PERFORMANCE

PHYSICS OF DIAGNOSTIC AND INTERVENTIONAL RADIOLOGY WITH X RAY - 2

Paola Bregant

Health Physics Department – ASU GI

paola.bregant@asugi.sanita.fvg.it

SCAN AND PATIENT POSITIONING ACCURACY

CT alignment lights

Internal Ligth

Patient positioning lights which identify the tomographic plane,

External Lights

They identify the sagittal and coronal planes, as well as a further set of lights identifying a transaxial plane, set at a fixed distance from the tomographic plane.

Once a patient or phantom is aligned to the external lights, the tomographic plane, as defined by the internal lights, can usually be reached by a single button press.

Testing the quality of the scanner involves establishing a level of certainty in the position of the scanner lights and their accuracy against requirements.

CT alignment lights

The lights are either tungsten or laser. With laser light, safety aspects need to be considered and care is needed for unconscious or anaesthetized patients.

In clinical practice, the lights are usually used as a rough guide for setting up the patient. The patient is first aligned on the scanner couch using the scanner tomographic plane lights, in order to establish which region of the body to scan and to centre the patient to the isocentre for best image.

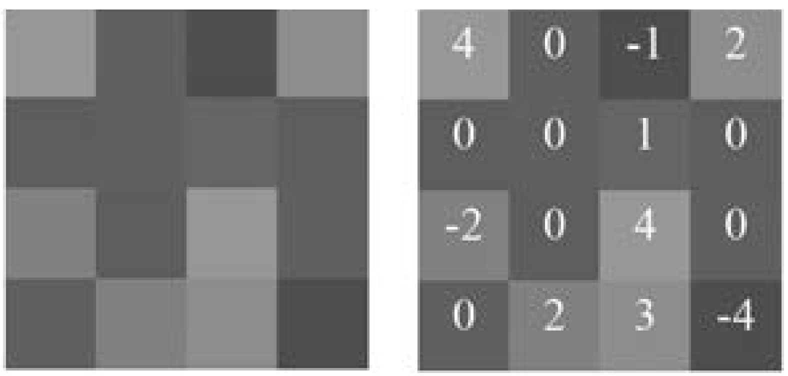
Precise preparation for cross-sectional CT scanning is taken from the scan projection radiography (SPR), and this is used to define the beginning and the ends of the required scanned volume.

IMAGE QUALITY

Image noise

When a uniform material is imaged on a CT scanner, examination of the CT values for individual pixels in a localized area shows that the CT numbers are not all the same, but fluctuate around a mean value .

Example: Variation in grey level for water phantom



Mean CT number = 0

Min = -4

Max = +4

This random variation is known as **image noise** and is due primarily to the statistical nature of X ray production and interaction with matter. It is also known as quantum noise.

Quantum noise

Quantum noise is depending on physical properties of X-Rays. Energy is absorbed by the detectors through single photons (energy quantum).

It can be considered a Poisson process and consequently:

- Signal is proportional to N (number of absorbed photons)
- Noise is proportional to $\sqrt{N}$
- Signal/noise ratio is equal to $N/\sqrt{N}$, that is $\sqrt{N}$

Increasing photons number, signal/noise ratio increases (…. and image quality improves)

Noise in digital systems

In digital systems there are two noise sources:

- **Quantum noise** (depending on exposure level)
- **Fixed noise** (not depending on exposure level)

  noise related to quantisation

  electronic noise

Image quality is strictly dependent on noise level

NOISE

Noise is depending on :

- Voltage (kV)
- Current (mA)
- Beam filtration
- Number of sampling
- Slice thickness
- Reconstruction algorithm
- Focal spot dimension
- Phantom dimension
- Phantom material

Noise

It is defined as **standard deviation of CT numbers** in a ROI (**R**egion **O**f **I**nterest) selected in the central area the image of a homogenous object.

IAEA Document «Quality Assurance Programme for Computed Tomography: Diagnostic and Therapy " uses also the **normalized standard deviation S** to make a direct comparison between CT scanners with different contrast scales.

$$S = \frac{\sigma_{water}}{CT_{scale}} \; x100\%$$

σ_{water} is the standard deviation of the pixel values within a ROI

$CT_{scale} = CT_{water} - CT_{air}$

CT_{water} and CT_{air} are the CT values obtained for water and air

Uniformity of image noise

Ideally, a scan of a uniform phantom should give a CT image with similar pixel values, and similar amounts of noise, across the whole field of view.

But… scans of uniform phantoms often show gradual variations of CT number and noise values across the image.

These variations may be particularly noticeable in the following conditions:

- when the uniform phantom is surrounded by a high contrast material, such as cortical bone substitute material.
- at the extremities of large phantoms

(Exceptionally large phantom is used to investigate the extended fields of view used on the large bore scanners for radiotherapy use)

Uniformity of image

The optimal function of a bowtie filter and AEC techniques require that the patient is centered appropriately in the CT gantry.

If a phantom, or patient, is not centred at the isocentre, a more pronounced variation of CT number and image noise is also likely to be observed.

In equipment used for radiotheraphy, the uniformity of CT number is of particular importance, because the scanner is used for quantitative assessment of CT values.

CNR (<u>**C**</u>ontrast to <u>**N**</u>oise <u>**R**</u>atio)

CNR is a parameter used to represent the capability to identify low contrast structures. Very small differences in photon attenuation in the tissue due to composition or density differences have to be distinguished.

To measure CNR, the contrast of two objects is determined by the difference of the mean CT numbers within selected ROIs and is divided by the average noise for these two ROIs:

$$CNR = \frac{CT_1 - CT_2}{(\sigma_1 + \sigma_2)^2}$$

This parameter is useful when optimizing a CT examination protocol for a particular contrast situation e.g. tissue density contrast, iodine contrast and air tissue contrast.

Spatial resolution

Spatial resolution describes the capability to distinguish small objects at high contrast.

It usually is defined in the tomographic plane

Spatial resolution

Subjective evaluation:

Visual inspection of the image of a test object

Objective evaluation:

Modulation transfer function (MTF)

The function can be calculated from the *point spread function* (PSF) or from the *edge spread function* (PSF).

These function can be derived from the image of suitable object (small sphere, thin wire…)

Usually the frequency values at which MTF is 50% and 10% are considered

Quality control programme

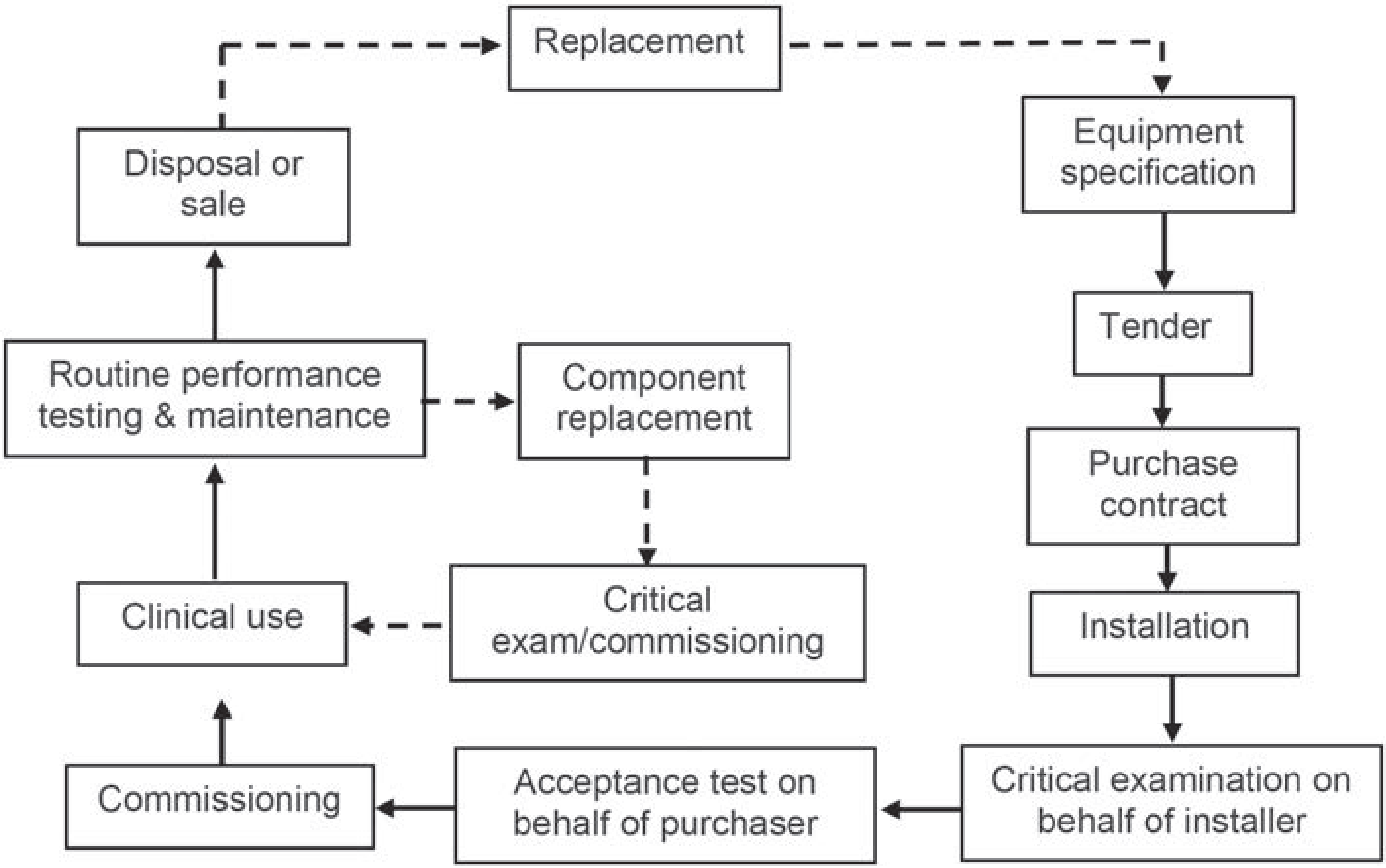
Quality control programme

Acceptance testing and commissioning

- Acceptance test: to verify that the purchase specifications have been met by the vendor (by company + medical physicist)
- Commissioning tests: to establish baseline levels of performance (medical physicist)

Constancy test

- To test the components of the radiological system and to verify that the equipment is operating satisfactorily


Replacement
Disposal or sale
Equipment specification
Tender
Routine performance testing & maintenance
Component replacement
Purchase contract
Clinical use
Critical exam/commissioning
Installation
Commissioning
Acceptance test on behalf of purchaser
Critical examination on behalf of installer

IAEA Document

<u>Test priority</u>

- **Desirable**

  A test procedures that should be performed, if feasible (for example, if adequate human resources and equipments are available).

- **Essential**

  A tests that must be carried out in a facility

<u>Frequency*</u>

- Annual
- Monthly

* The frequency is defined considering the possibility the test is likely to alter within a shorter timescale

IAEA Document

<u>Performance standard</u>

- Acceptable

  If a parameter is not within a certain tolerance, the equipment shall not be used

- Achievable

  A level of performance that should be attained under favourable circumstances

IAEA Document

- Radiographer’s QC tests
- Medical Physicist’s QC tests

Test number	Test name	Test personnel[a]	Diagnostic facility	Radiotherapy facility
8.2	CT alignment lights	R	✓	✓
8.3	SPR accuracy	R	✓	
8.4	CT number, image noise, image uniformity and image artefacts	R	✓	✓
8.5	Image display and printing	R	✓	✓
10.2	External CT positioning lasers	R		✓
10.3	Couch top alignment and positional accuracy	R		✓
10.4	CT number of multiple materials	R		✓
9.2	Visual inspection and review of programme	P	✓	✓
9.3	CT alignment lights	P	✓	✓
9.4	SPR accuracy	P	✓	✓
9.5	kV and half-value layer (HVL)	P	✓	✓
9.6	Radiation dose	P	✓	✓
9.7	CT number accuracy, image noise, image uniformity and image artefacts	P	✓	✓
9.8	Image display and printing	P	✓	✓
9.9	Imaged slice width	P	✓	✓
9.10	X ray beam width	P	✓	✓
9.11	Spatial resolution (MTF or modulation)	P	✓	✓
10.6	External CT positioning lasers	P		✓
10.7	Couch top alignment and index accuracy	P		✓
10.8	Gantry tilt	P		✓
10.9	CT number accuracy	P		✓

[a] R: radiographer; P: physicist.

Radiographer's QC tests

Test number	Test name	Priority[a]	Suggested frequency	Criteria	
				Acceptable	Achievable
8.2	CT alignment lights	E	Monthly	±5 mm	±1 mm
8.3	SPR accuracy	E	Monthly	±2 mm	±1 mm
8.4	CT number, image noise, image uniformity and image artefacts	E	Monthly	CT number ±5 HU[b] Noise ±25% BB[c] Uniformity ±10 HU Minimal artefacts	CT number ±4 HU Noise ±10% BB Uniformity ±4 HU Minimal artefacts
8.5	Image display and printing[d]	E	Monthly	See text	

[a] E: essential, basic requirement.
[b] HU: Hounsfield unit.
[c] % BB of baseline value.
[d] Circumstances may require more frequent testing of some printers and monitors.

Medical Physicist's QC tests

Test number	Test name	Priority[a]	Suggested frequency	Criteria	
				Acceptable	Achievable
9.2	Visual inspection and review of programme	E	Acceptance and annually	All items must meet local standards	
9.3	CT alignment lights	E	Annually	±5 mm	±1 mm
9.4	SPR accuracy	E	Annually	±2 mm	±1 mm
9.5	kV and HVL[b]	E	Acceptance and after changes	kV ±5% nominal HVL ≥ specified by radiation protection regulations and within the tolerances specified by the manufacturer	kV ±2% nominal HVL ≥ specified by radiation protection regulations and within the tolerances specified by the manufacturer
9.6	Radiation dose	E	Annually	±20% of manufacturer's specifications ±20% of baseline	±10% of baseline
9.7	Image noise	E	Commissioning and annually	±25% of baseline	±10% of baseline
9.7	Image uniformity	E	Commissioning and annually	±10 HU for head and body	±4 HU for head and body
9.7	CT number accuracy	E	Commissioning and annually	±5 HU (water) ±10 HU (other material) compared with baseline values	±4 HU

Medical Physicist's QC tests

Test number	Test name	Priority[a]	Suggested frequency	Criteria	
				Acceptable	Achievable
9.8	Image display and printing	E	Commissioning and annually	See text	
9.9	Imaged slice width	E	Annually	+0.5 mm for <1 mm ±50% for 1–2 mm; ±1 mm above 2 mm	
9.10	X ray beam width	D	Acceptance and after changes	Within manufacturer's specifications	
9.11	High contrast spatial resolution (MTF or modulation)	D	Acceptance and after changes	Within manufacturer's specifications	

[a] E: essential, basic requirement; D: desirable.
[b] It is considered that the measurement of kV and HVL is not necessary for CT scanners for either QA or patient safety reasons.

Other references …….

- **AAPM**
- **IMPACT**
- **CEI EN**
- **European Protocol**
- **……..**

X-Ray Tube

HVL

Pencil chamber + aluminium filter

Service modality, X-Ray Tube at 360° (no rotation!!)

kV Accuracy e Reproducibility

Multimeter on patient table .

Service modality, X-Ray Tube at 360° (no rotation!!)

Reproducibility and linearity

Pencil chamber Wellhofer in air at isocenter

Reproducibility and linearity of dose as function of kV and mAs

Mechanical Accuracy

- Correspondence of internal and external laser to identify acquistion range
- Check of laser used to identify sagittal and coronal plane
- Accuracy of table movement in axial scan
- Accuracy of table movement in spiral scan

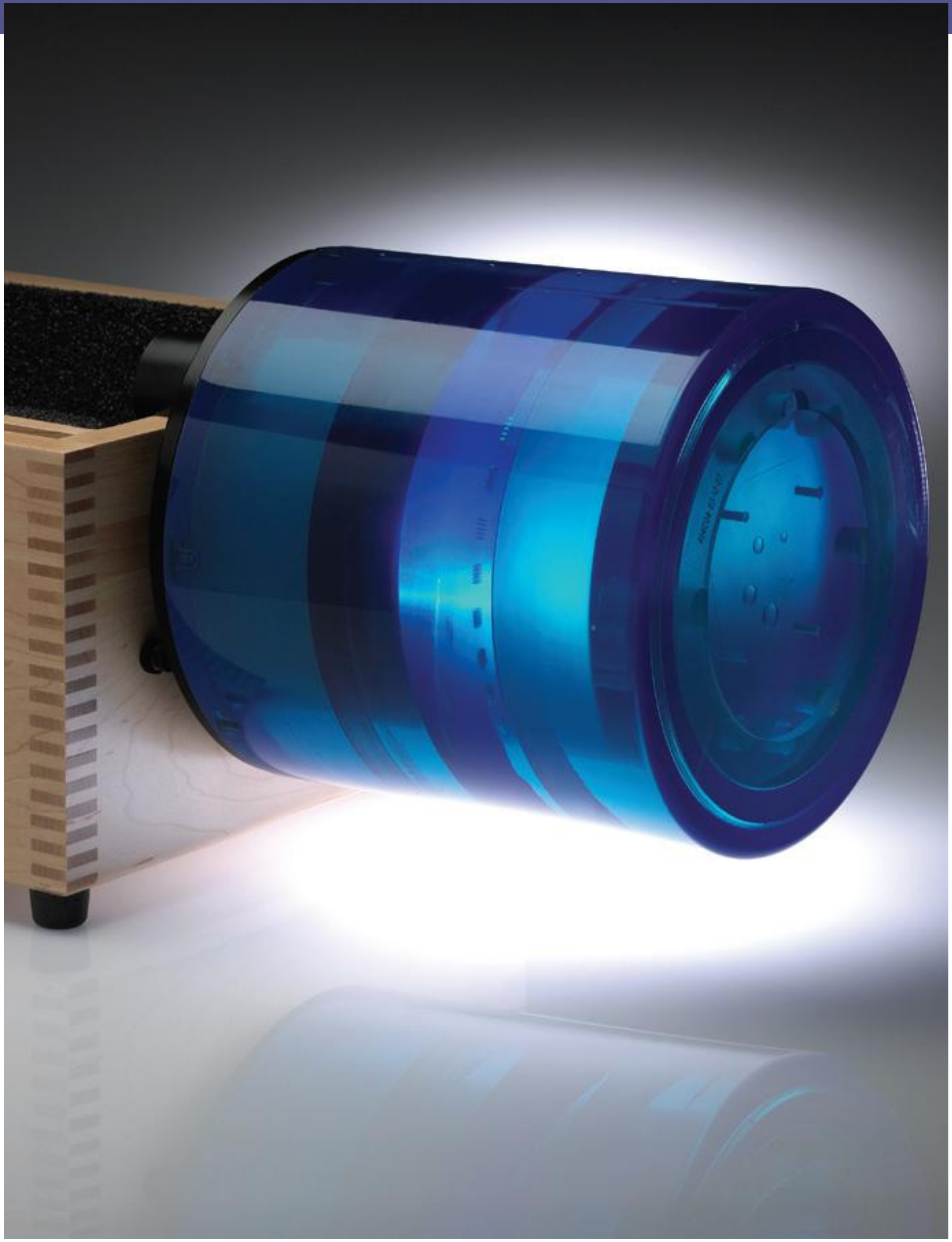
Phantoms to evaluate image quality

Cylinders which:

- Contain water
- Are made with «solid water», which are materials similar to water as attenuation coefficient (TC number = 0 ± 5 HU), usally PMMA. PMMA has the advantge to be more stable and does not create problems related to water filling and emptying.

Cylinder diameter: 15 cm ÷ 25 cm (smaller diameter phantom simulates head, larger diameter phantom simulates body)

Often phantoms are made using several layers of PMMA, each of them containing different details.



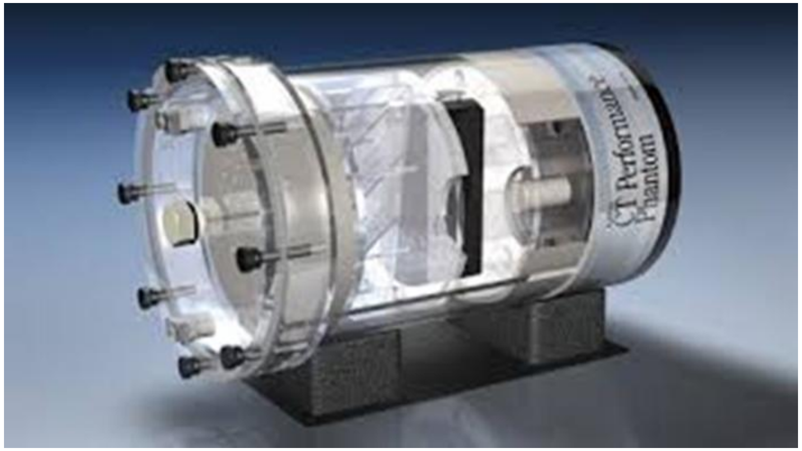
Catphan 600

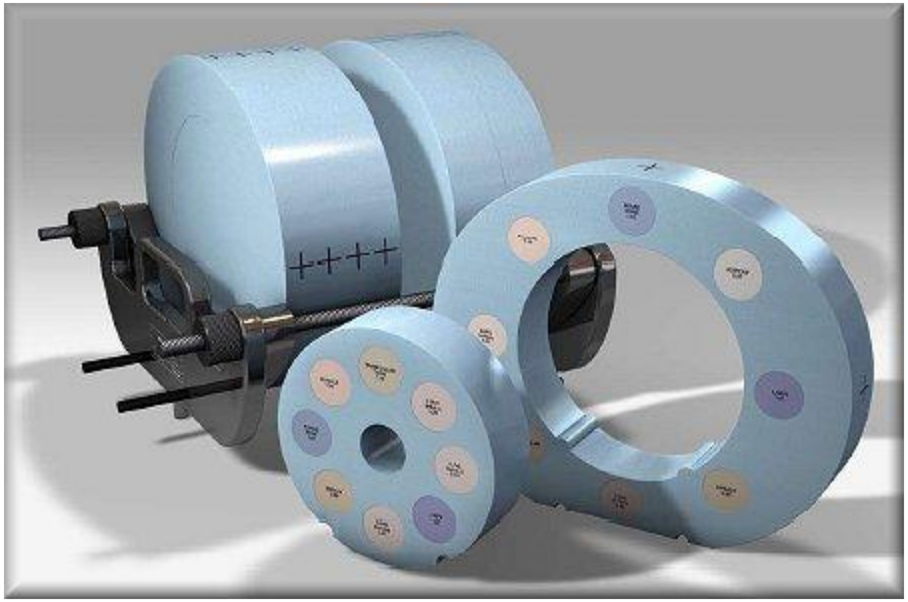
«body» annulus

ACR* Accreditation Phantom

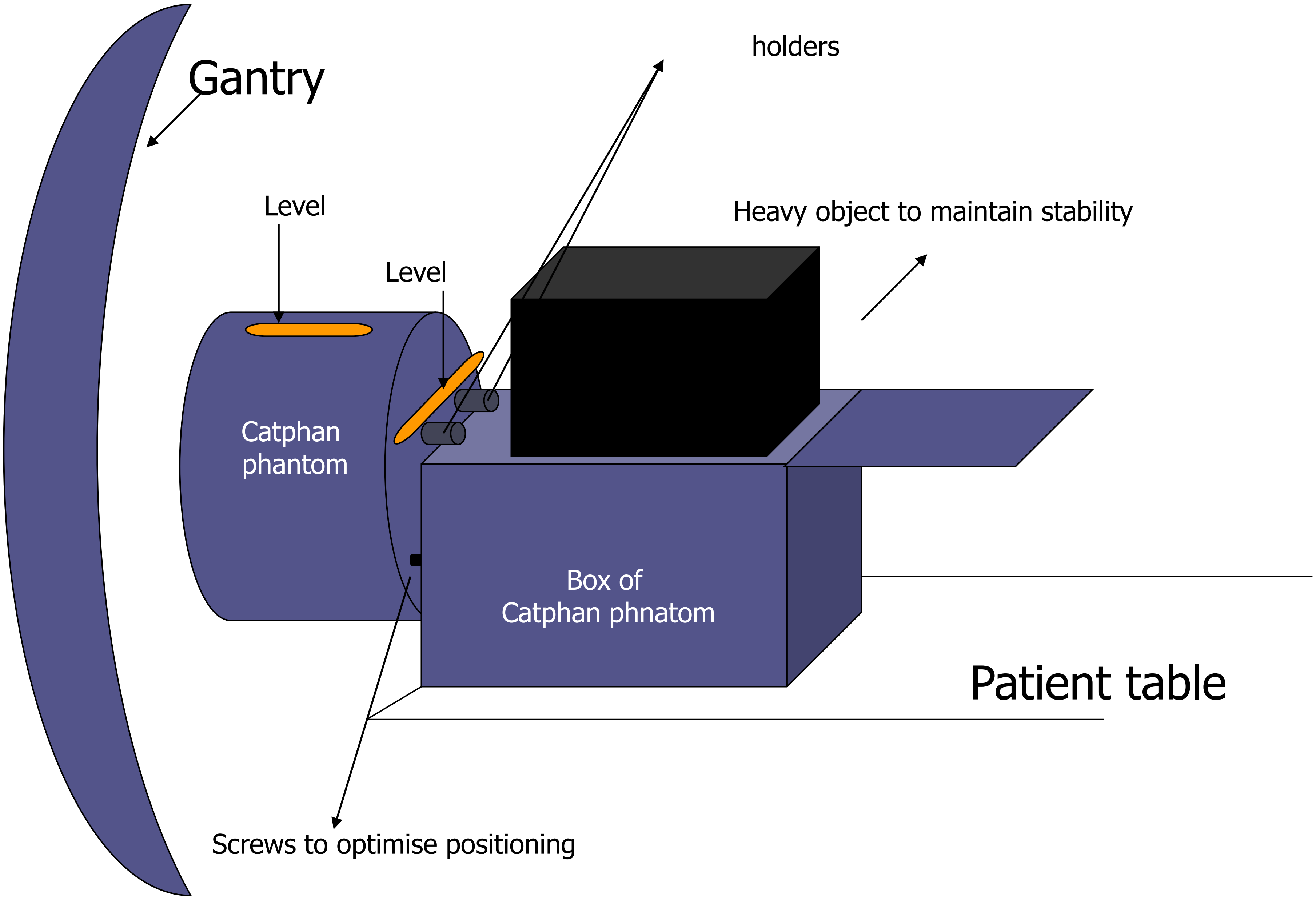
American College of Radiology

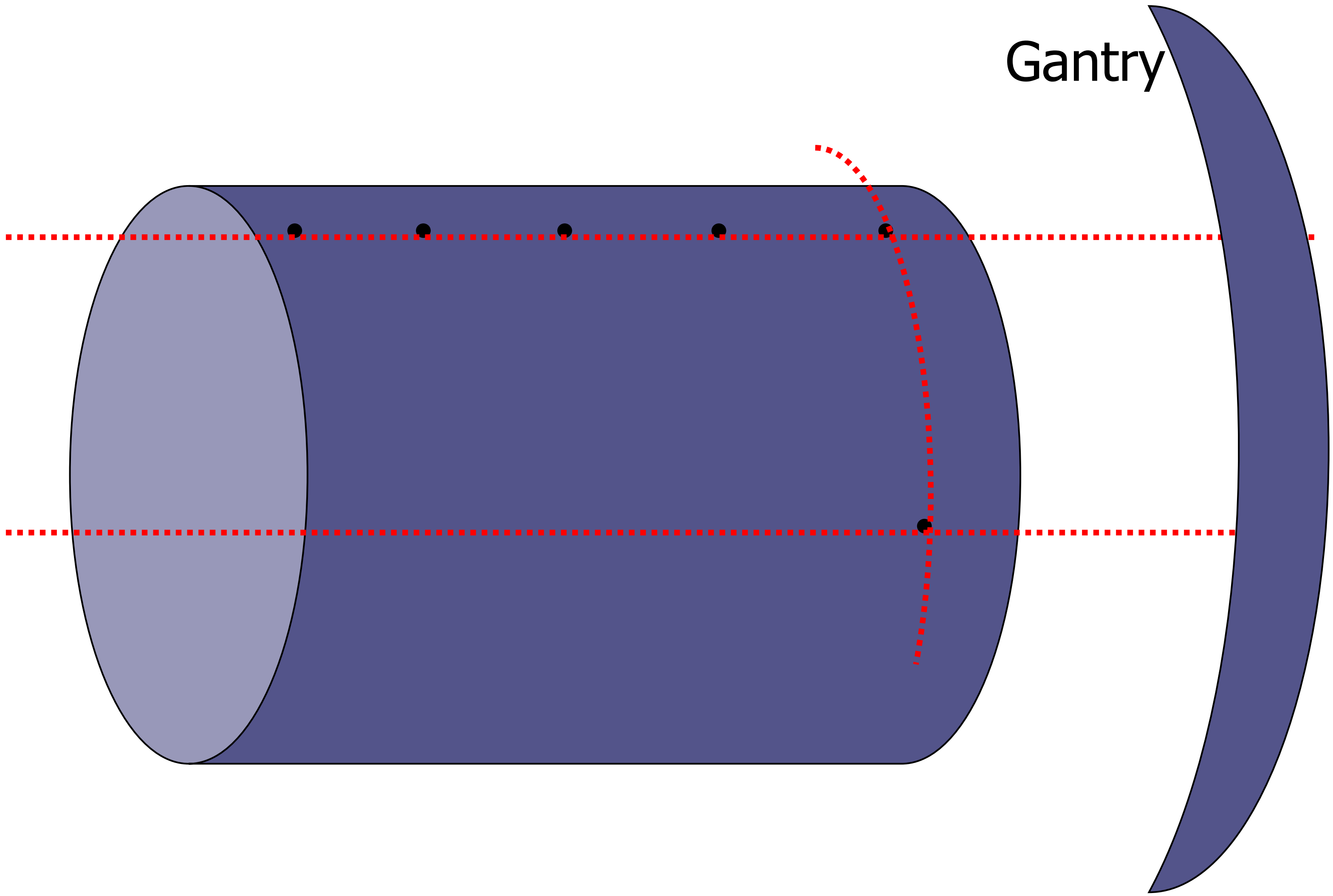
.....other phantoms (CIRS, AAPM...)



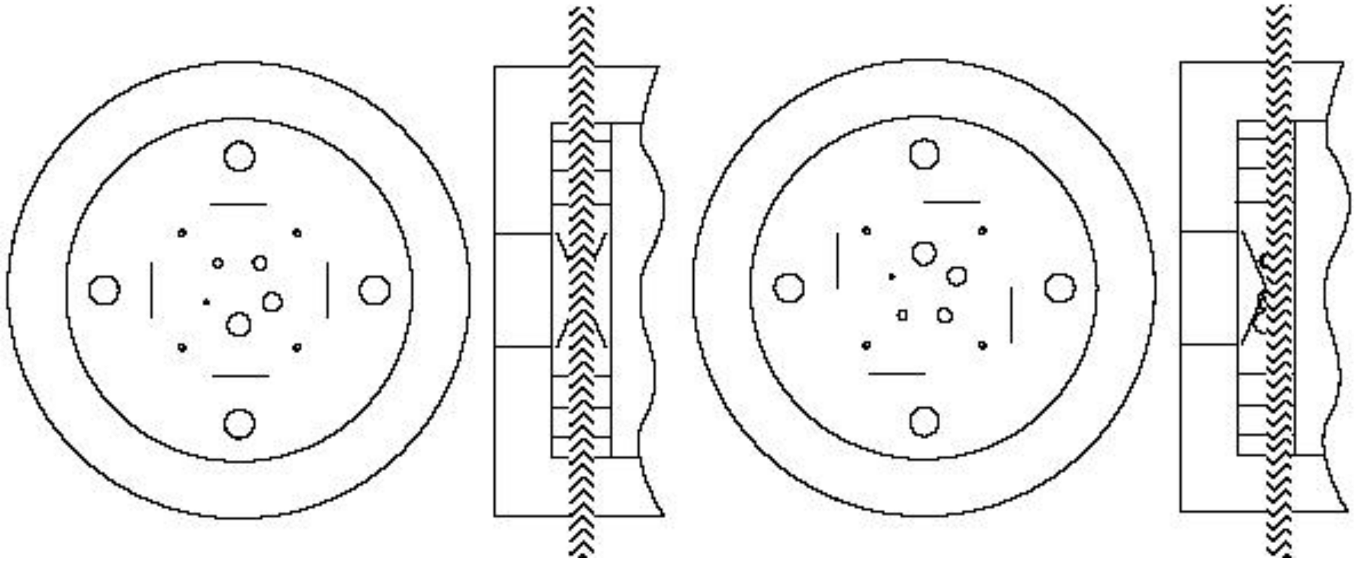


«Manufacturer» phantoms


holders
Gantry
Level
Level
Heavy object to maintain stability
Catphan
phantom
Box of
Catphan phnatom
Patient table
Screws to optimise positioning


Gantry

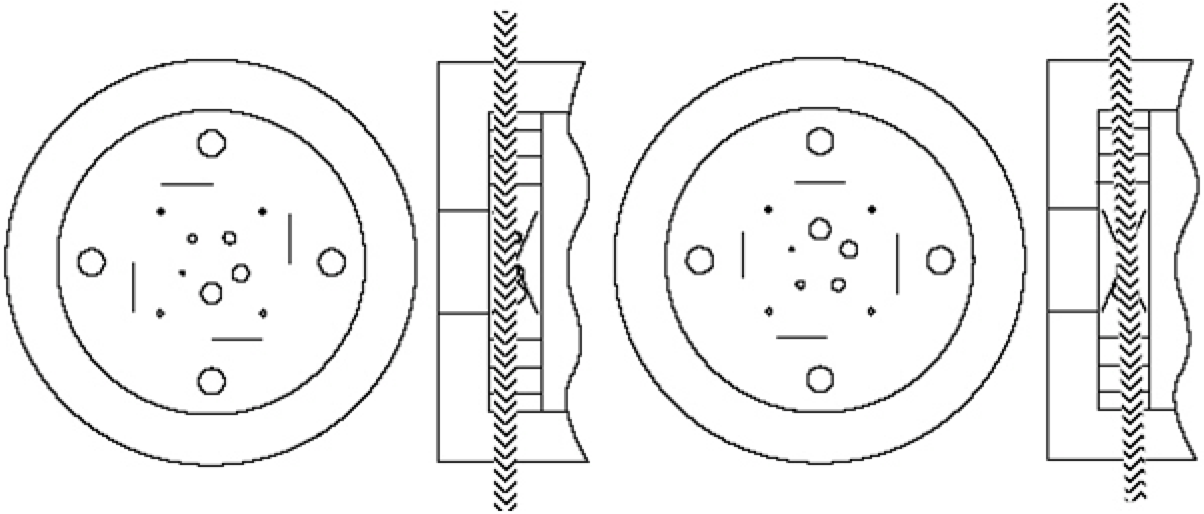
Alignment verification system



Proper Alignement

Bad Alignement

Alignment verification system



Bad Alignement

Protocol selection

MODALITA' DI ACQUISIZIONE										
MODALITA'	sec	kV	mA	Strato mm*str	Pitch HP(PF)	Thikn (mm)	Filtro	FOV (mm)	Mat	CTDIvol (mGy)
Cranio Standard (S&S)	1	120	200	2x4 (8mm)	/	4 (2 imm)	FC 63	240 (S)	512	47.6
Cranio Alta Ris. (Hel)	0,5	120	300	0,5x64 (32mm)	53 (0.828)	1	FC 31	180 (SS)	512	37.1
Corpo Standard (Hel)	0,5	120	250	0,5x64 (32mm)	53 (0.828)	5	FC 13	400 (L)	512	18.3

Cranio Standard = Standard Head
Cranio Alta Ris = High resolution Head
Corpo Standard = Standard abdomen

Image quality parameters

- **Noise**
- **CT number Uniformity**
- **CT number Linearity**
- **Low contrast resolution**
- **Spatial resolution**
- **Artifact**
- **Slice thickness**
- Dose index

NOISE

Noise of a CT image is due to the variation of CT numbers in the image of a homogenous object.

It is defined as **standard deviation of CT numbers** in a ROI selected in the central area the image of a homogenous object.

(The measurement includes quantum mottle and fixed noise)

An example

Standard Head						
ROI position	X (mm)	Y (mm)	Mean CT#	St. Dev.		
12	0	50	19.88	4.90		
3	50	0	20.92	5.51		
6	0	-50	20.20	6.52		
9	-50	0	18.86	7.37		Uniformity
Central ROI	0	0	21.16	6.66		2.30
High resolution Head						
ROI position	X (mm)	Y (mm)	Mean CT#	St. Dev.		
12	0	50	10.00	103.58		
3	50	0	9.00	100.06		
6	0	-50	11.00	101.69		
9	-50	0	11.00	105.72		Uniformity
Central ROI	0	0	16.00	144.61		7.00
Standard Abdomen						
ROI position	X (mm)	Y (mm)	Mean CT#	St. Dev.		
12	0	50	21.00	11.85		
3	50	0	23.00	11.86		
6	0	-50	21.00	14.65		
9	-50	0	22.00	12.95		Uniformity
Central ROI	0	0	25.00	17.55		4.00

CT number (HU) and linearity

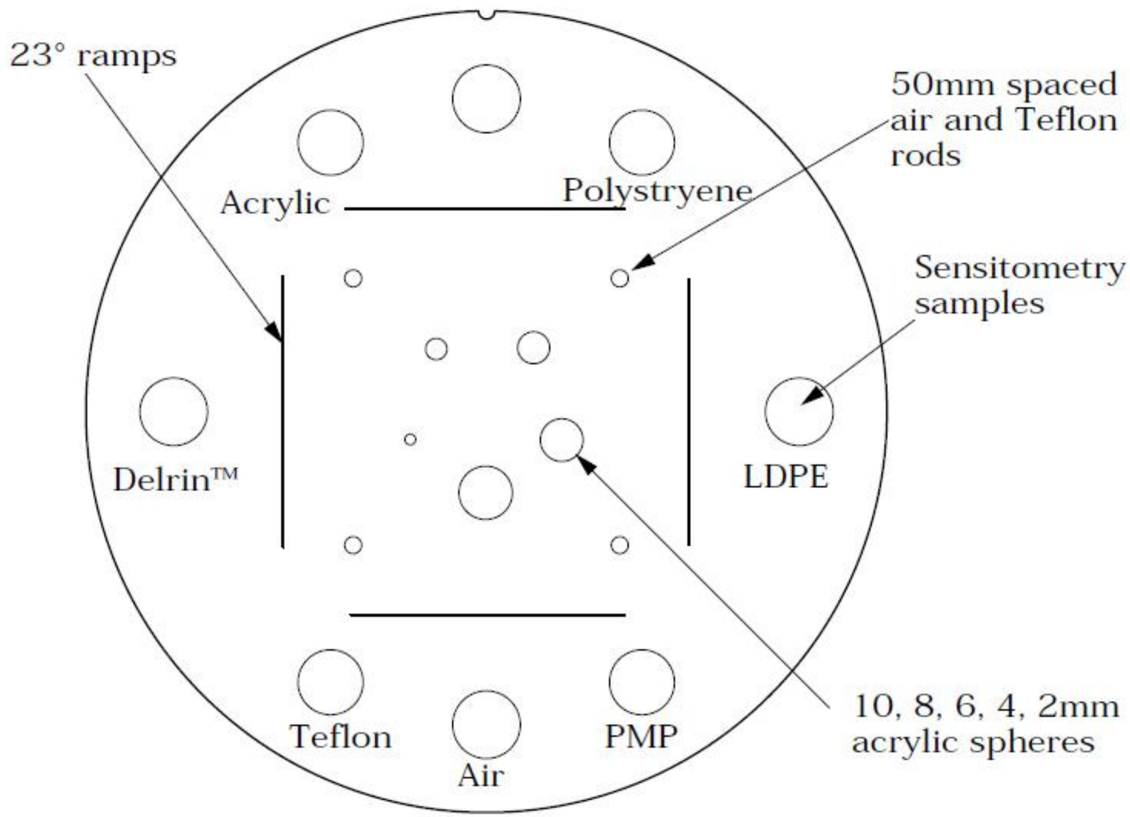
$$HU_{material} = \frac{\mu_{material} - \mu_{water}}{\mu_{water}} \times 1000$$

μ_{water} = linear attenuation coefficient of water

$\mu_{material}$ = linear attenuation coefficient of material

CT number and linearity

CTP404 Module with slice width, sensitometry and pixel size



CT number and linearity

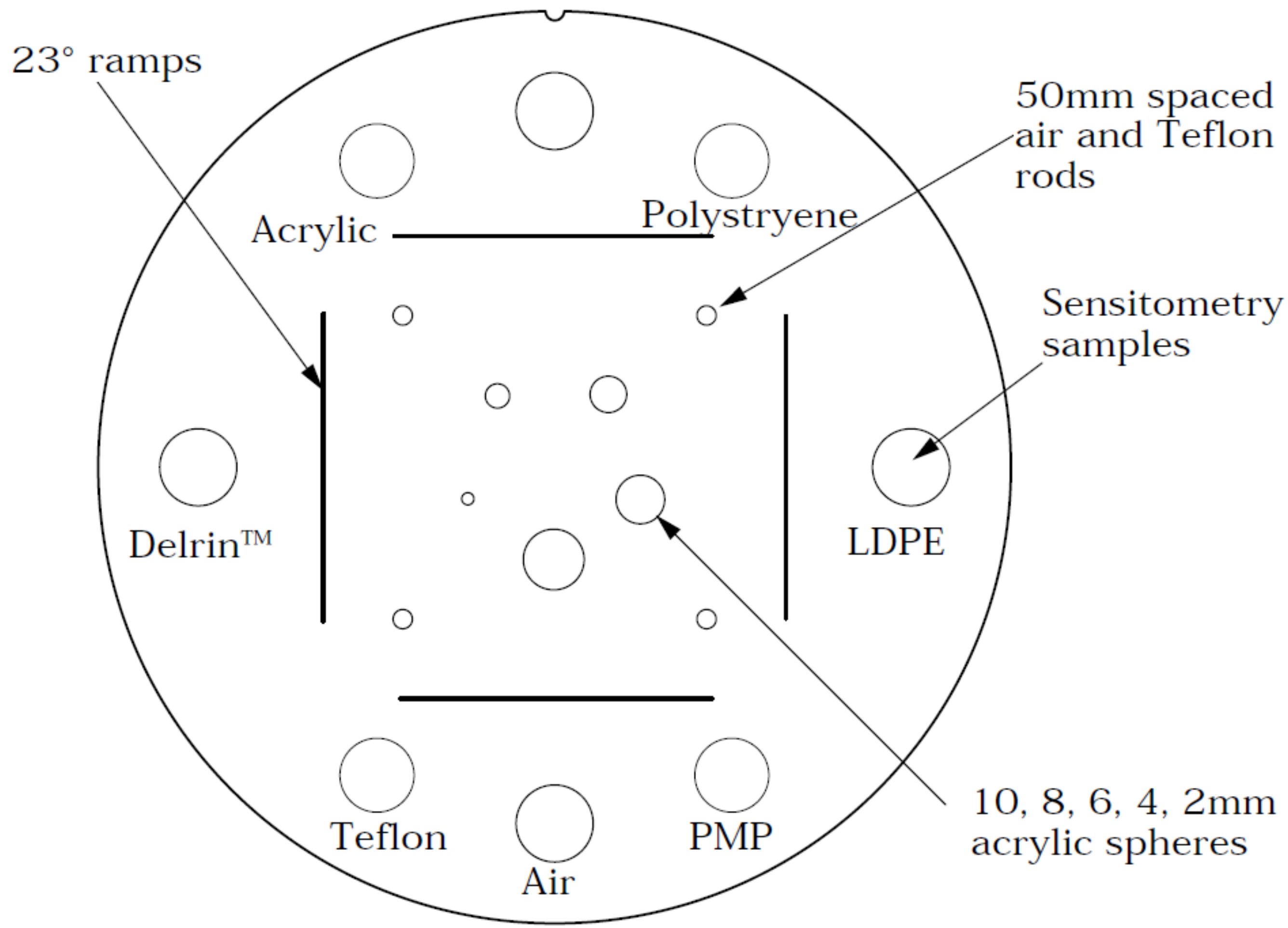
Linear attenuation coefficient μ [units cm^{-1}]

KEV	Teflon	Delrin	Acrylic	Polystyrene	Water	LDPE	PMP	Air
40	0.556	0.327	0.277	0.229	0.240	0.209	0.189	0
50	0.447	0.283	0.244	0.209	0.208	0.191	0.173	0
60	0.395	0.260	0.227	0.196	0.192	0.181	0.164	0
62	0.386	0.256	0.224	0.194	0.190	0.179	0.162	0
64	0.380	0.253	0.221	0.192	0.188	0.178	0.160	0
66	0.374	0.251	0.219	0.191	0.186	0.177	0.160	0
68	0.370	0.248	0.217	0.189	0.184	0.175	0.158	0
70	0.363	0.245	0.215	0.188	0.182	0.174	0.157	0
72	0.359	0.243	0.214	0.186	0.181	0.172	0.155	0
74	0.355	0.240	0.211	0.185	0.179	0.171	0.155	0
76	0.351	0.238	0.210	0.184	0.178	0.170	0.154	0
78	0.346	0.236	0.208	0.183	0.177	0.168	0.152	0
80	0.342	0.234	0.207	0.180	0.175	0.167	0.151	0
90	0.328	0.225	0.199	0.175	0.170	0.163	0.147	0
100	0.315	0.218	0.194	0.170	0.165	0.158	0.143	0

μ is depending on keV

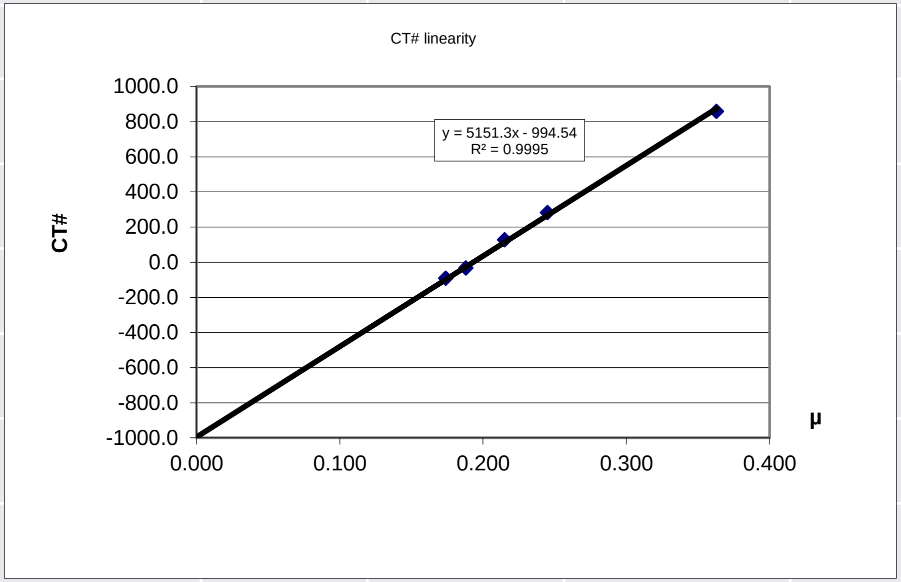
At 120 kV , μ values at 70 keV can be used

CTP404 Module with slice width, sensitometry and pixel size



Material	Teflon	Air	LDPE	Delrin	Acrylic	Polystryrene	Water
µ (at 70 KeV)	0.363	0	0.174	0.245	0.215	0.188	0.182
CT#	857.7	-1004.9	-92	282.3	127.4	-33.5	

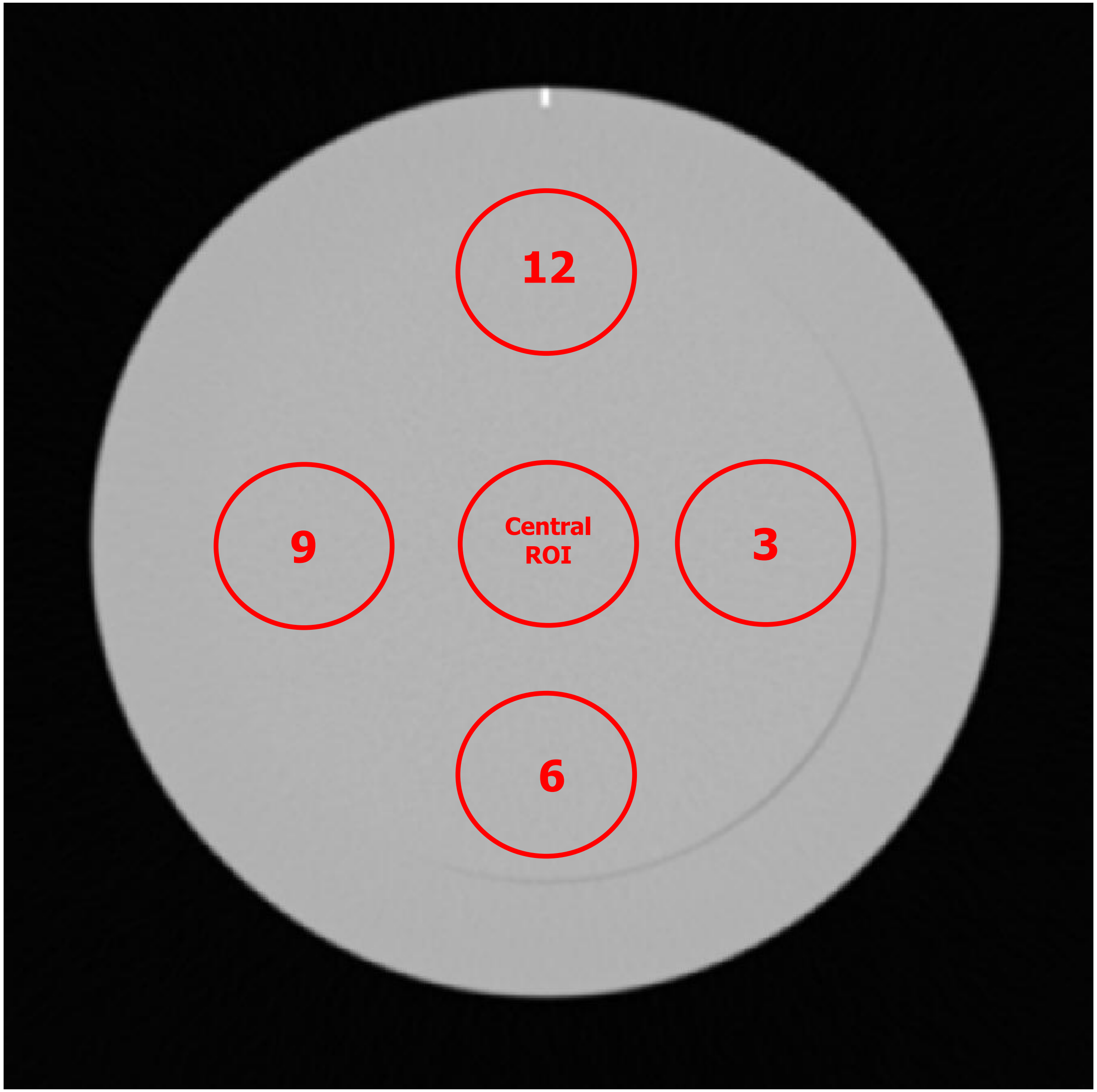
	µ	CT#
Air	0.000	-1004.9
Polystryrene	0.188	-33.5
LDPE	0.174	-92.0
Acrylic	0.215	127.4
Delrin	0.245	282.3
Teflon	0.363	857.7



CT number and CT number uniformity

- Mean value of CT number in the image of a homogenous object

- Maximum variation of mean value of CT number among a central ROI and 4 ROI at the peripheral of the image of a homogenous object.



IEC 61223-3-5: ROI Diameter ~10% Image Diameter

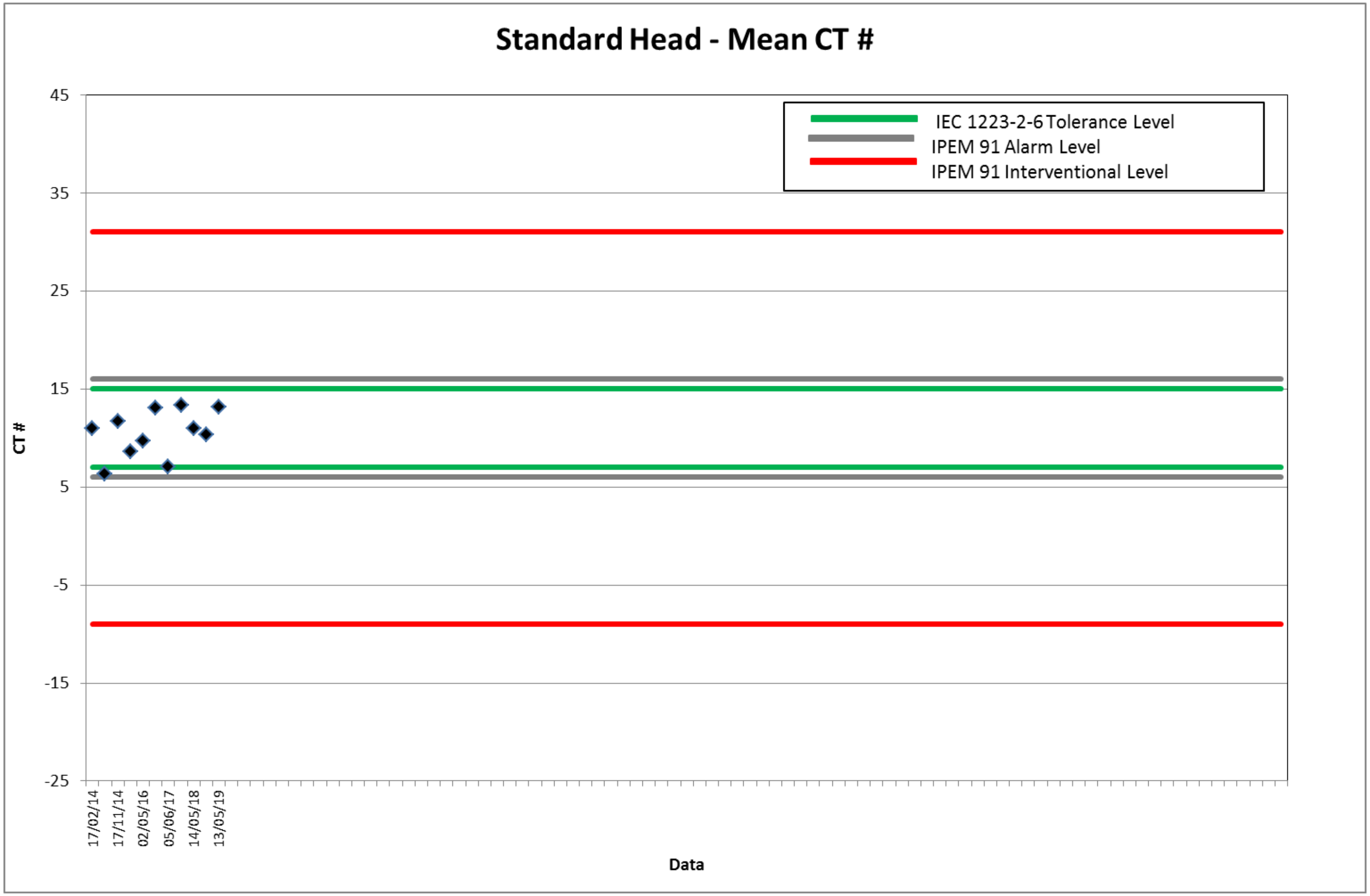
An example

Standard Head						
ROI position	X (mm)	Y (mm)	Mean CT#	St. Dev.		
12	0	50	19.88	4.90		
3	50	0	20.92	5.51		
6	0	-50	20.20	6.52		
9	-50	0	18.86	7.37		Uniformity
Central ROI	0	0	21.16	6.66		2.30

High resolution Head						
ROI position	X (mm)	Y (mm)	Mean CT#	St. Dev.		
12	0	50	10.00	103.58		
3	50	0	9.00	100.06		
6	0	-50	11.00	101.69		
9	-50	0	11.00	105.72		Uniformity
Central ROI	0	0	16.00	144.61		7.00

Standard Abdomen						
ROI position	X (mm)	Y (mm)	Mean CT#	St. Dev.		
12	0	50	21.00	11.85		
3	50	0	23.00	11.86		
6	0	-50	21.00	14.65		
9	-50	0	22.00	12.95		Uniformity
Central ROI	0	0	25.00	17.55		4.00

Mean CT



Standard Head - Mean CT #
IEC 1223-2-6 Tolerance Level
IPEM 91 Alarm Level
IPEM 91 Interventional Level
45
35
25
15
5
-5
-15
-25
CT #
17/02/14
17/11/14
02/05/16
05/06/17
14/05/18
13/05/19
Data

Noise, CT number and CT number uniformity

How can we evaluate these parameters??

- PACS tools
- «Image analysis» software (ImageJ…)
- CQ Software
- Software supplied from the manufacturer

Spatial resolution

Subjective evaluation:

Visual inspection of the image of a test object

Objective evaluation:

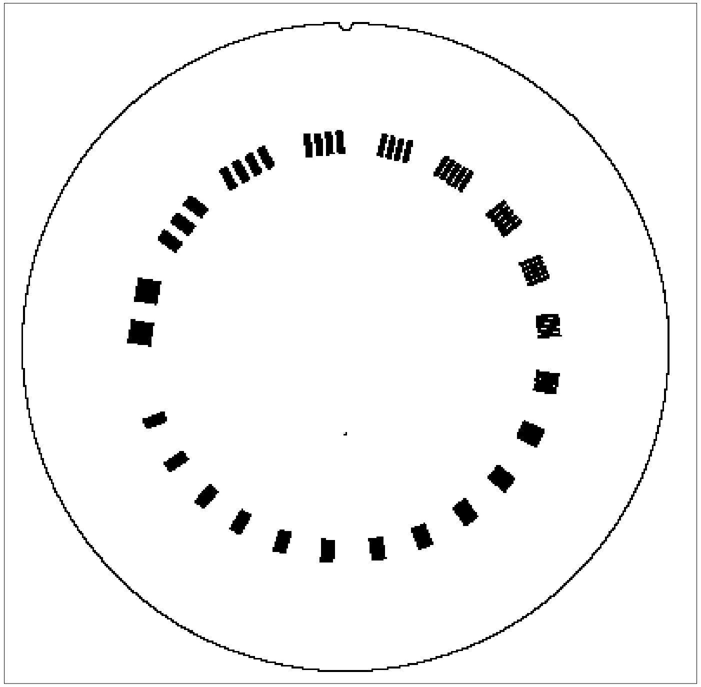
Modulation transfer function (MTF)

The function can be calculated from the *point spread function* (PSF) or from the *edge spread function* (PSF).

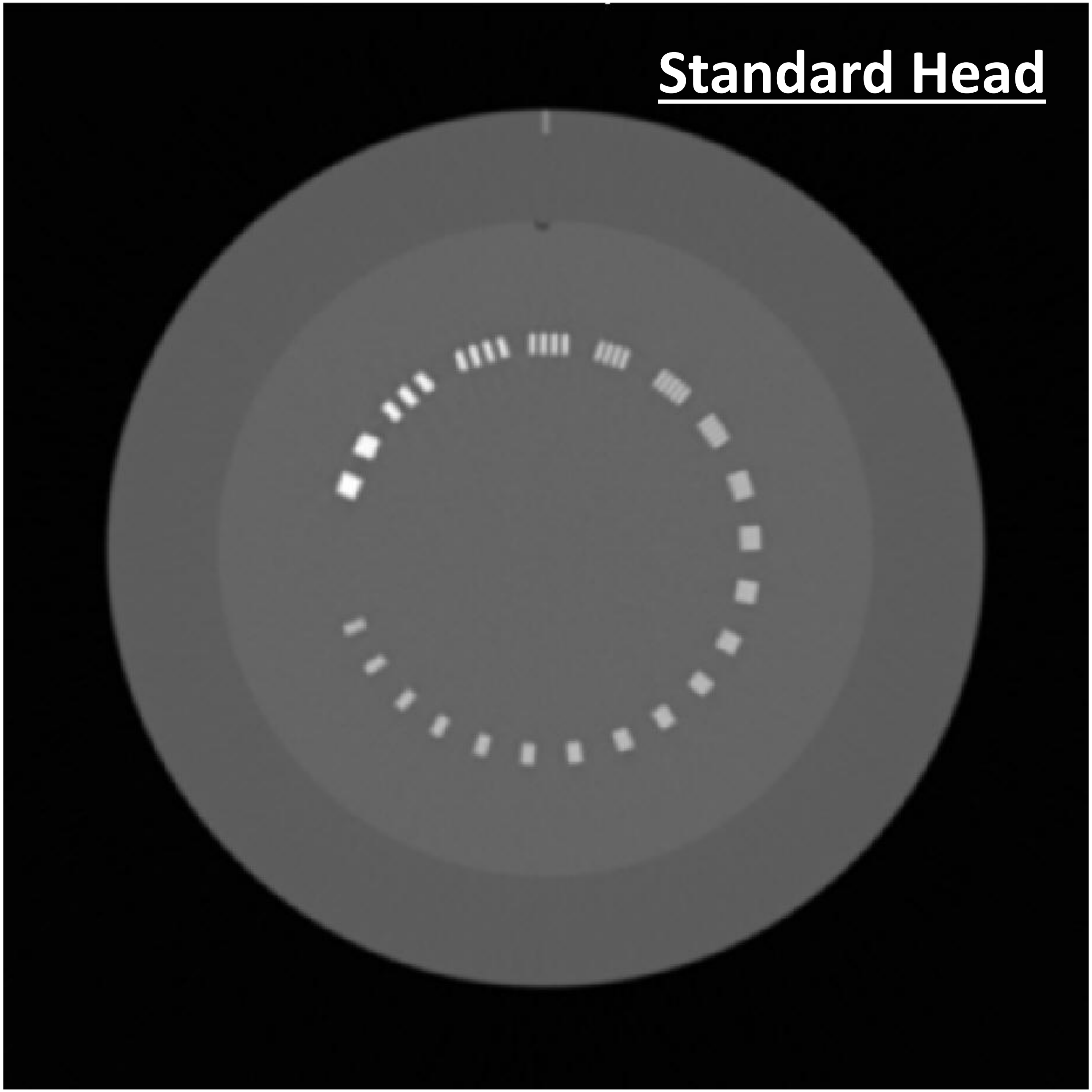
These function can be derived from the image of suitable object (small sphere, thin wire…)

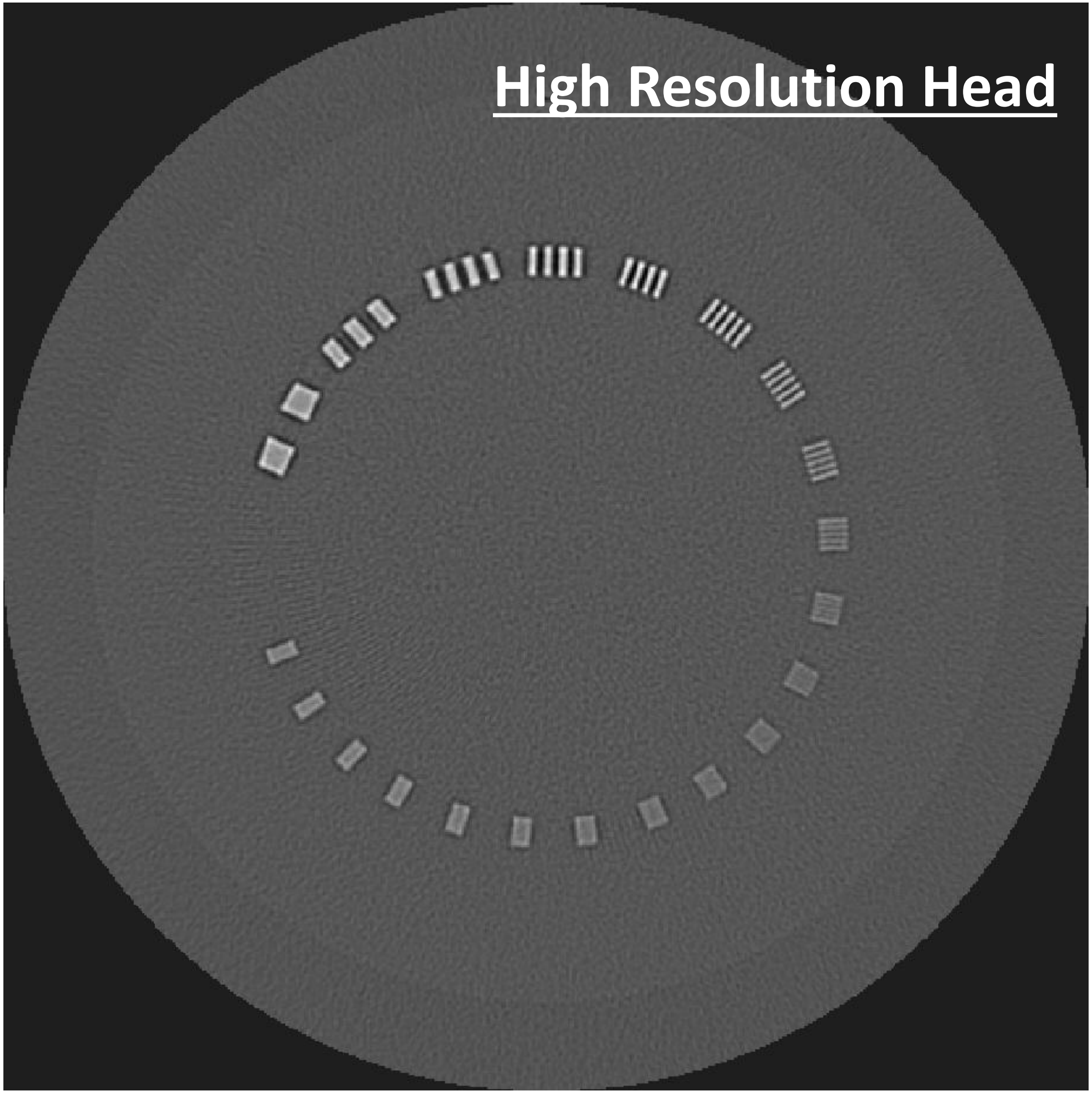
Usually the frequency values at which MTF is 50% and 10% are considered

Spatial resolution

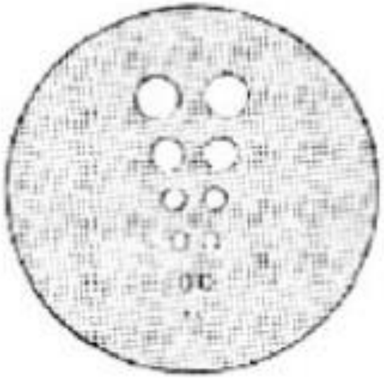


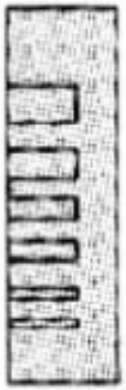
Line Pair/cm	Gap Size	Line Pair/cm	Gap Size
1	0.500 cm	11	0.045 cm
2	0.250 cm	12	0.042 cm
3	0.167 cm	13	0.038 cm
4	0.125 cm	14	0.036 cm
5	0.100 cm	15	0.033 cm
6	0.083 cm	16	0.031 cm
7	0.071 cm	17	0.029 cm
8	0.063 cm	18	0.028 cm
9	0.056 cm	19	0.026 cm
10	0.050 cm	20	0.025 cm
		21	0.024 cm

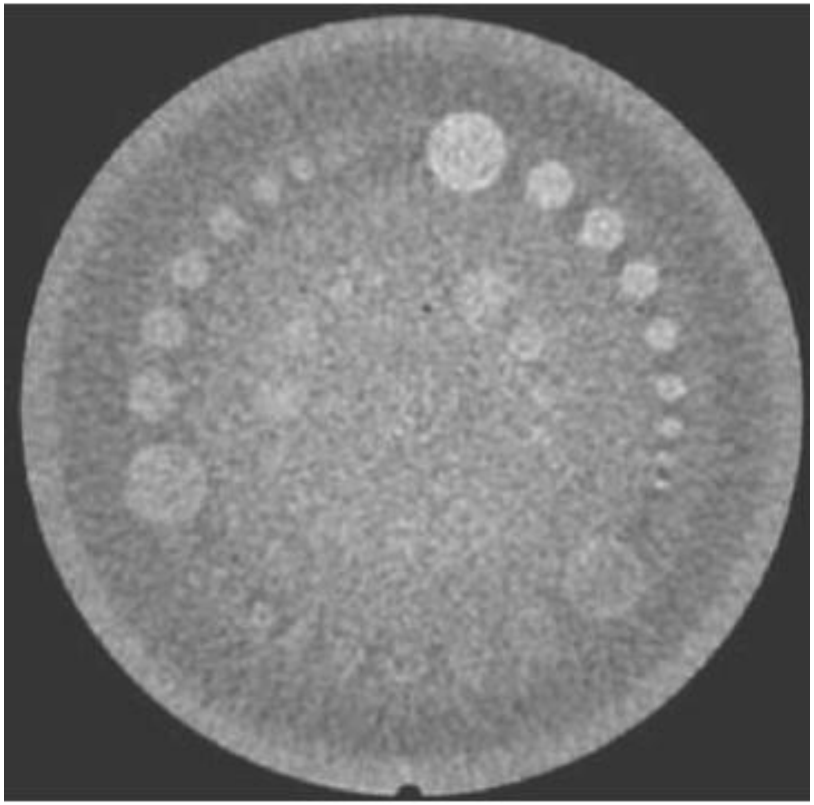

Standard Head


High Resolution Head

Low Contrast resolution



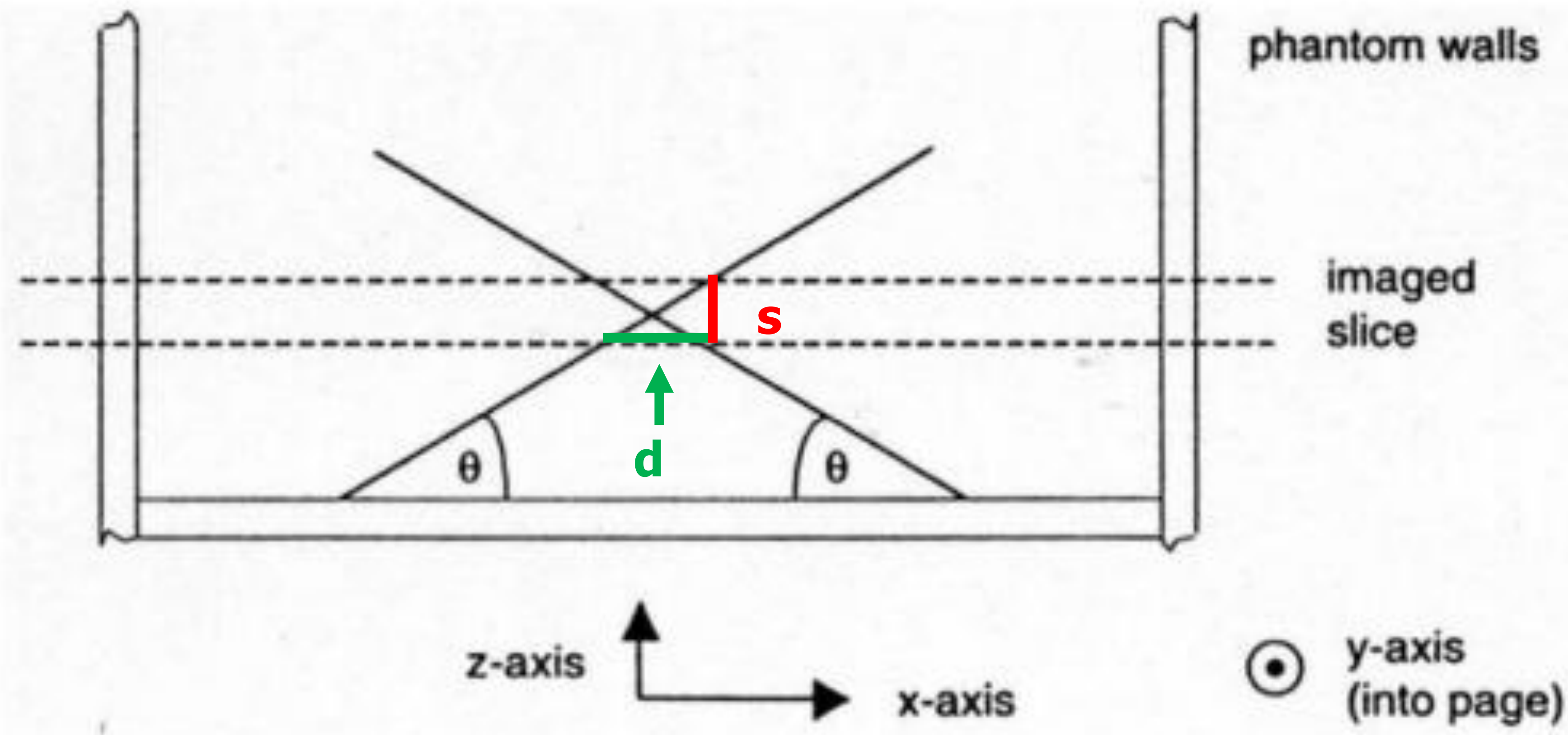




Z - Sensitivity (z) - Imaged Slice Thickness

The z-sensitivity is the value defining the width of the imaged slice along the z-axis.

The z-sensitivity for non-spiral scans is measured using an aluminium plate inclined at an angle (25°, 30° or 45° degrees) with respect to the scan plane. It is quoted as the full width at half maximum (FWHM) of the profile of CT numbers taken across the image of this plate with an appropriate correction factor for the angle and the thickness of the aluminium plate.



d = FWHM of the CT numbers profile on the image of the test object

s = d · tgθ

Slice thickness measurement in spiral scan requires different test object to evaluate z-sensitiviyt profile

Dose Profile Full Width Half Maximum - Irradiated Slice Thickness

The irradiated slice thickness is not the imaged slice thickness. The difference will depend on pre- and post-patient collimation settings. If measured at identical positions in the scan plane, the irradiated slice thickness will always be equal to or greater than the imaged slice thickness.

Specifically, the irradiated slice thickness is given as the full width half maximum (FWHM) of the dose profile along the z-axis obtained from a single scan. This can be obtained using GAFCHROMIC film.