Suggestions for testing evaluation of Dental and Maxillofacial CBCT

Current status and issues with dental and maxillofacial CBCT: Potential methodologies for quality control and management of this technology

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Objectives

- Introduction
- Current status on dCBCT recommendations, where are they coming from and what do they really cover?
- Quality control testing and methodology.
- Dose indices, what can one measure and track.
- Phantoms and setup for testing.
- What works and what does not in dCBCT testing.

Introduction

- CBCT for dental and maxillofacial (*dCBCT*) applications have a large number of different vendors and geometries.
- Most of these scanners are not "similar" to each other.
- Most of these scanners are "closed systems" with *vendor-specific* testing equipment and procedures.
- In most cases, these scanners have been installed as "upgrade" or "replacement" of panoramic imaging units, especially in the US.
- Most States do not have dedicated testing guidelines for dCBCT systems.
- There is limited guidance worldwide for "comprehensive" testing that **exclusively** applies to dCBCT and fits all models and vendors.

Current status of dCBCT testing recommendations

- **Available guidelines regarding QC procedures dCBCT:**
  - UK Health Protection Agency (HPA, 2010)
  - European Commission, Radiation Protection 172 (SEDENTEXCT guidelines) (EC, 2012)
  - German DIN 6868-161 / DIN 6868-15 (2013)
  - Unified protocol for CBCT (not exclusive for dental) (EFOMP-ESTRO-IAEA, 2017)
  - AAPM task group 261 (in preparation)

- Standard tests: ***Refer to manufacturer's specifications***, recent guidelines, national regulations
  - X ray tube potential, tube leakage, total filtration or HVL, repeatability/reproducibility, beam collimation, slice thickness, display performance, visual inspection of image artefacts, dose to operator

QC testing for dCBCT

- Simple description
- How to test
- What to use for your testing
- How to set the tolerances

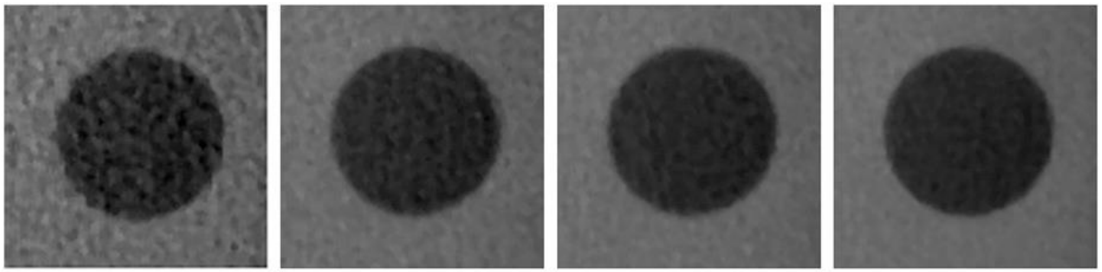
- **Equipment performance items**
  - Collimation verification (x-ray field size-to-Image Receptor size)
  - kVp accuracy
  - HVL meets FDA regulations and manufacturer's specifications
  - Output (dose) meets manufacturer's specifications

- **Image quality**
  - CT number accuracy and linearity
  - Uniformity, Noise (or CNR)
  - Spatial resolution
  - Geometric distortion
  - Artifacts
  - Image display device

It is important to set a baseline for all testing during initial acceptance evaluation of the unit

What image quality is acceptable?

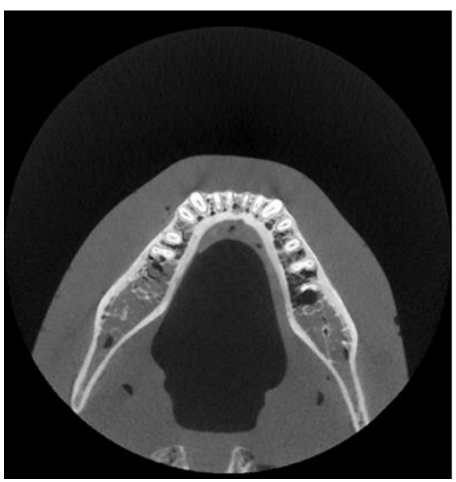
- Variations of technical parameters over time can indicate an issue, **but imaging performance should be verified based on clinical image quality**

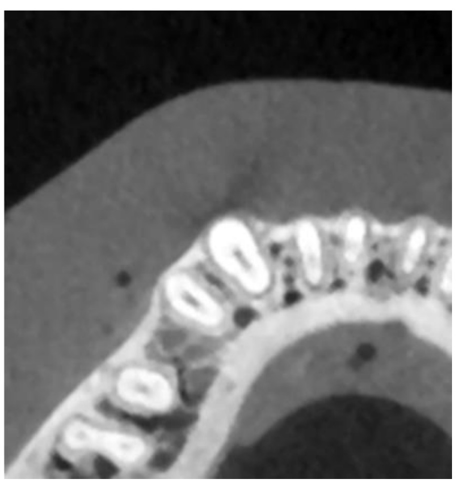


90 kV	90 kV	90 kV	90 kV
1 mA	3 mA	5 mA	8 mA
CNR: 5.2	CNR: 9.7	CNR: 12.2	CNR: 14.7

Difficult to relate technical parameters (MTF, CNR) to clinical acceptability

Pauwels et al. (2014)





Reference image provided by manufacturer or acquired during acceptance testing (skull phantom)

MDCT vs dCBCT: Density estimation using CBCT

- **In MDCT:** grey value calibrated as Hounsfield units (HU), according to their X ray attenuation (μ)

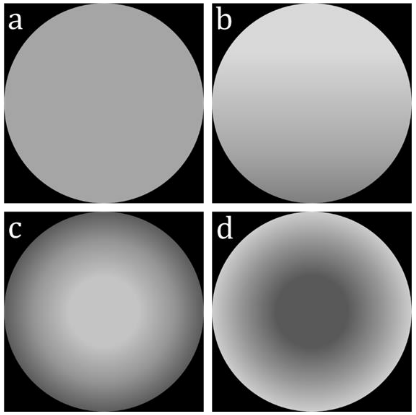
$$\mathrm{HU}_{\mathrm{material}} = 1000 \times \frac{\mu_{\mathrm{material}} - \mu_{\mathrm{water}}}{\mu_{\mathrm{water}}}$$

- **HU are also referred to as CT numbers**
- **In dCBCT:**
  - Depending on manufacturer, ***grey values (or Pixel Value-PV)*** may or may not be calibrated according to a (pseudo-) HU scale
  - Even when calibrated, several issues related to grey value stability are inherent to the CBCT technique
  - Uniformity issues due to beam hardening (and improper correction thereof) + asymmetrical FOV position (with mass irregularly distributed outside the FOV) can lead to A-P, L-R or central-peripheral 'shading'

Air	-1000 HU
Lung	-600 to -400 HU
Fat	-100 to -60 HU
Water	0 HU
Soft tissue	+40 to +80 HU
Bone	+400 to +1000 HU

Perfect uniformity

A-P shading

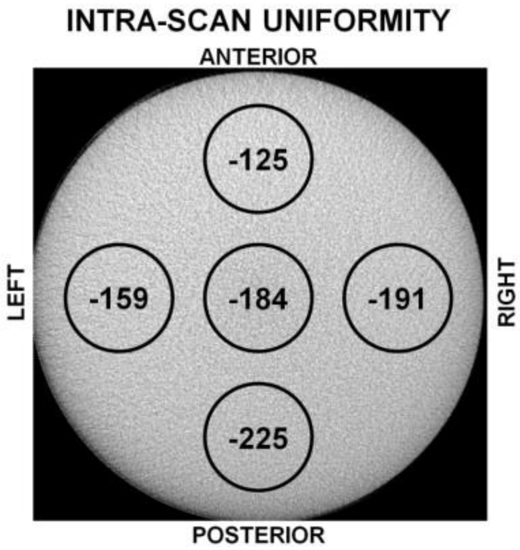


Peripheral shading

Central shading

QC testing: Uniformity

- **Uniformity for dCBCT**
  - Uniformity: *stability of grey values*
    - Conventionally: compare grey value for different regions in the FOV for a homogeneous object (intra-scan uniformity)
    - In CBCT, if grey values are to be used as HU, grey values for scans with central/peripheral test object position should be assessed as well (inter-scan uniformity)



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Uniformity test example

Table 2. Uniformity test example for a XORAN Mini-CAT with tolerances by manufacturer.

LOCATION	PV (mean, SD)		GOAL
	mean	***SD***	
CENTER	14.1	19.6	Min & Max values must be within ±50 units of each other
3-o'CLOCK	21.1	18.9	
6-o'CLOCK	32.2	18.5	
9-o'CLOCK	24.8	19.3	
12-o'CLOCK	16.8	19.5	

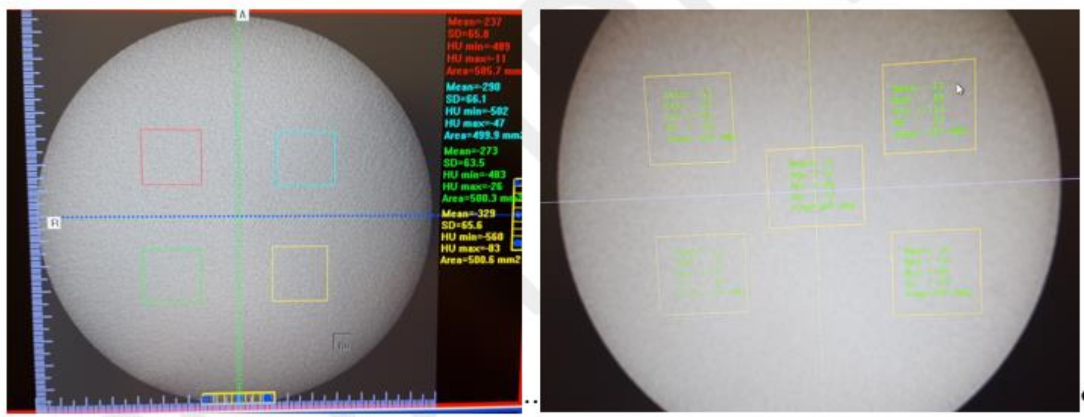

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Fig. 6. Example of uniformity test for a i-CAT (Left) and XORAN (Right)

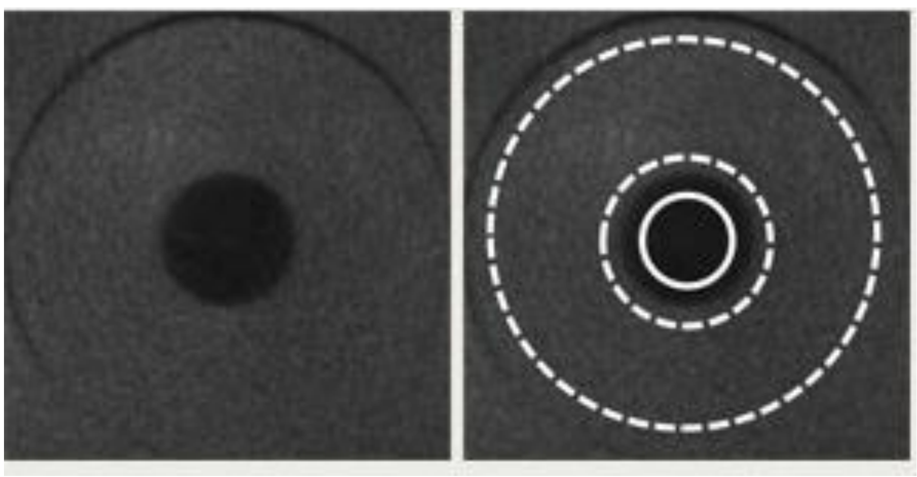
Recommendation: Satisfy the manufacturer's suggested tolerance and setup a baseline for this test at acceptance testing.

Tolerance level: 20% from baseline.

Frequency of testing: Annual

QC testing: Noise & Contrast resolution

- **Noise**: standard deviation of grey values in a homogeneous test object
  - Can be combined with contrast (contrast-to-noise ratio, CNR) and/or measured using the same region of interest as that used for uniformity
- **Contrast resolution**: contrast-to-noise ratio and/or visual / computer assisted evaluation of contrast-detail



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- CNR should be tested for Small, Medium and Large FOV for commonly used protocols. The physicist has to make sure that the same protocol and the same operation mode is employed each time the CNR is checked (for constancy).
- The CNR is calculated for <u>each</u> different material and for <u>each</u> selected protocol. A baseline for each case is derived. The phantom and insert should have the same position each time.

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Noise test example

PV=Pixel Value (same as Grey Value)

In this example (Fig. 5c and 5d) a central ROI surrounding the material is selected to measure the mean PV (MPV_m) of the material (red ROI). The ROI between the yellow lines is selected to measure the mean PV (MPV_b) and the standard deviation (SD_b) of the background signal. The CNR is calculated:

$$CNR = \frac{|MPV_m - MPV_b|}{SD_b} \qquad (1)$$

Table 1. Example of noise level test for i-CAT

Location	PV (mean, SD)	
400.0 mm² ROIs	**Water**	**Air**
Expected - Center	*0 (-70 to +70)*	*-1000 (-50 to +50)*
Measured - Center	-7, SD=23	-1000, 0.0

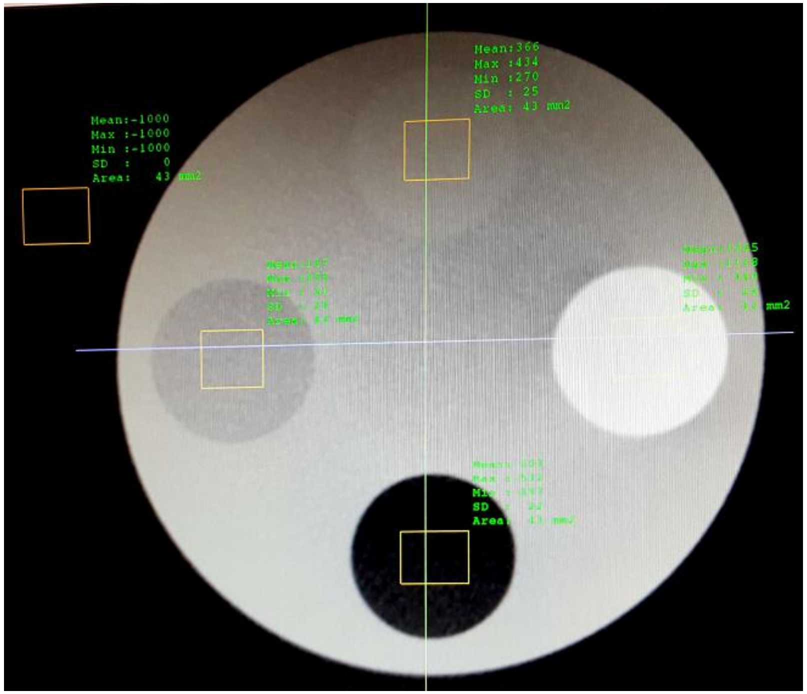
Recommendation: Set up a baseline at acceptance testing.

Tolerance level: 20% from baseline.

Test frequency: Annual

QC testing: Gray Value (Pixel Value) stability

- **Grey Value (GV) stability**: reproducibility of grey values for a number of materials over time
- **Hounsfield Unit (HU) accuracy** (only for machines which claim to yield HU): compare GV for different materials with corresponding nominal HU, check stability under varying exposure geometries (FOV, position of test object)



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PV stability test example

Table 3. Example for CBCT number accuracy and linearity test for a i-CAT

Material	**Data measured and Range**		**EXPECTED MEAN-PV**
40.0 mm² ROIs	**Mean PV (SD)**	**Range**	
Air (black)	-999 (0)	-980 to -1000	**-990**
LDPE (dark gray)	-129 (28)	-250 to -50	**-150**
Acrylic (light gray)	95 (28)	-50 to 220	**75**
Teflon (white)	936 (27)	580 to 1160	**870**

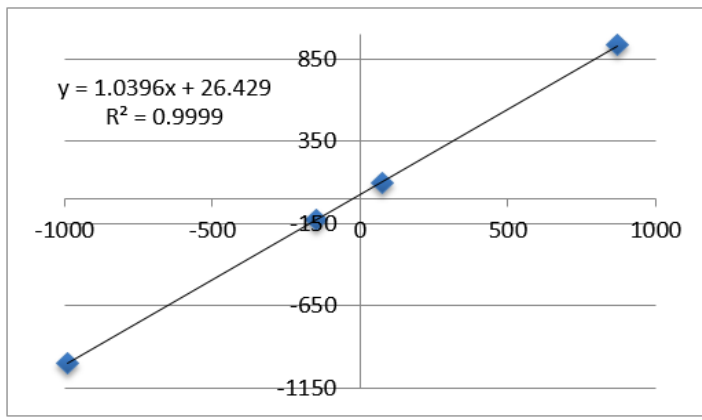

Fig. 8. CBCT number (PV) linearity based on Table 3 above, expected values (X-axis) vs. measured values (Y-axis).

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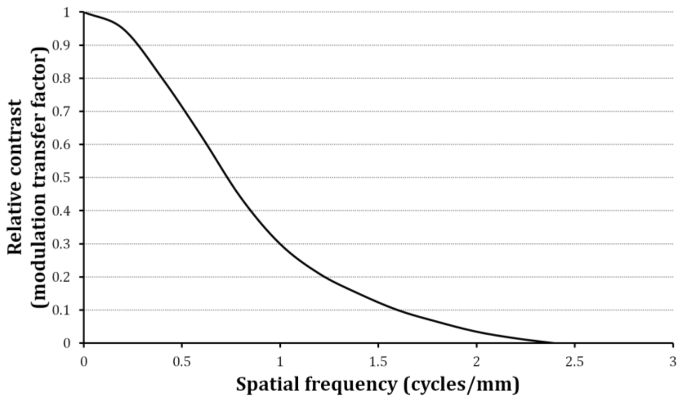
Recommendation: Establish a baseline during acceptance testing.

Tolerance level: Within ± 3SD from the baseline

Frequency of testing: Annual

QC testing: Spatial Resolution

- Spatial resolution
- Modulation transfer function (MTF)
  - Evaluates decrease in contrast at increasing resolution
  - Limit for visual perception at ~10% MTF



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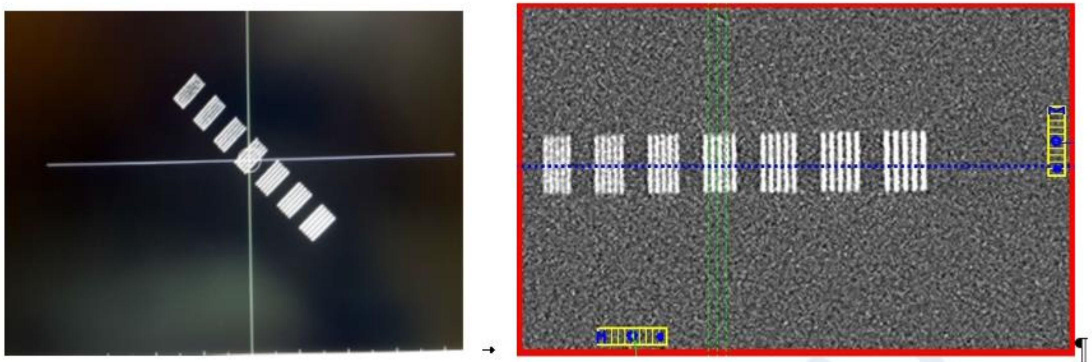

Fig. 10. All resolution groups are visible on the above examples.

Recommendation: Use the manufacturer's phantom with a high-resolution scanning protocol. Monitor the protocol scanning parameters and satisfy the manufacturer's tolerance or define a baseline for visible line pairs at acceptance testing. Determination of the resolution (in lp/mm, for example) should be performed under the same viewing conditions as the facility uses (e.g., monitor settings, ambient light conditions).

Tolerance level: No greater than one resolution group difference from baseline.

Frequency of testing: Annual

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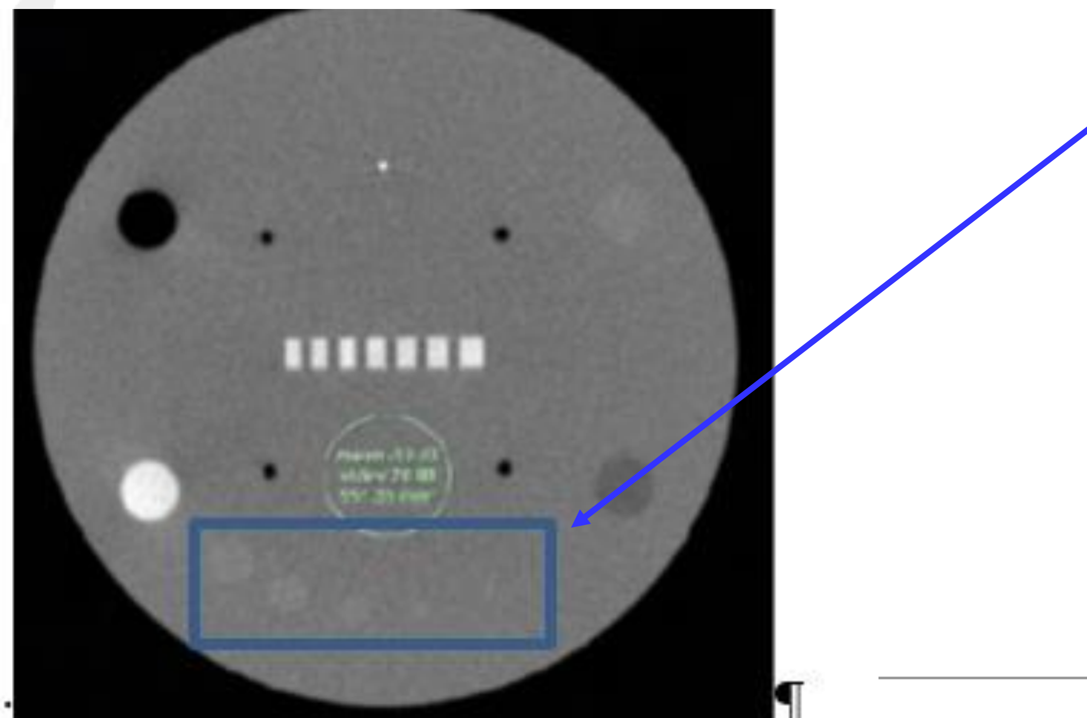
QC testing: Low contrast ?

The ability to distinguish a signal against its background, when the value of the signal is similar to the value of the background, represents the low contrast resolution. This can be quantified by measuring the contrast-to-noise ratio (CNR). Although soft tissue imaging is not clinically relevant in dental CBCT imaging, emerging technology aims to enhance the detectability of low contrast structures in dental CBCT scanners. For most dental CBCT units, the manufacturer requires this test to be performed based on the manufacturer's test phantom with specifications for that unit.



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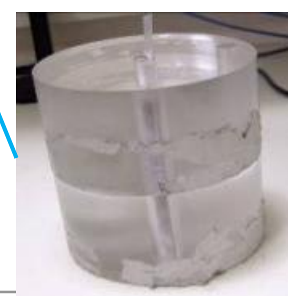
Challenges QC testing and QC phantoms

- Challenges with dosimetry testing
- Challenges with IQ testing
- QC phantoms

It is important to use the manufacturer-provided phantom for IQ testing and set a baseline, first, before a third party phantom is introduced.

QC testing challenges: Dosimetry

- There are variety of issues with both CTDI and DAP when it comes to dCBCT systems.



QC testing challenges: Dosimetry

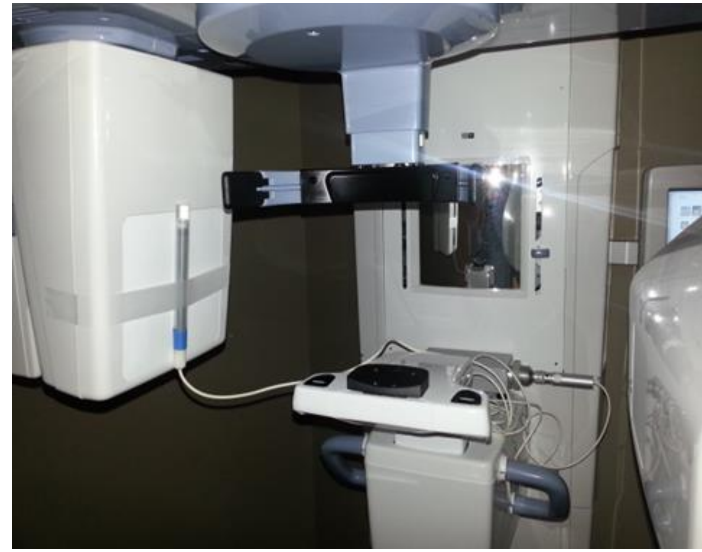
- *CTDI-like* for limited FOVs

$$CTDI(mGy) = \frac{1}{100} \cdot \left[\frac{X_{av} \cdot C_{TP} \cdot 0.87 \cdot 100}{BL} \right] (mGy)$$

Table 1: CTDI measurements for dental CBCT scanners ($CTDI_w = \frac{1}{3} CTDI_{center} + \frac{2}{3} CTDI_{periph}$).

Scanner	$CTDI_{center}$ (mGy)	$CTDI_{periph}$ (mGy)	$CTDI_w$ (mGy)
MiniCAT (Xoran)	2.7	3.7	3.4
i-CAT (Imaging Sciences Int.)	8.4	3.8	5.3
ILUMA (IMTEC)	3.7	3.4	3.5

- DAP in practice



$$DAP = Dose\ (mGy)\ x\ irradiated\ area\ (cm^2)$$

QC testing challenges: Dosimetry

- **CONSIDER:**

- **Suggestion:** Air-kerma at the detector and CTDI (when possible)
- **Tolerance level:** Comparison with baseline output, output reproducibility < 5%
- **Frequency of testing:** Air-Kerma at the detector surface or DAP annually, CTDI at acceptance testing, if possible

very unstable support

QC testing: Challenges with testing phantoms

SedentexCTIQ consists of a PMMA cylinder (160 mm diameter) with recesses to house test inserts (fig. 1). Within the body of the cylinder are features for the following tests:

- **Noise/Uniformity**
  The lower section of the phantom is uniform PMMA (density 1.20 +/- 1.00%)
- **Geometric Distortion**
  An array of 2.0 mm diameter, 3.0 mm deep Air gaps are uniformally pitched at 10.0mm intervals through one slice of the cylinder

Test Inserts are included to perform the following measurements:

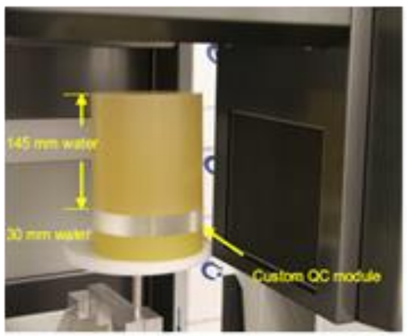
- **Spatial Resolution**
  - Line Spread Function (LSF) – PMMA/PTFE interface (fig. 2)
  - Point Spread Function (PSF) – 0.25mm diameter stainless steel wire suspended in air (fig. 3)
  - LP/mm – alternating Aluminium/polymer (XY)
    (1.0, 1.7, 2.0, 2.5, 2.8, 4.0 and 5.0 LP/mm) (fig. 4)
  - LP/mm – alternating Aluminium/polymer (Z)
    (1.0, 1.7, 2.0, 2.5, 2.8, 4.0 and 5.0 LP/mm) (fig. 5)
- **Contrast Resolution** (fig. 6)
  1.0, 2.0, 3.0, 4.0, 5.0 mm diameter Al, PTFE, Delrin, LDPE and Air rods suspended in PMMA
- **Pixel intensity** (fig. 7)
  10.0 mm diameter Al, PTFE, Delrin, LDPE and Air rods suspended in PMMA
- **Beam Hardening Artefacts** (fig. 8)
  A line of three 5.0 mm diameter rods of Ti suspended in PMMA
- **Blank PMMA insert** (fig. 9)
- **Automatic Scoring Software (available separately)**
  See **Radia software** for more details

- Large dimensions
- No mounting support
- Costly phantom
- Need special software to analyze-cost
- Potential incompatibility with the vendor provided phantom

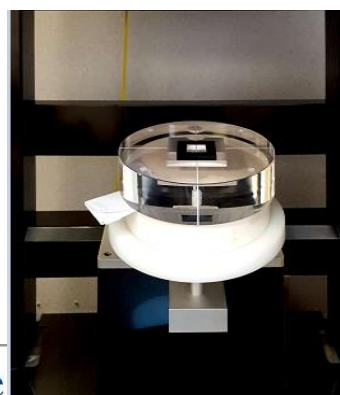
unstable

QC testing: Phantoms for testing

- Today, all vendors provide a *QC phantom* with a directions manual of how to run the QC tests.
- Today, all vendors provide *automated image analysis software* to analyze the phantom images as per *their expected tolerances*.

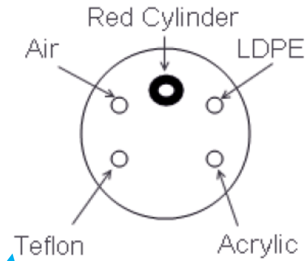


Another vendor provided phantom and support stand



Measure CT Number (HU) Accuracy

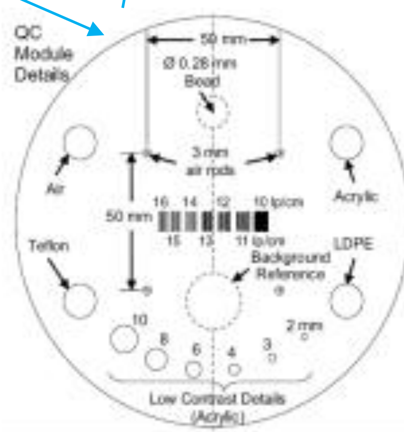
In this test, you will measure the CT number of several differer
phantom. Here is the arrangement of inserts as they appear w

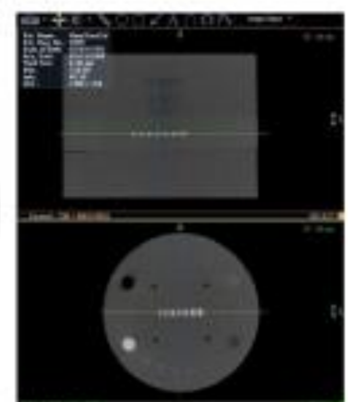


The red cylinder is between the air and LDPE inserts. This orie
appears in the image on page 106. This is the orientation you v
described on page 103.

The ideal CT numbers of the test objects are:

- Air: -1000 HU
- Low-Density Polyethylene (LDPE): -100 HU
- Acrylic: 120 HU
- Teflon: 990 HU





QC testing: So what to test for IQ?

- Use vendor provided phantom and mounting stand
- Use vendors provided testing software routine
- Use vendor provided test tolerances
- Establish baseline values
- Establish your own tolerances from baseline
- You can choose to benchmark with an independent phantom system at time of initial evaluation
- Document all your testing results and comparisons

- **Weekly or daily QC**
  - CT number accuracy (water only)
  - Uniformity
  - Noise or CNR
  - Artifact evaluation
- **Annual QC**
  - Assembly and facility evaluation
  - Laser alignment
  - Radiation field size
  - kVp and HVL
  - Radiation dosimetry
  - CT number accuracy and linearity
  - Image uniformity
  - Noise/CNR
  - Spatial resolution
  - Geometric distortion
  - Image artifact evaluation
  - Display monitor

THANK YOU