Introduction
The current paradigm used to evaluate the doses delivered during CT procedure is the computed tomography dose index (CTDI). It is measured with a 100mm-long pencil ionization chamber placed in a cylindrical PMMA phantom (14cm-long and 16 or 32cm-diameter) but this method excludes contribution of radiation scattered beyond the 100mm-range of integration along z. New methods are described in the AAPM TG111 report using small volume ionization chamber positioned in a phantom long enough to establish dose equilibrium at the location of the chamber.

Method and Materials
A Siemens, SOMATOM Spirit Power 2-slice CT scanner was used for these measurements. A PTW Farmer-type chamber (0.6cm3) connected to a PTW Unidos E electrometer was calibrated by an accredited dosimetry laboratory for beam quality ranges associated with those of CT scanner spectrums. A 30cm-diameter, 50cm-long water phantom was designed to allow the chamber position at the center (Figure 1) or at peripheral axis.

Measurements were made for each clinically CT protocols following the AAPM recommendations. The doses delivered during axial-scanning acquisition with adjacent tomographic sections and helical-scanning mode with a pitch factor of 1 were compared. A “reference” set of operation was chosen as the most frequently used clinical protocol. For this work, the reference CT conditions were (axial-scanning mode, adjacent slices, kVp=130kVp, 100mA, 1s per tube rotation, 2-slices of 5mm). The final results are presented for three frequently used protocols: breast protocol (helical-scanning mode, factor pitch=1, kVp=130kVp, 100mA, 1s per tube rotation, 2-slices of 5mm, reconstructed image of 10mm), IMRT prostate protocol (axial-scanning mode, adjacent slices, kVp=130kVp, 100mA, 1s per tube rotation, 2-slices of 1.5mm, reconstructed images of 3mm) and “axial 5mm” (axial-scanning mode, adjacent slices, kVp=130kVp, 100mA, 1s per tube rotation, 2-slices of 2.5mm, reconstructed images of 5mm).

The minimum scanning length Leq needed to obtain equilibrium cumulative dose Deq was evaluated. A group of scanning lengths ranging from L=50 mm to L=the phantom length minus m was made (Figure 2) and for each value of L used, the cumulative central dose Dc(z=0) was determined via measurements of the ionization chamber. Dc(z=0) was characterized as the product of a function “approach-to-equilibrium” h(L)=1-exp(-4L/Leq) and the equilibrium dose Deq. The α parameter is related to the scatter-to-primary ratio (SPR) extant on the phantom axis. The equilibrium dose was determined for each axis (central and peripheral). The planar average equilibrium dose was calculated with the assumption that Dα=α2 and compared to CTDI values informed by the CT scanner.

In order to validate the measurement set, the dose values were confirmed with TLD measurements (Figure 3). TLD100 (rods of LiF:Mg,Ti, Harshaw) were calibrated following the code of practice IAEA TRS-277, irradiated in the same conditions as the ionization chamber and read with a TLD Reader 4000 (Harshaw).

Results
Phantom and chamber positioning, repeatability
The water phantom central axis was aligned with the CT rotation axis and the ionization chamber was placed in the phantom in order to center the charge-collection volume with the plane z=0 of the CT scanner (Figure 4). The repeatability of the set-up installation was evaluated to 0.4% with a position variation inferior to 1mm.

Central (z = 0) cumulative dose and its approach to equilibrium
Comparison of axial and helical scanning modes
The objective of this work was to evaluate the dose delivered for each clinically relevant combination of CT parameters. As observed in the Figure 5, no significative differences were noticed if the two modes are comparable (adjacent slices for axial and pitch of 1 for helical). This allowed us to limit the number of measurements.

Approach to equilibrium of central- and peripheral-axis central cumulative dose
The measurements for the reference set of operation in the central and peripheral holes are presented in the Figure 6 (dots). All the data were analysed with the Origin software (OriginLab) using the equation h(L)=1-exp(-4L/Leq) and are presented in the Figure 6 (lines).

The fitted parameters calculated are summarised in the Table 1. For central-axis doses, where scatter contribution dominates the primary dose contribution, the α parameter is close to unity. Deq is lower and the length Leq for which the central cumulative dose is within 2% of Dαeq is higher.

Planar average equilibrium dose and Integral dose
With the assumption that Dαeq(r) varies with r2, the planar average equilibrium dose Dαeq can be calculated as Dαeq=1/2Dαeq central-1/2Dαeq peripheral. The total energy absorbed in the phantom or integral dose Etotal is a parameter used to evaluate the patient risk: Etotal(α)=R(2L/Leq) with p=1190kg/m2, n=3.14, R=0.150m, L=500m. The results obtained for the more frequently used protocols are summarised in the Table 2.

Comparison with TLD measurements and CTDI (eq) informed by the CT scanner
TLD measurements
The quality of the RX tube used to calibrate the TLD was 0.23mm of Cu. Using a Farmer type ionization chamber (calibration factor: Nk=47.90 mGy/mC) and following the TRS-277, the energy absorption coefficient ratio, water/air, was [ρu/ρw]radwater=0.332 (Table XIV), the perturbation factor was pρ=1.03 (Table XV) and the correction for spectral dependence was kρ=1. The calibration factor for the TLD was 3.8 E-5 mGy/C. The software used for the TLD analysis (GCA-New v3.0, Ciemat) only uses the signal integration of the last two peaks.

The results of the doses measured with the TLD in the water phantom and the comparison with the ionization chamber measurements are reported in the Table 3. Variations inferior to 3.4% were calculated for central-axis measures and inferior to 1.0% for planar average equilibrium dose.

Comparison with CTDI (eq) informed by the CT scanner
The CTDIeq indicated by the CT scanner for all protocols were between 32 and 35% inferior to the doses measured during this work. The results are presented in the Table 4.

Conclusions
As expected, this work shows the limitation of the CTDI and reveals a systematic underestimation of the dose delivered to the patient during CT exams. For new generations of CT systems with wider longitudinal detector size or cone-beam technology, it is therefore important to evaluate CT radiation dose with new methodology.