Evaluation of Postprocessing Dual-Energy Methods in Quantitative Computed Tomography

Part 2. Practical Aspects

CORNELIS VAN KUIJK, MD,* JAN L. GRASHUIS, PHD,† JACK C. M. STEENBEEK, MS,‡
HENRI E. SCHÜTTE, MD,* AND WILLEM TH. TROUERBACH, MD*

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Three facets of dual-energy quantitative computed tomography are studied: (1) the algorithm for postprocessing data (the methods of Cann, Laval-Jeantet et al, Goodsitt et al [two methods], and Nickoloff et al); (2) the influence of choice of tissue-equivalent materials for calibration; and (3) the difference between central and peripheral calibration. The different tissue-equivalent materials include bone mineral-equivalent (K_2HPO_4 solutions and calcium hydroxyapatite), fat-equivalent (liquid paraffin, polyethylene, and 70% ethanol solution), and red marrow-equivalent (plastic). Deviation from the manufacturer's quoted content is least with central positioning of the calibration materials. The accuracy of estimates is best when the same tissue-equivalent materials are used for calibration that are being measured. The deviations produced by the use of different tissue-equivalent materials indicate the importance of using materials that mimic the components of bone most closely. The two methods of Goodsitt et al and the method of Nickoloff et al produced the best results.

Key words: dual energy; quantitative computed tomography; bone mineral content; fat content assessment.

SINGLE ENERGY QUANTITATIVE computed tomography (SEQCT) is a well-established method for determining the bone mineral content in the vertebral body.[1-3] The accuracy of SEQCT is, however, limited due to the occurrence of other constituents of the vertebral body, such as fat[3-8] and collagen.[9] Dual-energy quantitative computed tomography (DEQCT) has been proposed to improve the accuracy of bone mineral measurements[4,10-18] and to provide additional information about the composition of the trabecular region of the vertebral body.[17-21] DEQCT can be done using either preprocessing[14,15] or postprocessing methods.[10-13,16-18] Preprocessing methods require access to the raw projection data at the two scanning energies together with sophisticated software that is not available for all commercial CT scanners. In the past decade, several postprocessing methods have been proposed that can be divided into two different approaches. The first approach uses materials that mimick tissue for calibration purposes, as in the single energy method;[11,12,16] the second uses material-specific coefficients calculated for the effective scanning energies.[13,18]

In a study[22] reported previously, the authors evaluated the various postprocessing methods theoretically, by transforming the original sets of equations to a standard set. A detailed description of the various DEQCT methods and the similarities and differences between these methods was reported.[22]

In the current study, the authors report the practical aspects of using these methods, as evaluated in a phantom study. The study design allowed control of the composition of the vertebral body, which is not possible with in vivo studies. The following items were assessed: (1) the influence of the choice of DEQCT method; (2) the influence of the choice of the tissue-equivalent materials for calibration; and (3) the difference between peripheral and central calibration.

The aim of the authors was to establish the distinct value of these methods and, if possible, to appoint a method of choice.

Materials and Methods

An anthropomorphic phantom was used (Computerized Imaging Reference Systems, [CIRS], Norfolk, VA) as the "patient," allowing the authors to change the vertebral body composition by using "trabecular bone" inserts. A range of different concentrations of bone, red marrow, and fat-simulating inserts was available. An extra set of CIRS trabecular inserts that contained 0, 50, 100, and 150 mg/cm³ of calcium

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From the *Department of Diagnostic Radiology, †Department of Medical Informatics, Erasmus University Rotterdam/Academic Hospital Rotterdam, ‡Philips Medical Systems, Best, The Netherlands.

Reprint requests: C. van Kuijk, Erasmus University Rotterdam, Department of Diagnostic Radiology, Ee 2338, P.O. Box 1738, 3000 DR Rotterdam, The Netherlands.

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hydroxyapatite in a red marrow-equivalent solid plastic and 100% fat equivalent material was used as a reference device.

To study the influence of tissue-equivalent materials in the reference device on the estimation of bone mineral content and fat content, a homemade reference device was used (Erasmus University Rotterdam [EUR] device, The Netherlands). This device contains freshly made solutions (0, 50, 100, 200 mg/cm^3) of dry K_2HPO_4 (Baker Chemicals BV, Deventer, Holland) in water as bone mineral-equivalent within tubes provided with an air-lock to entrap air bubbles. Furthermore, it contains liquid paraffin, polyethylene, and 70% ethanol as fat-equivalent materials. These devices were placed under the anthropomorphic phantom for the performance of simultaneous peripheral calibration.

Nonsimultaneous central calibration was done using either the CIRS inserts without fat and with 100% fat, or the materials of the EUR device placed in the trabecular slot of the phantom. Scanning was done with a Philips Tomoscan 350 (Philips Medical Systems, Best, The Netherlands). Two separate scans were made through every insert; one at 70 kVp and the other at 120 kVp (the lowest and highest kVp setting possible on the Tomoscan 350) with a standard slice thickness of 6 mm. A circular region of interest was used to determine the mean CT number (CT#) of the trabecular insert and of the materials in the calibration device.

Calculations were done for the postprocessing methods of Cann et al,[11] Laval-Jeantet et al,[12] the calibration approach of Goodsitt et al,[16] the basic approach of Goodsitt et al,[16] and the method of Nickoloff et al.[18] These methods were outlined in detail in Part I in the current issue of *Investigative Radiology*.[22] In addition, for comparison, the single energy results are given. For the basic approach of Goodsitt et al,[16] the CT numbers of the pure material were not found by scanning these materials, because it is not possible to scan 100% calcium hydroxyapatite without artifacts. Therefore, these CT numbers were calculated from the linear attenuation coefficients of these materials for the effective scanning energies. This approach will be called "the modified method."

For the method of Nickoloff et al,[18] the slope of the calibration equations was used to estimate the effective scanning energies. The water offset value used by Nickoloff et al is a red marrow offset value when using the CIRS inserts as the calibration device. It is determined by the difference between the measured CT number for the insert, consisting of 100% red marrow-equivalent material and the "ideal" CT-number, calculated for this insert at the effective scanning energy. The "ideal" CT numbers were calculated using knowledge of the elemental composition and mass densities for the different materials used by CIRS. Furthermore, the effective scanning energies were determined independently for the two calibration devices.

All measurements were corrected for drifts in the CT number scale. Because the water offset value used in the method of Nickoloff et al is an empirical correction for scale drift,[22] this correction was applied to all other DEQCT methods; thus, a uniform correction was made for all methods.

The precision was assessed by scanning the samples six times and by calculating the standard deviation of these measurements. In some cases, for illustration purposes, differences in estimates between the different postprocessing DEQCT methods have been evaluated statistically with a paired Student's t test.

Results

Single Energy Results

The single energy results for the different calibration devices and techniques (peripheral vs central) are shown in Table 1. The influence of the fat content on the estimates of bone mineral is shown. For the EUR reference device, decreases of 8 mg/cm^3 of K_2HPO_4 at 70 kVp and 10 mg/cm^3 at 120 kVp for the peripheral calibration technique are observed for an increase of 10% fat by volume. For the central calibration technique, the decreases are 9 mg/cm^3 and 11 mg/cm^3 at 70 kVp and 120 kVp, respectively.

For the CIRS reference device, decreases of 9 mg/cm^3 of calcium hydroxyapatite at 70 kVp and 11 mg/cm^3 at 120 kVp for the peripheral calibration technique are seen. For the central calibration technique, the decreases are 10 mg/cm^3 and 12 mg/cm^3 at 70 kVp and 120 kVp, respectively.

TABLE 1. Single Energy Results for Different Reference Devices and Calibration Techniques

True Content of CIRS Insert*		1		2		3		4	
mg/cm^3†	% fat‡	70 kV	120 kV	70 kV	120 kV	70 kV	120 kV	70 kV	120 kV
0	0	19.4	17.5	19.8	18.8	−1.8	−1.2	−0.7	0.2
50	0	59.1	57.3	63.9	61.8	44.0	43.2	51.0	49.9
100	0	98.9	98.3	106.0	104.7	87.2	88.0	100.2	99.7
150	0	139.9	138.7	148.1	148.4	131.4	132.4	149.5	150.3
0	100	−53.7	−72.2	−59.9	−78.2	−83.8	−101.6	−93.9	−112.2
50	15	46.6	40.2	48.7	43.3	28.1	24.1	33.1	28.5
100	15	87.5	83.1	93.8	87.7	74.7	70.4	86.0	79.9
150	15	127.1	123.9	135.9	132.1	117.4	116.2	135.3	131.4
50	30	34.9	26.4	35.5	27.0	14.4	7.0	17.7	9.6
100	30	77.6	70.5	81.7	75.1	61.7	57.1	71.7	65.4

Calibration device: 1. EUR Reference Device (peripheral); 2. EUR Reference Device (central); 3. CIRS Reference Device (peripheral); 4. CIRS Reference Device (central).

Results in mg/cm^3 K_2HPO_4 for 1 and 2; in mg/cm^3 calciumhydroxyapatite for 3 and 4. All CT-measurements are corrected for CT-number scale drift.

*According to the manufacturer.

†Calciumhydroxyapatite.

‡Percent fat by volume.

Dual-Energy Results

Dual-energy results for bone mineral content and fat content determination are cited in Tables 2 through 5. The results vary depending on the postprocessing method used.

Dual-Energy Results for Central Calibration Technique with CIRS Reference Device

Table 2 shows the estimates for the CIRS reference device and the central calibration technique. This technique can be considered the ideal calibration setup in the current phantom study because the same materials are used in the reference device as in the trabecular inserts. Furthermore, calibration is done at the same place as for the trabecular inserts. The estimated effective energies were 59.0 kV at 70 kVp and 75.3 kV at 120 kVp. Cann's method decreases the fat-induced error, as seen with SEQCT, by a factor of approximately two. For the other methods, the fat-induced error is suppressed completely. All the estimates of bone mineral for the method of Laval-Jeantet et al are 3.1 mg/cm^3 lower than for the method of Goodsitt et al. In comparison with the method of Nickoloff et al, the estimates for the method of Laval-Jeantet et al are 1.8 mg/cm^3 (average; standard deviation [SD] 1.3 mg/cm^3; *P*-value .0014; $t = 4.52$) lower. Consequently, the estimates for the method of Goodsitt et al are 1.3 mg/cm^3 (average; SD 1.3 mg/cm^3; *P*-value .01; $t = 3.22$) higher than the estimates for the method of Nickoloff et al.

All estimates of fat content are 16.3% higher for the method of Laval-Jeantet et al compared with the method of Goodsitt et al. The estimates of fat content with the method of Laval-Jeantet et al are systematically too high compared with the true fat content. Compared with the method of Nickoloff et al, the estimates of fat content for the method of Laval-Jeantet et al are 19.2% higher (average; SD 3%; *P*-value $< .0001$; $t = 20.4$). The results for the modified method of Goodsitt et al and for the method of Nickoloff et al are identical; this is due to the fact that all CT measurements are corrected for CT number scale drift. Therefore, the offset value used in the approach of Nickoloff et al is zero, leading to the identical results.[22] The results for the modified method, therefore, will be omitted in the remainder of the current study.

TABLE 2. Bone Mineral Estimates (in mg/cm^3 Calciumhydroxyapatite) and Fat Content Estimates (in Percentage of Volume) for the Postprocessing Dual Energy Methods.

True content of CIRS inserts*		Method				
C†	F‡	Cann	Laval-J	Goodsitt	Modified	Nickoloff
0		−2.7	−8.1	−5.0	−4.8	−4.8
	0		11.7%	−4.6%	−4.1%	−4.1%
50		53.3	52.9	56.0	55.6	55.6
	0		21.8%	5.4%	4.6%	4.6%
100		101.5	100.0	103.1	102.7	102.7
	0		19.4%	3.0%	2.3%	2.3%
150		147.9	142.9	146.0	145.8	145.8
	0		12.5%	−3.8%	−4.0%	−4.0%
0		−52.9	−8.1	−5.0	−9.2	−9.2
	100		111.7%	95.4%	85.6%	85.6%
50		43.6	52.8	55.9	54.7	54.7
	15		40.7%	24.4%	21.6%	21.6%
100		99.6	112.4	115.5	113.8	113.8
	15		48.0%	31.7%	27.9%	27.9%
150		144.0	151.1	154.2	153.0	153.0
	15		36.7%	20.3%	17.6%	17.6%
50		35.9	54.0	57.1	55.1	55.1
	30		58.7%	42.3%	37.7%	37.7%
100		86.1	99.8	102.9	101.1	101.1
	30		49.7%	33.4%	29.5%	29.5%

Calibration is performed centrally with the CIRS reference device. The effective energy is determined centrally. All CT-measurements are corrected for CT-number scale drift.

*According to the manufacturer.

†mg/cm^3 calciumhydroxyapatite.

‡Percent fat by volume.

Dual-Energy Results for Peripheral Calibration Technique with CIRS Reference Device

The results for the peripheral calibration technique with the CIRS reference device are cited in Table 3. The estimated effective energies are 54.8 kV at 70 kVp and 69.4 kV for 120 kVp. The bone mineral content determination becomes less accurate by this calibration technique. There is an underestimation of the estimates of bone mineral for the inserts with a higher true bone mineral content (> 50 mg/cm^3). Compared with the central calibration technique (Table 2), the estimates of bone mineral for all DEQCT methods are significantly lower: for Cann's method, 10.2 mg/cm^3 (average; SD 9.3 mg/cm^3; *P*-value .0073; t = 3.45); for the method of Laval-Jeantet et al, 13.2 mg/cm^3 (average; SD 13.6 mg/cm^3; *P*-value .0136; t = 3.06); for the method of Goodsitt et al, 12.0 mg/cm^3 (average; SD 11.8 mg/cm^3; *P*-value .0105; t = 3.22), and for the method of Nickoloff et al, 11.7 mg/cm^3 (average; SD 11.6 mg/cm^3; *P*-value 0.011; t = 3.19). The estimates of fat content are not changed significantly.

With the peripheral calibration technique, the estimates of bone mineral for the method of Laval-Jeantet et al are 4.3 mg/cm^3 lower than for the method of Goodsitt et al (average; SD 3.1 mg/cm^3; *P*-value .0015; t = 4.48), and 3.3 mg/cm^3 lower than for the method of Nickoloff et al (average; SD 4.6 mg/cm^3; *P*-value .0496; t = 2.27). There is no significant difference between the estimates of bone mineral for the methods of Goodsitt et al and Nickoloff et al. The estimates of fat content for the method of Laval-Jeantet et al are 14.3% higher than for the method of Goodsitt et al (average; SD 2.7%; *P*-value < .0001; t = 16.5), and 19.4% higher than for the method of Nickoloff et al (average; SD 7.9%; *P*-value < .0001; t = 7.75). The fat content estimates for the method of Goodsitt et al are 5.2% higher (not significant) than for the method of Nickoloff et al (average; SD 7.5%; *P*-value .0583; t = 2.17).

Dual-Energy Results for Central Calibration Technique with EUR Reference Device

To study the influence of choosing other tissue-equivalent materials in the calibration device, the EUR reference device was used.

If the bone-equivalent calibration is changed to K_2HPO_4 solutions in water, without changing the fat equivalent calibration, the bone mineral content and fat content estimates are changed (Table 4).

TABLE 3. Bone Mineral Estimates (in mg/cm^3 Calciumhydroxyapatite) and Fat Content Estimates (in Percentage of Volume) for the Postprocessing Dual Energy Methods.

True content of CIRS inserts*		Method			
C†	F‡	Cann	Laval-J	Goodsitt	Nickoloff
0		−3.3	−9.2	−5.6	−5.1
	0		11.8%	−4.5%	−3.5%
50		45.8	43.0	48.3	47.7
	0		19.7%	5.1%	3.9%
100		85.5	76.5	82.9	83.2
	0		7.8%	−5.1%	−4.4%
150		129.3	119.1	125.4	126.4
	0		6.1%	−7.1%	−5.5%
0		−46.0	−3.4	−5.3	−0.3
	100		119.5%	108.9%	89.7%
50		36.8	43.9	51.0	47.0
	15		39.9%	27.4%	20.2%
100		83.8	93.4	94.6	94.5
	15		43.0%	24.1%	21.1%
150		120.0	116.2	123.6	122.9
	15		19.5%	7.6%	5.7%
50		31.4	60.3	62.2	51.6
	30		75.7%	57.4%	39.7%
100		71.4	77.8	83.9	83.0
	30		40.9%	27.3%	22.7%

Calibration is performed peripherally with the CIRS reference device. The effective energy is determined peripherally.

All CT-measurements are corrected for CT-number scale drift. The ROI-measurements are corrected for their central place and the calibration device measurements are corrected for their peripheral place.

*According to the manufacturer.

†mg/cm^3 calciumhydroxyapatite.

‡Percent fat by volume.

Compared with the central calibration technique, using the CIRS reference device (Table 2), the bone mineral estimates for the methods of Cann, Laval-Jeantet et al, and Goodsitt et al are higher for the insert with a lower true bone mineral content (< 150 mg/cm^3). However, for the method of Nickoloff et al, the estimates are lower for the inserts with a higher true bone mineral content (> 50 mg/cm^3). For the central calibration technique with dipotassium hydrogenphosphate, the estimated effective energies are 54 kV at 70 kVp and 70 kV at 120 kVp. This differs from the effective energies estimated with the CIRS reference device. The bone mineral estimates and fat content estimates for the methods of Laval-Jeantet et al and Goodsitt et al have a fixed difference, although the estimates are nearly the same. There is a difference of 1.8 mg/cm^3 (average; SD 0.1 mg/cm^3; P-value $< .0001$; $t = 49.3$) for the bone mineral estimates, and a difference of 3.8% (average; SD 0.05%; P-value 0; $t = 250$).

Dual-Energy Results for Central Calibration Technique with Different Fat Equivalent Materials

In Table 5, the bone mineral content estimates and fat content estimates are given for the insert that contains 100 mg/cm^3 of calcium hydroxyapatite and 30% fat. The estimates are obtained with various fat equivalent calibration materials. As bone mineral equivalent, either the CIRS inserts without fat or the K_2HPO_4 solutions are used. The uncorrected CT numbers of the fat equivalent materials are for CIRS fat equivalent, −135 Hounsfield Units (HU) at 70 kVp and −115 HU at 120 kVp; for paraffin, −195 HU and −165 HU, respectively; for 70% ethanol, −140 HU and −130 HU, respectively; and for polyethylene, −102 HU and −71 HU, respectively. Thus, a proper choice of fat equivalent material and of bone equivalent material is important, especially for the fat content determination.

Precision

The precision for the bone mineral estimates, expressed as standard deviation, is 0.5 mg/cm^3 for SEQCT at 120 kVp; 0.8 mg/cm^3 for SEQCT at 70 kVp; 3 mg/cm^3 for the DEQCT method of Cann; and 5 mg/cm^3 for all other postprocessing DEQCT methods. The precision for the fat content estimates was 5% (by volume) of fat. All data in the current study should be interpreted with the precision figures in mind.

TABLE 4. Bone Mineral Estimates (in mg/cm^3 Dipotassiumhydrogenphosphate) and Fat Content Estimates (in Percentage of Volume) for the Postprocessing Dual Energy Methods.

True content of CIRS inserts*		Method			
C†	F‡	Cann	Laval-J	Goodsitt	Nickoloff
0		21.9	21.3	23.4	13.5
	0		1.7%	5.5%	12.5%
50		68.6	69.4	71.1	55.7
	0		8.3%	12.2%	10.0%
100		108.8	108.6	110.4	87.2
	0		3.5%	7.3%	−2.0%
150		147.5	145.3	147.1	115.2
	0		−5.5%	−1.7%	−17.6%
0		−20.0	0.0	1.8	25.3
	100		100.0%	103.8%	112.1%
50		60.5	65.2	67.0	57.9
	15		27.0%	30.8%	28.9%
100		107.2	112.7	114.5	98.9
	15		31.0%	34.8%	24.0%
150		144.3	147.0	148.8	123.6
	15		17.8%	21.6%	4.8%
50		54.1	62.5	64.2	60.9
	30		44.5%	48.4%	46.5%
100		96.0	102.0	103.7	90.6
	30		33.3%	37.2%	28.3%

Calibration is performed centrally with the EUR reference device and CIRS fat-equivalent. The effective energy is determined centrally with the EUR device. All CT-measurements are corrected for CT-number scale drift.

*According to the manufacturer.

†mg/cm^3 calciumhydroxyapatite.

‡Percent fat by volume.

Discussion

Single Energy

Underestimation of the bone mineral content by SEQCT due to the fat content is comparable with data reported in the literature[4,6,7] (Table 1). Bone mineral content estimates for the CIRS reference device are lower than for the EUR reference device. The difference is too large to be explained by the differences in attenuation characteristics between calcium hydroxyapatite and dipotassium hydrogenphosphate alone. Mainly, it is due to the red marrow equivalent within the CIRS inserts. The attenuation characteristics of this material are dissimilar from those of water. The estimates for the inserts without fat show that bone mineral determination is improved by performing a central calibration technique. With this technique, differences in scanner-related error sources, such as beam-hardening and scatter, between the centrally located vertebra and the peripherally located reference device are avoided.

Dual Energy

The method suggested by Cann et al[11] assumes that the influence of constituents other than bone mineral on the mean CT number of the vertebral body is approximately the same at every energy. Then, the difference in the mean CT number is due only to the bone mineral component in the vertebral body; therefore, this method uses only calibration equations of bone equivalent materials. As shown, this method reduces the fat-induced error by a factor of two, but it does not provide an estimation of fat content.

The methods suggested by Laval-Jeantet et al and by Goodsitt et al use calibration of bone mineral-equivalent and fat-equivalent materials. These methods take into account the energy-dependence of the fat influence. Furthermore, these methods allow estimation of the fat content of the vertebral body, thus offering potentially useful clinical information.

The method of Laval-Jeantet et al does not provide accurate estimates of fat content; even when the most ideal calibration is done, eg, central calibration with the same materials, the estimates are disappointing. The cause is the use of a double intercept.[22] Apart from this intercept problem, the methods of Laval-Jeantet et al and Goodsitt et al are essentially the same, and there is a fixed relation between the estimates obtained with these methods.[22] These estimates, however, will show larger variations dependent on the calibration materials chosen.

The differences noted between the estimates obtained with the two reference devices for the methods of Laval-Jeantet et al and of Goodsitt et al (Tables 2 and 4) are caused by the assumptions made when K_2HPO_4 solutions in water are used for bone-equivalent calibration. First, it is assumed that K_2HPO_4 has the same attenuation characteristics as calcium hydroxyapatite; this, however,

TABLE 5. Bone Mineral Estimates (in mg/cm^3 Calciumhydroxyapatite or Dipotassiumhydrogenphosphate) and Fat Content Estimates (in Percentage of Volume) for the Insert With 100 mg/cm^3 and 30% Fat.*

	Method			
Calibration Device	Cann	Laval-J	Goodsitt	Nickoloff
BEQ† CIRS	86.1	99.8	102.9	101.1
FEQ‡ CIRS		49.7%	33.4%	29.5%
BEQ CIRS	86.1	99.9	102.9	101.1
FEQ Paraffin		36.1%	24.2%	29.5%
BEQ CIRS	86.1	84.9	92.9	101.1
FEQ 70% Ethanol		32.8%	22.0%	29.5%
BEQ CIRS	86.1	767.8	551.4	101.1
FEQ Polyethylene		970.2%	651.4%	29.5%
BEQ K_2HPO_4	96.0	102.0	103.7	90.6
FEQ CIRS		33.3%	37.2%	28.3%
BEQ K_2HPO_4	96.0	104.0	106.0	90.6
FEQ Paraffin		24.3%	27.1%	28.3%
BEQ K_2HPO_4	96.0	96.1	97.2	90.6
FEQ 70% Ethanol		22.5%	25.0%	28.3%
BEQ K_2HPO_4	96.0	219.7	235.0	90.6
FEQ Polyethylene		322.7%	359.8%	28.3%

Calibration is performed centrally with the EUR reference device or the CIRS reference device. All CT-measurements are corrected for CT-number scale drift.

*According to the manufacturer.

†BEQ: Bone-equivalent calibration.

‡FEQ: Fat-equivalent calibration.

is not true.[6] Secondly, it is assumed that red marrow is water-equivalent; for the CIRS inserts this is not the case. The 100% red marrow-equivalent has a CT number of 40 HU to 25 HU in the energy range of 50 to 75 keV.

With the EUR reference device and the central calibration technique, the estimates for the methods of Laval-Jeantet et al and Goodsitt et al are approximately the same. They would be exactly the same if both the intercepts of the bone-equivalent and fat-equivalent calibration lines were zero.[22] Although the CT number correction sets the CT number of water at zero, the intercepts will not be zero because they are the results of a linear regression fit between the CT numbers and the actual concentrations of the K_2HPO_4 solutions.

Furthermore, these methods give accurate results only if a central calibration technique is done, avoiding differences in effective energy between the central place of the vertebral body and the peripheral place of the calibration device.

The method of Nickoloff et al[18] provides accurate results if the effective energy is estimated centrally with materials that have exactly the same attenuation characteristics as the materials in the region of interest. Furthermore, it requires an offset value that is a correction for CT number scale drift. This value should be determined centrally.

Goodsitt and Rosenthal[17] compared the methods of Cann, Laval-Jeantet et al, and their own calibration approach in a phantom study. A nonsimultaneous central calibration technique was used with the CIRS reference device, and a simultaneous peripheral calibration technique was used with the USCF phantom that contained K_2HPO_4-solutions. The fat-equivalent used for calibration purposes was not specified. Furthermore, it is not clear if an attempt was made to correct their measurements for CT number scale drift. The results in their study cannot be used to compare the results obtained with both reference devices or to compare the peripheral calibration technique with the central one, because both parameters were changed simultaneously. Nevertheless, the study of Goodsitt and Rosenthal was important because it discussed the variance in bone mineral and fat content estimates with DEQCT methods due to the choice of the reconstruction circle size, which can be varied on the CT scanner used in their study (GE 9800, GE, Milwaukee, WI).

In summary, the results obtained in the current study indicate that application of the DEQCT methods are hampered by several restrictions: (1) The calibration or effective energy determination should be done centrally. If it is done peripherally, a conversion should be made to the central place of the vertebral body. (2) The CT number scale drift should be corrected for the central focus of the vertebral body. (3) The calibration materials should mimic exactly the attenuation properties of the anatomic constituents of the vertebral body for the scanning energies used, or the composition of these constituents should be known exactly so that the material-specific coefficients can be calculated.

If these conditions can be fulfilled, only the methods of Goodsitt et al[16] and Nickoloff et al[18] will give accurate results. However, the postprocessing methods reported in the current study assume that the vertebral body can be described as a three-component entity. In the current phantom study, the composition of the trabecular inserts could be described perfectly as a three-component model. The consequences of this simplification should be studied first, before a definite judgment can be given about the proper use of methods for postprocessing dual-energy quantitative computed tomography in medicine.

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