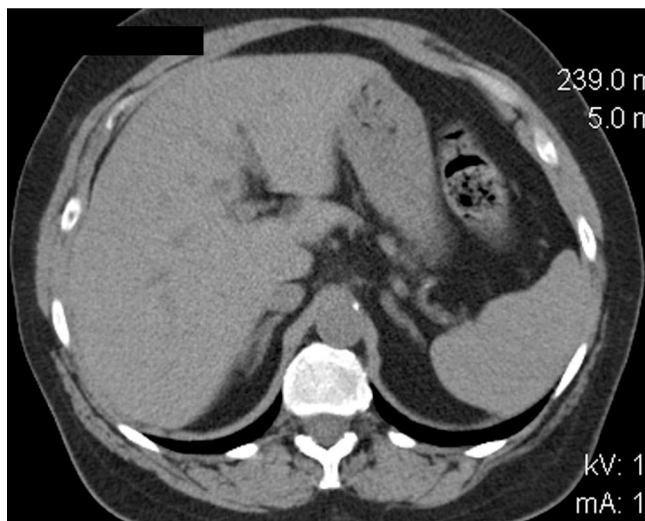
The availability of multiple choices of image noise is consistent with recent attempts to reduce patient dose by careful matching of technique not only to patient habitus but also to diagnostic needs. By incorporating the choices of image quality and dose within the stored protocol, the operator can make modifications at the time of scanning to ensure that radiation dose reduction is achieved while a specific image quality is generated.

Angular Modulation

In many studies, angular modulation (eg, CARE Dose) has been reported to help reduce radiation exposure in phantom experiments and clinical studies in-



a.



b.

Figure 5. Transverse CT images obtained with CARE Dose technique (140 kVp, 0.5-second rotation time, 1:1 pitch) in a 65-year-old woman evaluated for metastases from colon cancer. (a) Chest image obtained at 177 mAs (effective) and (b) abdominal image obtained at 188 mAs (effective) show satisfactory image quality.

involving both adults and children (18–20). With angular modulation, the effective tube current–time product is the key difference. Scanners with the angular modulation technique offer users the option of scanning with angular modulation or fixed tube current (Fig 1b). After selecting other scanning parameters such as peak voltage, table feed, and detector configuration, the user enters a value for the effective tube current–time product for the scan. The effective tube current–time product (mAs_{eff}) is defined as follows: $mAs_{eff} = (TC \cdot GR)/PF$, where TC is the tube current (in milliamperes), GR is

the gantry rotation time (in seconds), and PF is the CT pitch factor.

The scanner maintains a constant effective tube current–time product irrespective of pitch value so that radiation dose does not vary as pitch is changed. This helps to maintain a constant image quality as the pitch factor (table feed) changes. Consequently, an increase in pitch leads to an increase in tube current, and a decrease in pitch leads to a reduction in tube current. After selection of the effective tube current–time product, the scanner performs real-time modulation of tube current in the x-y plane. The se-

lected effective tube current–time product represents the maximum effective value that will be used for scanning. The angular-modulation technique reduces the effective tube current–time product to a value less than that selected for projection angles with a lower attenuation profile. The final displayed effective tube current–time product represents an average of various effective values used in different projections (Fig 5).

Real-time online selection of the effective tube current–time product with angular modulation enhances the radiation dose efficiency of the CT scanner. The user must remember that, like z-axis modulation, accurate centering of patients in the scanning field of view is critical with angular modulation, since shifts from the center can lead to erroneous estimation of the projection angle area and tube current modulation, resulting in noisier images. The scanning protocol used at our institution for routine abdominal and pelvic CT with angular modulation is summarized in Table 2.

In initial investigations in patients in which online angular modulation was used (3), authors have reported an average reduction in tube current–time product of up to 38%, with less image noise in 75% of CT studies, better low-contrast detectability in 51%, and superior overall image quality in 71%, compared with images obtained with fixed-tube-current protocols. Authors of a subsequent study (17) in which angular modulation was used for scanning six anatomic regions, including head, shoulder, thorax, abdomen, pelvis, and extremities (knee), reported a 15%–50%-mAs reduction. Mastora et al (19) used an angular-modulation technique and reported dose reduction with improved image quality for CT angiograms of the thoracic outlet (which is often affected by noise and artifacts when a fixed-tube-current protocol is used). A 10%–60% reduction in the tube current–time product, depending on patient geometry and anatomic region, has been reported in children scanned with angular modulation with a mean effective tube current–time product reduction of 22.3% (20% for neck, 23% for thorax, 23% for abdomen) (20).

The Dose-Right Dose Modulation technique of ATCM uses the milliamperage value of the default protocol as a near-upper (within 10%) bound and modulates the tube current during gantry rotation on the basis of the system's prior attenuation measurements in cross-sectional anatomy. The Dose-Right Dose Modulation technique produces an im-

age signal-to-noise ratio and image quality that are very close to those of the full nonmodulated milliamperage image quality of the system but with marked reduction in radiation dose. Within a particular protocol, the user can select both ACS and Dose-Right Dose Modulation independently or together. As described in a previous section, the ACS icon on the user interface automatically suggests a patient-tailored tube current–time product setting; Dose-Right Dose Modulation then modulates this setting downward during rotation to reduce dose without affecting the desired image quality. The volume CT dose index and dose length product are displayed according to the protocol tube current–time product and the selected protocol parameters. Radiation dose reduction with Dose-Right Dose Modulation ranges between 15% and 40%, depending on the patient's size and the anatomy being scanned. If Dose-Right Dose Modulation is selected, the actual volume CT dose index and dose length product are displayed after the scan on the basis of the actual average tube current–time product used for the scan, which aids the operator in monitoring reductions in the volume CT dose index and dose length product by comparing the prescan (programmed) and postscan (actual) dose values.

LIMITATIONS OF AVAILABLE ATCM TECHNIQUES

At our institution, both angular- and z-axis-modulation techniques have been in use for over 18 months for routine scanning of patients. While each technique has strengths, there are some limitations with each technique. With angular modulation, the user has to prescribe a specific tube current value, which introduces subjectivity in the selection of an effective tube current–time product. On occasion in scanners with an angular-modulation technique, selection of higher effective tube current–time product values for scanning of larger patients may require an increase in the scanning time (especially if the operator believes that selected or allowed effective tube current–time product will not result in optimum image quality).

Because z-axis modulation is a recent innovation, there is a noticeable lack of scientific documentation in the medical literature regarding appropriate noise indexes for specific sizes or ages of patients and specific clinical indications. In addition to selecting manufacturer-recom-

mended noise indexes, however, users can restrict the range of tube currents that can be used for scanning in order to cap the maximum dose to ensure a minimum image quality. However, use of an arbitrary range of tube currents introduces subjective constraints to the technique. A lower minimum tube current may result in reduced patient exposure, which occasionally results in noisier images in small patients who are scanned at a substantially reduced tube current. Conversely, large patients occasionally receive higher tube current with z-axis modulation than they would receive if a fixed-tube-current technique was used in order to maintain the selected image noise. While ATCM results in better image quality in this setting, it can result in greater radiation exposure than would a fixed-tube-current protocol in large patients.

The foremost limitation of ATCM is the lack of uniformity between techniques developed by different vendors. With the addition of ATCM techniques to the technologic revolution in CT scanners, user comprehension is confounded by the separate protocols for systems from different vendors. Industry standards organizations need to build a consensus so that a more uniform ATCM technique is offered to the user in order to minimize confusion and ensure appropriate use of the technique. Further experience and research with ATCM techniques, regardless of type, will aid in optimization these techniques. In addition, the introduction of ATCM to an institution requires close communication between radiologists, medical physicists, and technologists, because a definite learning curve exists.

Presently, no vendor offers a combined ATCM technique that uses both angular and z-axis modulation as complementary approaches for maximum radiation benefits, although industry expects to release a combination technique by the end of 2003. A work-in-progress installation (Care Dose 4D; Siemens Medical Solutions), which combines the angular- and z-axis-modulation techniques, has been reported (22,23). This technique modulates the tube current within the section (angular modulation) and also effects a change of attenuation in different anatomic regions (z-axis modulation). To adapt the tube current in the z-axis, this technique uses a database that correlates image quality at a specific effective tube current–time product for different anatomic regions and a “standard” body with the effective tube current–time product

that is necessary for individual patient body habitus to achieve similar image quality. For the examination, the user enters an effective milliamperage-seconds setting for a “normal-sized” patient to obtain a specific expected image quality. The CARE Dose 4D protocol adapts the tube current to the patient's individual anatomy and modulates the tube current in the section and the z-axis to obtain the desired image quality for all images at the lowest dose levels. Initial results (22,23) have shown a 20%–60% dose reduction, depending on the anatomic region and patient habitus, with improved image quality.

Authors of another study (24) in which combined angular and z-axis modulation (3D Auto mA; GE Yokogawa Medical Systems, Tokyo, Japan) was used have also reported dose reductions of 60% in abdominal-pelvic CT examinations. This technique uses a single localizer radiograph to determine patient asymmetry and appropriate angular and z-axis modulation for the patient. The investigators added noise (computer modification of original raw scan data to simulate lower tube current noise levels) to patients' scan data to produce images and calculate the radiation dose reduction.

CONCLUSION

Currently available ATCM techniques can be used to maintain acceptable image quality while reducing radiation exposure on the basis of patient geometry and clinical indications. ATCM techniques represent an exciting recent technologic innovation toward radiation dose optimization. Further research is needed to standardize these techniques and define appropriate protocols for different patient sizes and indications.

References

1. Gies M, Kalender WA, Wolf H, Suess C. Dose reduction in CT by anatomically adapted tube current modulation. I. Simulation studies. *Med Phys* 1999; 26:2235–2247.
2. Kalender WA, Wolf H, Suess C. Dose reduction in CT by anatomically adapted tube current modulation. II. Phantom measurements. *Med Phys* 1999; 26:2248–2253.
3. Greess H, Wolf H, Baum U, Kalender WA, Bautz W. Dosage reduction in computed tomography by anatomy-oriented attenuation-based tube-current modulation: the first clinical results. *Rofo Fortschr Geb Rontgenstr Neuen Bildgeb Verfahr* 1999; 170:246–250.
4. Kalra MK, Maher MM, Toth TL, Kamath RS, Halpern EF, Saini S. Comparison of z-axis automatic tube current modulation

- technique with fixed tube current CT scanning of abdomen and pelvis. *Radiology* 2004; 232:347-353.
5. Kalra MK, Maher MM, Kamath RS, et al. Sixteen detector-row CT of abdomen and pelvis: study for optimization of z-axis modulation technique performed in 153 patients (abstr). *Radiology* 2004; 233:241-249.
 6. Kalra MK, Maher MM, D'Souza RV, et al. CT detection of urinary tract stones using z-axis automatic tube current modulation technique with low radiation dose: phantom and clinical studies. *Radiology* (in press).
 7. Rehani MM, Bongartz G, Kalender W, et al. Managing x-ray dose in computed tomography: ICRP special task force report. *Ann ICRP* 2000; 30:7-45.
 8. Li F, Sone S, Abe H, MacMahon H, Armato SG 3rd, Doi K. Lung cancers missed at low-dose helical CT screening in a general population: comparison of clinical, histopathologic, and imaging findings. *Radiology* 2002; 225:673-683.
 9. Kalra MK, Blake MA, Maher MM, et al. Does low dose abdominal-pelvic CT compromise the lesion detection and morphological appearance? (abstr). *AJR Am J Roentgenol* 2003; 180(suppl):8.
 10. Donnelly LF, Emery KH, Brody AS, et al. Minimizing radiation dose for pediatric body applications of single-detector helical CT: strategies at a large children's hospital. *AJR Am J Roentgenol* 2001; 176:303-306.
 11. Kalra MK, Maher MM, Toth TL, et al. Strategies for CT radiation dose optimization. *Radiology* 2004; 230:619-628.
 12. Kalra MK, Prasad S, Saini S, et al. Clinical comparison of standard-dose and 50% reduced-dose abdominal CT: effect on image quality. *AJR Am J Roentgenol* 2002; 179:1101-1106.
 13. Kopka L, Funke M, Breiter N, Hermann KP, Vosschenrich R, Grabbe E. An anatomically adapted variation of the tube current in CT: studies on radiation dosage reduction and image quality. *Rofo Fortschr Geb Rontgenstr Neuen Bildgeb Verfahren* 1995; 163:383-387.
 14. Lehmann KJ, Wild J, Georgi M. Clinical use of software-controlled x-ray tube modulation with "Smart-Scan" in spiral CT. *Aktuelle Radiol* 1997; 7:156-158.
 15. Giacomuzzi SM, Erckert B, Schopf T, et al. The smart-scan procedure of spiral computed tomography: a new method for dose reduction. *Rofo Fortschr Geb Rontgenstr Neuen Bildgeb Verfahren* 1996; 165:10-16.
 16. Kalender WA, Wolf H, Suess C, Gies M, Greess H, Bautz WA. Dose reduction in CT by on-line tube current control: principles and validation on phantoms and cadavers. *Eur Radiol* 1999; 9:323-328.
 17. Greess H, Wolf H, Baum U, et al. Dose reduction in computed tomography by attenuation-based on-line modulation of tube current: evaluation of six anatomical regions. *Eur Radiol* 2000; 10:391-394.
 18. Greess H, Baum U, Wolf H, et al. Dose reduction in spiral-CT: detection of pulmonary coin lesions with and without anatomically adjusted modulation of tube current. *Rofo Fortschr Geb Rontgenstr Neuen Bildgeb Verfahren* 2001; 173:466-470.
 19. Mastora I, Remy-Jardin M, Suess C, Scherf C, Guillot JP, Remy J. Dose reduction in spiral CT angiography of thoracic outlet syndrome by anatomically adapted tube current modulation. *Eur Radiol* 2001; 11:590-596.
 20. Greess H, Nömayr A, Wolf H, et al. Dose reduction in CT examination of children by an attenuation-based on-line modulation of tube current (CARE dose). *Eur Radiol* 2002; 12:1571-1576.
 21. Westerman BR. Radiation dose from Toshiba CT scanners. *Pediatr Radiol* 2002; 32:735-737.
 22. Greess H, Wolf H, Suess C, Lutze J, Kalender WA, Bautz W. Automatic exposure control to reduce dose in subsecond multislice spiral CT: phantom measurements and clinical results (abstr). *Radiology* 2002; 225(P):593.
 23. Suess C, Chen XY. Dose optimization in pediatric CT: current technology and future innovations. *Pediatr Radiol* 2002; 32:729-734.
 24. Horiuchi T. Study on 3D modulation Auto mA (abstr). *Jpn Soc Radiol Technol* 2002; 78(P):166.