Gerrit J. Kemerink, PhD • Rob J. S. Lamers, MD • Guillaume R. P. Thelissen, MSc
Jos M. A. van Engelshoven, MD, PhD

Scanner Conformity in CT Densitometry of the Lungs[1]

PURPOSE: **To quantify inter- and intrascanner conformity in computed tomographic (CT) densitometry of the lungs.**

MATERIALS AND METHODS: **With six scanners from four manufacturers, a lung densitometry protocol with several variations was applied for performance comparison. Phantoms included water, air, and a humanoid thorax phantom equipped with a dog lung and exchangeable pseudolungs of polyethylene foam.**

RESULTS: **All scanners produced acceptable CT numbers (Hounsfield units) for water, but some not for air. An incorrect calibration of air density affected all CT numbers at lung densities, but the error was easily correctable. Some systems were more sensitive to object size than others were. Sensitivity of CT numbers to section thickness, reconstruction filter, zoom factor, and table height was small, except for two scanners in relation to section thickness.**

CONCLUSION: **After correction for poor air calibration, scanner conformity was acceptable when the reproducibility of lung densitometry in clinical practice was set as a reference.**

Index terms: Lung, CT, 60.12118 • Lung, density, 60.91

Radiology 1995; 197:749–752

Computed tomographic (CT) densitometry of the lungs is extensively used in research and is of growing clinical interest (see, eg, references 1-4 and references therein). A relevant issue for present applications, and certainly for a more general introduction, is conformity among the various scanners on the market. In other fields of densitometry, relatively poor interscanner, and even intrascanner, conformity of CT numbers (Hounsfield units) has been reported (5–7). Moreover, CT scanners were traditionally not optimized for the low-attenuation studies that are relevant to investigations of lung disease. To our knowledge, no systematic scanner comparison in lung densitometry has been published so far, although the scale of activities seems to warrant such an investigation. The present study reports the results from a few widespread scanners, and it addresses the problem of correcting CT-determined densities obtained with a scanner having a poor calibration at air density.

MATERIALS AND METHODS

CT Scanners

Six CT scanners were included in the study (Table 1). All systems are third-generation scanners, except the Picker system, which is fourth-generation. With all systems, scans were obtained that might be chosen for a combined densitometric and high-resolution CT study. The scanning parameters chosen according to this approach are given in Table 1. Only densitometric results were evaluated. A specialist from the manufacturing or sales company of each scanner collaborated in the measurements, except in the case of the two Siemens scanners of our own hospital.

Phantoms

The following phantoms were used:

1. A circular, water-filled phantom of 20-cm diameter.
2. A humanoid thorax phantom (8) containing lungs of a dog and an empty lower thorax section that could be equipped with polyethylene foam to simulate lungs. A ring of 3-cm-thick pig fat was placed around the "lean" phantom to simulate an "obese" thorax. This ring of lard was frozen to stabilize its form.
3. Various pieces of polyethylene foam (PSG, Wellen, Belgium) with a relatively uniform and accurately determined density (9) were used as pseudolungs in the thorax phantom.

Measurements

CT numbers for water and air, yielding the two calibration points of the Hounsfield scale, were measured. The CT number of air was measured within the empty lean and obese thorax, as well as in the empty gantry. The CT number of water was determined with the 20-cm-diameter phantom in the middle of the gantry, by using a large circular region of interest covering about 80% of the phantom cross section.

The dog lungs in the humanoid phantom were measured at a position that had been marked on the outside of the phantom. The CT number was calculated as an average over a hand-drawn region completely including the left lung.

The CT numbers of the various pieces of polyethylene foam were determined with the foam in the lean and in the obese phantom. The results, consisting of CT numbers versus foam density, were fitted with the linear function CT number = offset + slope · density. The CT number for air (empty phantom) was included in the fit. χ^2 analysis was used as a measure of the quality of the fit; for a proper fit and realistic error estimates χ^2 should be on the order of 1.

The correlation of CT number with some variations in the standard protocol was also investigated. We determined the influence of section thickness, reconstruction filter, zoom factor, and table height. In principle these parameters should not affect the average CT number, at least not for homogeneous materials. We used the water phantom, air, and the obese thorax phantom with polyethylene foam at a density of 109 kg/m^3 (for short, foam 109). We also looked for the possible occurrence

---

[1] From the Department of Diagnostic Radiology, University Hospital Maastricht, The Netherlands. Received March 7, 1995; revision requested May 3; revision received May 30; accepted June 6. **Address reprint requests to** G.J.K., Department of Radiology, University Hospital Maastricht, PO Box 5800, 6202 AZ Maastricht, The Netherlands.

of data truncation: Some scanners do not use CT numbers below −1023 or −1024, whereas owing to noise such values may well occur for lungs of extremely low density (eg, in patients with emphysema) (9).

Assuming a well-calibrated scanner, the density of water-equivalent tissue, as lung is (10), can simply be calculated from the measured CT number by adding 1,000 (strictly, the correction at air density should be 1,001.3, changing to about 998.0 at water density). The density so obtained is in kilograms per cubic meter. This relation shows the equivalence between CT number and density. In the remainder of this article we use CT numbers because they are the numbers given by the scanner.

Table 1
Scanners and Scanning Protocol

Manufacturer*	Scanner	HV† (kV)	Section Thickness (mm)	mAs	Scanning Duration (sec)	Reconstruction Filter‡
GE	Highlight	140	1.5	250	2	STD
Philips	SR 7000	140	1.5	250	2	4
Philips	LX	120	1.5	175	1.9	4
Picker	PQ-2000	130	1.5	200	1	STD
Siemens	Somatom Plus	137	1.0	220	1	AB 7055
Siemens	Somatom Plus	137	1.0	220	1	AB 7055

* GE Medical Systems, Milwaukee, Wis; Philips Medical Systems, Best, The Netherlands; Picker International, Cleveland, Ohio; Siemens Aktiengesellschaft, Erlangen, Germany.

† HV = high voltage.

‡ All reconstruction filters are the standard type. Shown are the manufacturer's code number or acronym.

RESULTS

The CT numbers found for water, air, dog lung, and foam 109 are shown in Table 2. The results for water were similar among all scanners. For air, dog lung, and foam 109, the CT numbers obtained with the Philips scanners deviated from the results of the other scanners. Table 3 presents the results of the measurements of foam in the lean and obese thorax phantom. The latter results are presented in the form of the offset and slope of the linear function fitted to the data. The figure shows, as an example, the foam data points, together with the line fitted to them, for the Philips SR 7000 scanner (top) and a Siemens Somatom Plus scanner (bottom). The quality of the fit was usually good, as was also evidenced with the χ^2 value.

With all scanners, the CT numbers of air, water, and foam 109 were also measured at section thicknesses of 3, 5, and 10 mm. The Philips scanners, in contrast to the other scanners, showed considerable section thickness-dependent differences in CT numbers for air and foam. Averaging for each of the non-Philips scanners the results for the four different section thicknesses, where the averaging is performed separately for air, water, and foam 109, produced standard deviations of these intrascanner averages between 0.1 and 1.2 HU. For air, the Philips SR 7000 produced −984 HU (1.5-mm section thickness), −992 HU (3 mm), −994 HU (5 mm) and −996 HU (10 mm); and the LX produced −984 HU (1.5 mm), −991 HU (3 mm), −994 HU (5 mm), and −992 HU (10 mm). Especially for sections of 1.5-mm thickness, large deviations from the ideal value of −1,000 HU were observed. The CT numbers for foam 109 showed similar shifts.

The influence of the type of reconstruction filter was normally very small: Intrascanner changes were almost always less than 1 HU, the maximum change being 2.0 HU. Greater deviations might be found in those cases in which data truncation occurs. The filters tested were, for the GE Highlight scanner, STD (standard), bone, detail, soft, and smooth; for the Picker PQ-2000 scanner, STD, sharp, and smooth; for the Philips SR 7000 and LX scanners, 4, 5, 8, and 9; and for the Somatom Plus scanners, standard, high-resolution, ultra-high-resolution, and soft.

Zoom factor variation between 1.0 and 3.0 never modified CT numbers by more than 1 HU.

Changes in table height over a 5-cm range never affected CT numbers by more than 1.5 HU. Some systems (Picker, Philips) allow scanning with the table in such a low position that it is partly outside the scan field, which leads to falsification of CT numbers (often in the form of streak artifacts). Another system (Siemens) allows only a 5-cm vertical positioning range.

The Highlight and the Somatom Plus scanners are prone to data truncation: Data are truncated at −1024 and −1023 HU, respectively.

DISCUSSION

The CT numbers for water indicate that all scanners tested are reasonably well adjusted at this major calibration point. For air the situation is dependent on the scanner. The Siemens Somatom Plus scanners produced values that are under all tested circumstances, within 1 or 2 HU from the ideal value of −1,000 HU. In contrast, both Philips scanners showed a deviation of slightly more than 15 HU when a section thickness of 1.5 mm was used. Without correction, such a deviation induced a large error in the estimated lung density (eg, at a density of 100 kg/m^3 the error would be 15%).

The GE system produces CT numbers for free air that are approximately −1,008 HU, 8 HU too low. For air within the thorax phantom, the Picker and GE systems show differences on the order of 4–5 HU between data from the lean and obese thorax.

All foam data could be fitted well with a linear function, indicating that within the experimental accuracy of about 2%, all tested scanners appear to be linear in the low-density range for a given phantom. Between the lean and obese thorax data obtained with the GE and Picker systems, however, a systematic difference of 3–4 HU existed in all data points, similar to the difference observed for air. For one scanner the difference is positive; for the other, however, it is negative. In these experiments each piece of foam was measured in the lean thorax; then the ring of lard was placed in position, and with the foam lung in place, the obese thorax data were acquired. The shift in CT numbers must therefore be related to phantom size or phantom composition. Phantom size will affect the relative amount of scattered radiation, and phantom composition, since fat is not equivalent to water, affects beam hardening. The resulting effects in the various scanners are dependent on a number of instrumental details and calculational corrections. Factors that at least in principle are beneficial for quantitative CT are (*a*) relatively heavy x-ray beam filtration, (*b*) a detector diaphragm that limits section thickness, (*c*) a flat beam filter, and (*d*) good detector collimation, which is more difficult to achieve in a fourth- than in a third-generation scanner. The presence of a detector diaphragm is especially important for thin sections, but only the Somatom Plus scanners have it as a standard feature. Not only these systems, however, but also the

Table 2

CT Numbers (Hounsfield units) for Water, Air, Dog Lung, and Foam 109

Scanner Type	Water	Air	Air in Lean Thorax	Air in Obese Thorax	Dog Lung*	Corrected Dog Lung*†	Corrected Lean Thorax Foam 109†	Corrected Obese Thorax Foam 109†
Highlight	+1.2	−1,008	−1,005	−1,000	−912	−907	−890	−893
SR 7000	+1.0	−984	−985	−985	−887	−902	−896	−896
LX	−2.4	−984	−983	−983	−888	−905	−896	−894
PQ-2000	−0.3	−999	−997	−1,001	−912	−915	−897	−896
Somatom 1	+2.6	−999	−1,001	−1,000	−910	−910	−893	−894
Somatom 2	−1.5	−1,000	−999	−1,000	−911	−911	−894	−894

Note.—Scanning parameters are in Table 1.

* Lean thorax.

† Corrected for error in CT number for air (see text).

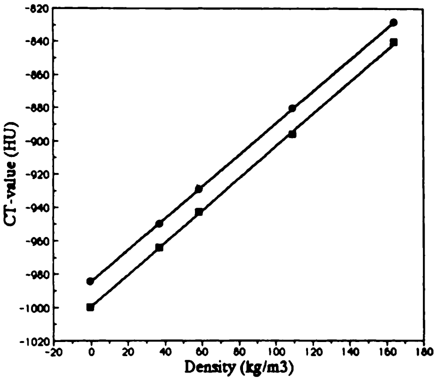
Table 3

Measurements of Foam in the Lean and Obese Thorax

	Lean Thorax			Obese Thorax		
Scanner	Offset* (HU)	Slope* (HU/[kg/m³])	χ^2	Offset* (HU)	Slope* (HU/[kg/m³])	χ^2
Highlight	−1,005	0.999	0.64	−1,000	0.985	0.24
SR 7000	−985	0.953	0.37	−985	0.961	0.33
LX	−983	0.949	0.1	−983	0.961	0.26
PQ-2000	−997	0.950	0.71	−1,001	0.951	1.15
Somatom 1	−1,001	0.973	1.58	−999	0.959	1.23
Somatom 2	−1,000	0.978	1.32	−999	0.967	3.30

Note.—Scanning parameters are in Table 1.

* Results from a fit with the linear function CT number = offset + slope · polyethylene density.



CT numbers of polyethylene foam in the lean and obese thorax phantom versus polyethylene density. Experimental data, together with a fitted linear function, are shown for the Philips SR 7000 scanner (●) and a Siemens Somatom Plus scanner (■) (Somatom 2 in Tables 2 and 3).

two Philips systems showed no systematic shift in data between the lean and obese thoraxes. It is probable that these subtle effects are dependent not only on the hardware but also on the exact implementation of several corrections with the software.

The slope of the foam curves for the different scanners varies between 0.949 and 0.999 HU/(kg/m^3). No substantial difference exists between the slopes for the lean and obese thorax data for any scanner. When the x-ray spectrum, filtration, and detector response of the scanner are known, the polyethylene slope can be used to obtain an estimate of the calibration curve for low-density water-equivalent tissue. In essence, under the present circumstances the ratio of the effective mass attenuation coefficients of water and polyethylene is needed for this conversion. Complications due to scanners using a water-based beam-hardening correction are neglible, since the thickness of polyethylene is small: For all foam lungs it is less than 2.5 g/cm^2. For the Somatom Plus scanner the required simulations were performed (9), resulting in slopes for water-equivalent tissue that are close to the ideal value of 1.00. The calculations were not performed for the other scanners.

It is found, without exception, that the foam curves shift with the corresponding air point, as exemplified in the Figure. This finding suggests a simple method for the correction of CT numbers obtained by using a scanner with poor air calibration. It necessitates the measurement of the CT number of air, preferentially within a phantom that resembles a thorax as closely as possible, and it simply entails a correction of every measured CT number with the error in the air value. For example, when the air value equals −1,008 HU, +8 HU is added to all measured CT numbers. In Table 2 the corrected CT numbers for the dog lung and foam 109 were calculated according to this method. Averaged over all scanners, the CT number for foam 109 in the lean thorax was −894.3 HU ± 2.4, and in the obese thorax, −894.4 HU ± 1.2. The largest difference between the results of any two scanners was 7 HU. These results indicate a fair inter- and intrascanner conformity in densitometric estimates in the low-density range. For the dog lung, a larger spread in CT numbers was observed: The average corrected CT number was −908.2 HU ± 4.7 A considerable part of the variation is due to the inhomogeneous density of the lung and the resulting sensitivity to phantom positioning, section thickness, and region definition. Homogeneous foam is clearly preferred for studies of this type.

A theoretically better approach to correcting poor air calibration consists in effectively making a calibration curve with an air and a water point and calculating the density according to the equation lung density = (1,000/[CT number water − CT number air]) · (measured CT number lung − CT number air). This method should be more accurate, especially at higher densities.

Concerning the tested acquisition and reconstruction parameters that in principle should not affect CT numbers, it can be concluded that all scanners appear to be well designed. The only serious exception is the section thickness dependence of CT numbers of air for the two Philips scanners. Philips stated that they have largely solved this problem and that they started installing modifications. Substantial CT number falsification by truncation at −1,023 or −1,024 HU

(9), as is possible with the Somatom Plus and Highlight scanners, is likely to occur only at extremely low densities or low mAs values, especially in combination with a high-resolution filter. When it occurs, it leads to an erroneous upward shift of the average CT number. The phenomenon is easily recognized in a histogram: At the low end, tail truncation is seen, with a peak containing the truncated pixels at the most negative CT number the system can handle. Reconstruction with a smoother filter often will remedy the problem as far as the average CT number is concerned.

The present results compare favorably with those reported in the past (5–7). Several explanations exist for this observation. First of all, the equipment has been greatly improved in the decade since the previous measurements were performed. Second, the older work concentrated on densitometry of small, nearly water-equivalent objects, sometimes within a medium of greatly different density, where partial volume effects and reconstruction filter-related effects are of importance. In the present work, in which CT numbers averaged over large areas are considered, these problems do not play a role.

CONCLUSION

All scanners tested have an acceptable calibration at water density. At low densities, the scanners differ in their behavior. CT numbers from the GE Highlight and Picker PQ-2000 scanners show some sensitivity to phantom size or composition. The Philips scanners SR 7000 and LX have a poor, section-thickness-dependent calibration, but the systems are not very sensitive to phantom size or composition. The Siemens Somatom Plus systems are well calibrated and not very sensitive to phantom size or composition.

A simple correction for the scanners with a poor calibration at air density has been proposed. After this correction is applied, the conformity of all scanners in the low-density range was fair: At a density of about 100 kg/m^3 the standard deviation of the average over all scanners is less than 3 HU, and the maximum observed interscanner difference is 7 HU. The observed interscanner variability will generally still be smaller than the reproducibility of CT densitometry in clinical practice (9,11).

All scanners are well designed with respect to CT number sensitivity to reconstruction filter, zoom factor, table height, and section thickness, with the exception of the two Philips systems in relation to sensitivity to section thickness.

In conclusion, when correction for poor air calibration is applied, all systems tested can be used for densitometry of the lungs, and meaningful comparison of results from the various scanners tested is possible. ■

Acknowledgments: We thank the following persons (all from The Netherlands) for their cooperation in this study: F. A. M. Selder, St Laurentius Ziekenhuis, Roermond; J. F. M. Ticheloven, St Clara Ziekenhuis, Rotterdam; D. J. J. M. Touw, MSc, Maasland Ziekenhuis, Sittard; C. W. M. Versteege, MD, PhD, de Wever Ziekenhuis, Heerlen. The cooperation of the four CT manufacturing companies is also gratefully acknowledged.

References

1. Stern EJ, Frank MS. CT of the lung in patients with pulmonary emphysema: diagnosis, quantification, and correlation with pathologic and physiologic findings. AJR 1994; 162:791-798.
2. Rienmüller RK, Behr J, Kalender WA, et al. Standardized quantitative high resolution CT in lung diseases. J Comput Assist Tomogr 1991; 15:742-749.
3. Lamers RJ, Thelissen GR, Kessels AG, Wouters EF, van Engelshoven JM. Chronic obstructive pulmonary disease: evaluation with spirometrically controlled CT lung densitometry. Radiology 1994; 193:109-113.
4. Adams H, Bernard MS, McConnochie K. An appraisal of CT pulmonary density mapping in normal subjects. Clin Radiol 1991; 43:238-242.
5. Levi C, Gray JE, McCullough EC, Hattery RR. The unreliability of CT numbers as absolute values. AJR 1982; 139:443-447.
6. McCullough EC, Morin RL. CT-number variability in thoracic geometry. AJR 1983; 141:135-140.
7. Zerhouni EA, Spivey JF, Morgan RH, Leo FP, Stitik FP, Siegelman SS. Factors influencing quantitative CT measurements of solitary pulmonary nodules. J Comput Assist Tomogr 1982; 6:1075-1087.
8. Pearce JG, Milne ENC, Gillan GD, Roeck WW. Development of a radiographic chest phantom with disease simulation. Invest Radiol 1979; 14:181-184.
9. Kemerink GJ, Lamers RJS, Thelissen GRP, van Engelshoven JMA. CT-densitometry of the lungs: scanner performance. J Comput Assist Tomogr (in press).
10. ICRU-report 44: photon, electron, proton and neutron interaction data for body tissues. Bethesda, Md: International Commission on Radiation Units and Measurements, 1989.
11. Kalender WA, Rienmüller R, Seissler W, Behr J, Welke M, Fichte H. Measurement of pulmonary parenchymal attenuation: use of spirometric gating with quantitative CT. Radiology 1990; 175:265-268.