COLLEGE ON MEDICAL PHYSICS
Applied Physics of Contemporary Medical Imaging – Expanding Utilization in Developing Countries

27 August - 14 September 2018
Trieste, Italy

ICTP

Interventional Radiological Equipment – selection and installation

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ICTP

Learning objectives

- To understand the main components of an interventional radiology equipment
- To understand the relevance of equipment commissioning for the quality of the procedure and the radiation safety of patient and staff

Introduction

- Dynamic imaging systems
- Wide range of applications in the hospital
  - Radiology
  - Cardiology
  - Operating theatres
  - Urology
  - Special applications such as lithotripsy
- Such a wide range of applications … these systems are very flexible and can be configured to perform a wide range of tasks that require temporal sequences of images

Applications: Gastro Intestinal

- GI studies: Barium Contrast Swallow, Meal, Enema studies
- Needs:
  - Large field of view (FOV)
  - Image rates can be up to 30 fr/s for swallow, down to 3 fr/s for enema
  - Some use of spectral filtration
  - Tilting table to distribute the contrast through the organs or structures of interest
  - Flat panel detectors (FPD) used these days
- Less commonly performed procedure these days?

Application: surgical theatre

- Mobile C-arms
  - Provide imaging in the operating theatre
  - Can be 'simple' C-arms and more complex systems than can be used for special procedures (cystograms, cholangiography etc)
  - Generally smaller FOVs, shorter SID (x-ray tube)
  - Still, flexible program set up, pulsed fluoro spectral filter options
  - X-ray image intensifier (XR IITV) systems still used/available, FPD now taking over

Application: interventional radiology

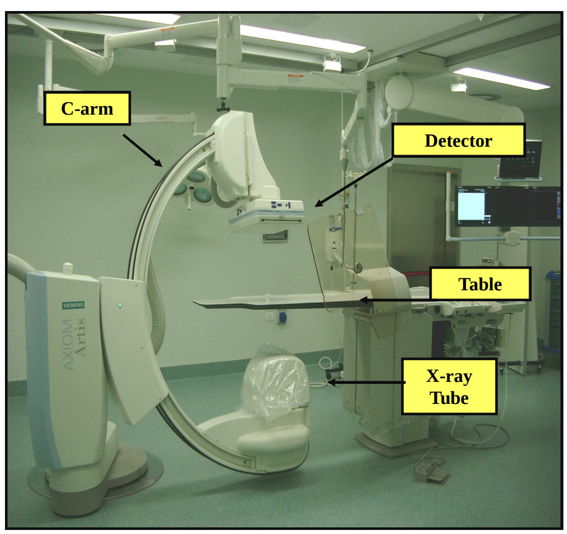
- Imaging for diagnostic and image guided therapy purposes
  - Increased procedure complexity
  - Extensive use of iodine-based contrast media
  - Extended procedure times
  - Long fluoroscopy times, many acquisition runs
  - Many different angulations, views
  - Temporal subtraction (DSA)
- This places high demands on system performance:
  - Need to produce the required image quality at the lowest possible doses
  - Visibility of small anatomical details, guidewires and thin catheters, low density contrast media, many other devices

Application: interventional radiology

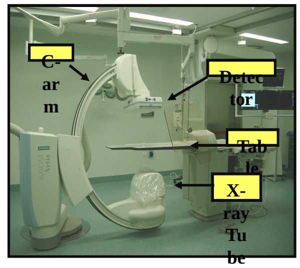
- Many different angulations, views
- Detector and tube are linked on a C-arm (mono or biplane) that rotates around the **isocentre**
  - Anatomy at the isocentre remains at centre of FOV as the C-arm rotates around the patient
  - Detector can be moved in and out to rapidly change the SID
- Powerful x-ray tube
  - Spectral pre-filtration (typically Cu)
- Detector sizes
  - 22 cm to 48 cm radiology
  - 15 cm to 22 cm neuroradiology
  - 15 cm to 22 cm cardiology

System

- X-ray production
- X-ray detection
- Exposure control
- Display
- Processing



System components



The key components include:

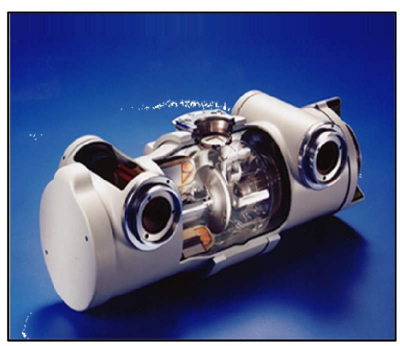
- X-ray tube
- spectral shaping filters
- a field restriction device (collimator)
- anti-scatter grid
- image receptor (II or FPD)
- image processing computer
- display device

Ancillary but necessary components include

- high-voltage generator
- patient-support device (table or couch)
- hardware to allow positioning of the X-ray source assembly and the image receptor assembly relative to the patient.

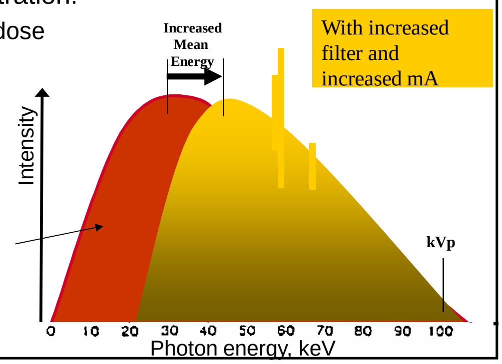
X-ray tube

- Characteristics depends on the usage
- X-ray quality: 60 – 125 kV
- High tube current
- Typically 3 focal Spots:
  - Small 0.6 mm (the standard)
  - Big 1-1.2 mm (for high voltages)
  - Micro 0.3 mm for high spatial resolution (interventional neuroradiology)
- High performances in heat: High-speed rotating anode tubes (up to 10000 rpm) coupled to cooling circuits to water or oil



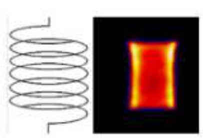
X-ray tube

- Tungsten (W) target tube:
  - Bremsstrahlung soft X-rays removed by filter
  - This eliminates non-imaging x-rays, crucial for patient safety
  - Minimum 2,5 mm Al equiv. filtration required
- Significant spectral shaping is used in interventional systems, typically using up to 0.9 mm Cu filtration:
  - This greatly reduces patient skin dose (up to 90%)
  - Requires a powerful tube (up to 120 kW)

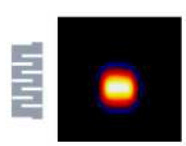


X-ray tube: cathode

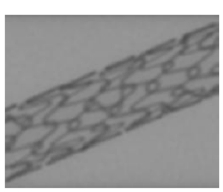
- Flat emitter on the Gigalix (Siemens) x-ray tube anode

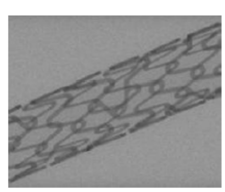


filament emitter



flat emitter





X-ray tube: testing

- Standards to allow the user to perform quality control.
- In particular to measure:
  - HVL
  - Dose reproducibility
  - mA linearity
  - kVp, mA pulse width accuracy
  - CAK and DAP accuracy
  - X-ray tube output

(According to IEC 60601-2-43)

2.3 QUALITY CONTROL TESTING OF THE XRAY CONTROL PARTS OF THE EQUIPMENT

To enable x-ray dose related constancy testing, the EQUIPMENT shall provide means for the QUALITY CONTROL USER to perform x-ray dose related QA/QC tests.

In addition to manufacturer recommended tests, the EQUIPMENT shall provide means to perform the following tests described in IEC 60601-2-43:

- Half-value layer
- Dose reproducibility
- mA linearity
- kVp, mA, pulse width accuracy
- CAK and DAP accuracy
- X-ray tube output measurement

The EQUIPMENT shall provide x-ray acquisition conditions to perform the QA/QC tests. The EQUIPMENT shall enable selection of values, either by a MANUAL CONTROL MODE or by selecting preset combination values, for:

- kV
- mA
- ms
- spectral filtration
- focal spot size

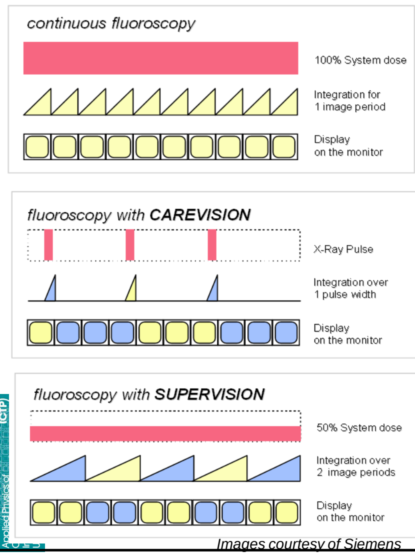
The EQUIPMENT shall ensure that normal x-ray tube protection mechanisms remain active during USER QUALITY CONTROL MODE. In order to protect the x-ray detector from excessive radiation, the user is responsible to shield the detector with sufficient lead material.

Note 1: quality control testing of the x-ray control parts of the EQUIPMENT is not inclusive of the imaging detector, therefore there is no need to store images acquired while in this mode.

Imaging modes

- Pulsed Fluoroscopy (7.5 - 30 p/s): low emissions (low mA) with variable width
- Pulsed Fluorography or Cine
  - 1-5 fr/s for vascular procedures, 15-30 fr/s for cardiac procedures, 60 fr/s for children
  - High intensity (450 mA e up) with impulse width from 5 to 100 ms (5-15 ms for cardiac procedures)
- DSA (digital subtraction angiography)
- Roadmap: two images overlap, one obtained in Subtractive mode and a fluoroscopic image
- ConebeamCT (CT like images)

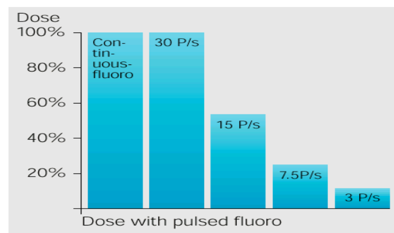
Pulsed fluoroscopy mode



Images courtesy of Siemens

With pulsed fluoroscopy several levels of patient dose saving can be achieved:

- The number of pulses per second is one of the critial parameters
- The other is the dose per pulse
- Several processing approaches exist in the market to improve the visualization of moving organs with pulsed fluoroscopy

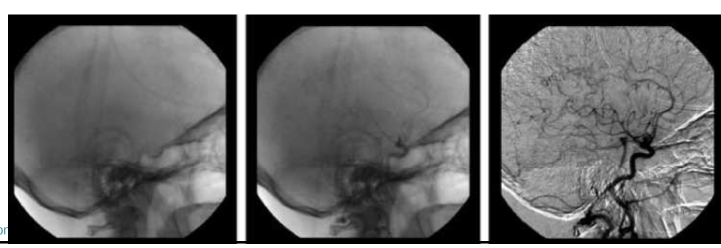


Digital Subtraction Angiography (DSA)

- Imaging mode that uses temporal subtraction of images to reduce the impact of overlying anatomy
  - A **mask**image is acquired
  - Iodine contrast is injected
  - **mask**image is subtracted from later (**contrast**) images

(anatomy + vessel with contrast) – anatomy = vessel with contrast

- Log transform of both the mask and the contrast before subtraction (removes modulation of contrast by overlying anatomy)



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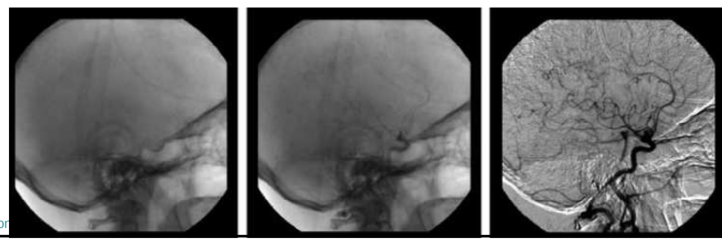
Digital Subtraction Angiography (DSA)

- Noise sums in quadrature in the subtraction
  - Variance in the DSA image is a factor of 2 higher
  - stdev('noise') is a factor of $\sqrt{2}$ higher in DSA image
- To overcome this, DSA programs operate at higher air kerma rate/image



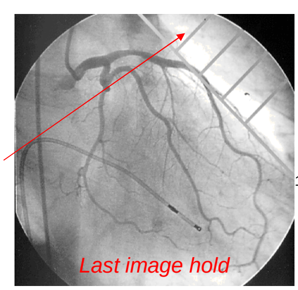
Collimation

In fluoroscopy, the collimation may be circular or rectangular in shape, matching the shape of the image receptor.

Virtual collimation: In Last Image Hold (LIH):

- Manipulation of diaphragms
- Manipulation of wedge filters
- Movement of patient table

The wedge filter is positioned without the need of fluoroscopy



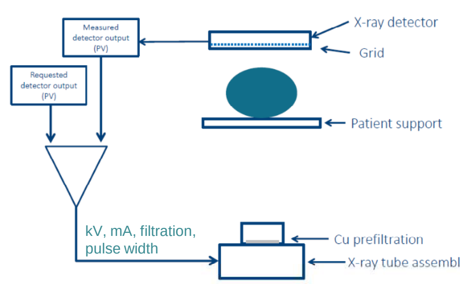
Anti scatter grid

- Standard component in fluoroscopic systems
  - Grid ratios range (6:1 – 10:1)
- Grids should be removable for paediatric procedures

Automatic Doserate Control (ADRC)

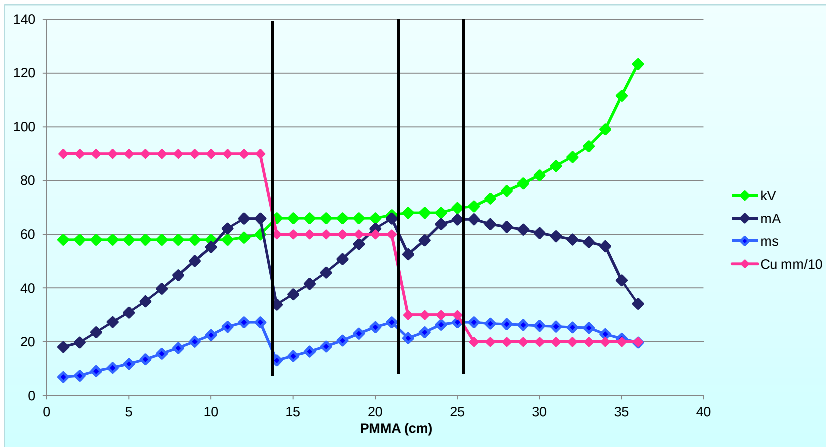
ADRC maintains the detector radiation dose per frame at a pre-determined level, for different X-ray attenuation of the patient's anatomy, and maintaining the pre-defined image quality:

- ADRC changes the different parameters: kV, mA, filtration, pulse width and image processing, during delivery according with the curve of predetermined loading
- ADRC keeps the system within regulatory limits of patient skin doserate



Automatic Doserate Control (ADRC)

Complex and different trajectories (characteristic curves) for each imaging mode



ADRC: operation

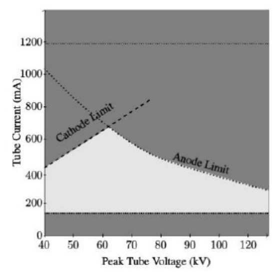
- Each imaging mode has defined air kerma rate at the image receptor (µGy/s and or µGy/fr)
  - Defined in the program set up
- ADRC loop
  - The difference between measured and requested detector output is calculated
  - The x-ray factor changes (kV, mA, ms, pulse width, added filtration, focus size) are calculated and applied

CARD	Coro ND (7,24)	LV (7,4)	Coro LD (7,26)	DOCU (7,11)	CoroCARE (7,34)
EXPOSURE	CARD	CARD	CARD	CARD	CARD
kV	70	70	73	70	70
Pulse Width	8	6.4	6.4	6.4	8
kV Filter	73	73	85	81	73
kV ms	96	77	96	96	96
dose	170	140	120	200	140
kV dose	109	102	109	102	109
Mfield	C	C	C	C	C
Focus	L	L	L	L	L
kv Focus µ->S	off	off	off	off	off
kv Focus S->L	off	off	off	off	off
ACQUISITION					
Scene Time	10	10	10	10	10
Frame Rate	15 fps	30 fps	15 fps	15 fps	15 fps
Frame Control	Fixed	Fixed	Fixed	VFR Time	Fixed
No Phases	1	1	1	1	1

Example of factors defined for different imaging mode and procedure type (courtesy from Siemens)

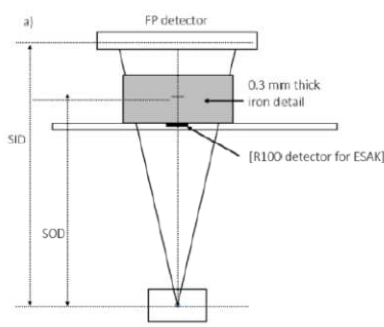
ADRC: limits

- Regulatory limits to ADRC parameter selection
  - FDA (USA) limits fluoroscopy patient exposure rate to 10 R/min (88 mGy/min) (very influential limit, applies in many countries)
  - IEC states that within one clinical application, switching from low to high dose mode then patient dose is at most doubled
- Technical limits: certain combinations are not allowed:
  - Heating of the focus track
  - Heat capacity and rate of cooling for the anode
  - Restricted electron emission (cathode) at low tube voltage



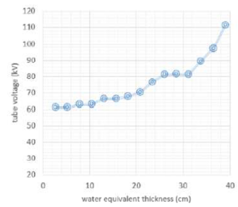
After the installation: to assess ADRC performances (I)

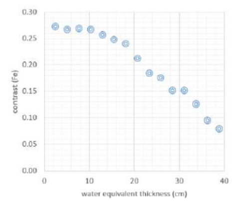
- Phantom thickness (PMMA or water equivalent) from 5 to 40 cm
- A thin iron plate in the phantom to measure SNR
- A detector at the beam entrance to measure entrance air kerma rate (k_e rate)
- Changing imaging mode we have an assessment of image and dose performances

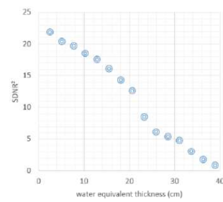


After the installation: to assess ADRC performances (II)

- For fluoroscopy (usually 3 modes: low, medium and high contrast mode)
  - as expected, contrast and SNR is decreasing as patient thickness increases
  - This information allows:
    - To identify imaging mode required to answer/perform the clinical task (commissioning)
    - To monitor during the life of the equipment the equipment performances (periodic quality control)

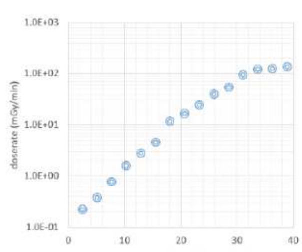


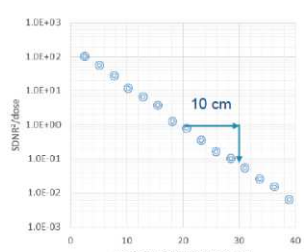




After the installation: to assess ADRC performances (III)

- Entrance air kerma increase as thickness increases
- A common metric to summarize image quality is SDNR²/dose
  - This shows a continual drop in image quality per unit dose as thickness increases (an order of magnitude reduction in SDNR²/dose for 10 cm of thickness increase)





Imaging detector

Dynamic Flat Panel Detector

- Operating principle similar to static DR:
  - High image quality at radiographic exposure levels for a large field of view (acquisition mode) – superior to I.I.
  - High image quality by low exposure levels (fluoroscopic mode) – similar to I.I.

  - Detector was designed to produce a large signal per exposure (low exposure levels) and to have very low additive electronic noise

DFPD – Indirect Conversion

- Scintillator Layer: CsI:Tl
  - High X-ray absorption efficiency of energies mostly used influoroscopy and fluorography
- Matrix: a-Si:H
  - Exposures repeatability
  - High time resolution

Each photodiode represents one pixel and is coupled to a thin film transistor (TFT) that acts as a switch. Each X photon that hits the scintillator produces fluorescence light that illuminates the photodiode and is converted into electric charge. The charge accumulated in each pixel is proportional to the X-rays absorbed (typically 1000 photons/pixel).

- ADC: Analogic-Digital Converter
  - The electric charges are then read out sequentially line-for-line

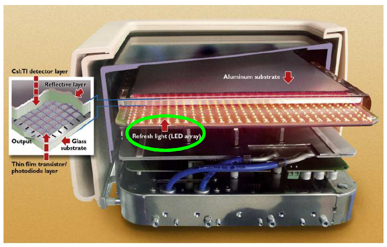
DFPD: operation

Dynamic solid-state detectors incorporate measures to minimize lag and memory effect. Many modern dynamic detectors achieve this using a so-called refresh (or reset) light, which reconditions the detector prior to each new image acquisition cycle.[9,20,28,34] The refresh light usually takes the

Clinical Radiology (2008) 63, 1073–1085

The design and imaging characteristics of dynamic, solid-state, flat-panel x-ray image detectors for digital fluoroscopy and fluorography

A.R. Cowen[a,*], A.G. Davies[a], M.U. Sivananthan[b]



Trixell Pixium 4800 with refresh light

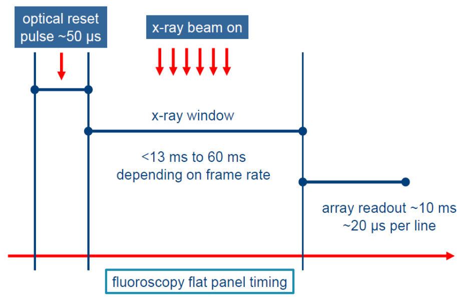
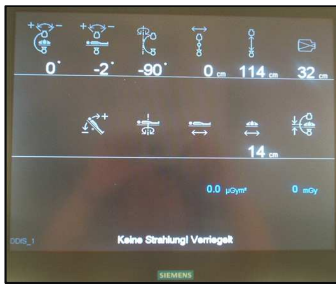


Image display

- High-quality video displays
  - high maximum luminance
  - high-contrast ratios
- Displays should be calibrated to a standard luminance response function (such as the DICOM part 14 Grayscale Standard Display Function) to ensure that the widest range of gray levels are visible.

other characteristics

- Patient dose measurement (KAP and CAK), display and archive.
- Dosimetric indications inside the interventional room.
- Protective tools in the system.



Dose information archive: DICOM Dose Objects

- DICOM Header
- DICOM Radiation Dose Structured Report (RDSR)

DICOM Header

- Text file → a lot of information (depending on the modality and the manufacturer):
  - Patient data
  - Procedure data
  - Geometry
  - Image characteristic
  - Estimated dose quantities
- Information encoded in TAGs

```
First 128 bytes: unused by DICOM format
Followed by the characters 'D','I','C','M'
This preamble is followed by extra information e.g.:

0002,0000,File Meta Elements Group Len: 132
0002,0001,File Meta Info Version: 256
0002,0010,Transfer Syntax UID: 1.2.840.10008.1.2.1.
0008,0000,Identifying Group Length: 152
0008,0060,Modality: MR
0008,0070,Manufacturer: MRIcro
0018,0000,Acquisition Group Length: 28
0018,0050,Slice Thickness: 2.00
0018,1020,Software Version: 46\64\37
0028,0000,Image Presentation Group Length: 148
0028,0002,Samples Per Pixel: 1
0028,0004,Photometric Interpretation: MONOCHROME2.
0028,0008,Number of Frames: 2
0028,0010,Rows: 109
0028,0011,Columns: 91
0028,0030,Pixel Spacing: 2.00\2.00
0028,0100,Bits Allocated: 8
0028,0101,Bits Stored: 8
0028,0102,High Bit: 7
0028,0103,Pixel Representation: 0
0028,1052,Rescale Intercept: 0.00
0028,1053,Rescale Slope: 0.00392157
7FE0,0000,Pixel Data Group Length: 19850
7FE0,0010,Pixel Data: 19838
```

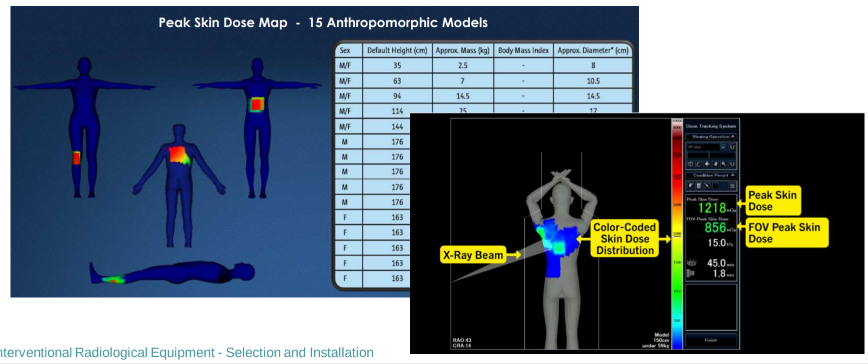

RDSR: Non-dosimetric and dosimetric information

- Patient info → ID, weight, height, age, gender, …
  - Anatomical part of interest
- For each exposure (pedal press):
  - C-arm Orientation
  - Geometry (angles, collimators,…)
  - Exposure parameters (kV, mAs, …)
  - KAP and cumulative air Kerma, no.images or fluoroscopy time
- Summary of all exposures:
  - No. series, no. images, total fluoro time, total KAP, total air kerma at the IRP

Recent developments: Real time tools for Skin dose mapping

- Data collected through the DICOM RDRS
- Different types of phantoms

- Commercially available (e.g: Radimetrics, Bayer; DoseWatch, GE)



3D : ConeBeamCT

- The increase of angiographic procedures each time more complex, made urgent the need of an accurate 3D characterization of the vessels and adjacent structures, so as to make it often necessary the execution of CT scans before and after the intervention. In some situations, however, there is the need to have at the same time fluoroscopic images and 3D:
  - Neurological applications (bleeding, stent placement)
  - Aortic aneurysms
  - Vertebroplasty
  - Chemoembolization, splenic embolization

3D : ConeBeamCT

Eur Radiol (2007) 17: 2767–2779
DOI 10.1007/s00330-007-0651-9

Flat-detector computed tomography (FD-CT)

Willi A. Kalender
Yiannis Kyriakou

foreseeable, however, that they will be replaced by FD-based C-arm CT systems (Fig. 1c), which offer higher dose efficiency, higher image quality and, to a good approximation, CT-like performance. In particular, they provide the possibility for assessing soft-tissue structures, as shown by the example in Fig. 1d.

3D : ConeBeamCT

- C-arms for angiography: → large differences from MSCT:
  - Smaller focus size
  - Power and high voltage lower
- AEC works in different mode: in CBCT system: the circuit AEC modifies the current level (not kV)

Table 1 Typical parameters for MSCT and FD-CT

	MSCT	FD-CT
Tube voltage	80–140 kV	50–125 kV
Tube current	10–600 mA	10–800 mA
X-ray power	20–100 kW	10–80 kW
Focal-spot size	0.6–1.2 mm	0.3–0.8 mm
Rotation time	0.33—1 s	5–20 s
Detector elements		
- in fan direction	512–1,024	512–2,490
- in z-direction	16–64	512–2,490
Field of measurement		
- in fan direction	500–700 mm	100–250 mm
- in z-direction	2–40 mm	100–200 mm
Min. slice thickness	0.6 mm	0.1–0.3 mm
Typ. scintillator/thickness	Gd_2O_2S/1.0–1.4 mm	CsI:(Tl)/0.4–0.8 mm
Data rate	≤1,000 MB/s	≤60 MB/s

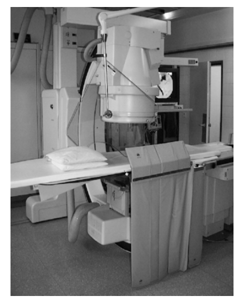
Accessories: staff protection tools

Not only Personal Protective Equipment (protective aprons, thyroid protector, glasses)

Also and very important:

- Ceiling suspended screen (0.5 mm Pb)
- Table suspended screen (0,5 mm lead)

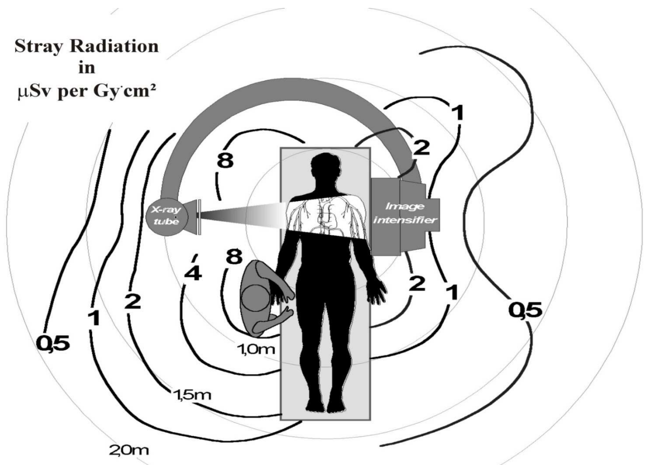
Equivalence Pb (mm)	Beam Quality		
	50 kVp	75 kVp	100 kVp
0.25	97	66	51
0.50	99.9	88	75
1.00	99.9	99	94



X-ray room design

- Room should be large enough to accommodate all of the equipment as well as radiologic and ancillary staff.
- Special procedures sometimes require a general anesthesia that necessitates extra equipment and staff.
- These procedures are also more hazardous to the patient and each room must be equipped to deal with emergencies that may occur.
- Room should be shielded to have outside doses below the dose limit for the public (for non controlled or supervised areas)

Staff safety: scatter radiation map



Dose maps provided in IR equipment manuals (IEC standards)

COLLEGE ON MEDICAL PHYSICS Applied Physics of Contemporary Medical Imaging - Expanding Utilization in Developing Countries ICTP

After installation: acceptance test and commissioning

- Definition: Commissioning is the process of assuring that all systems and components of a system are designed, installed, tested, operated, and maintained according to the operational requirements of the owner or final client.

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Clinical programme setup

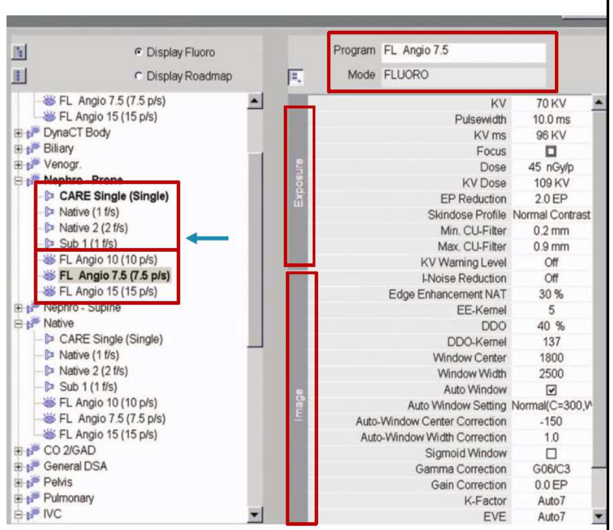
- Angiography systems have great flexibility
  - Same base system can be configured differently
- Program parameters can be select by the user to get image quality necessary for each clinical task (Optimisation: at the lowest possible patient dose)

- There are different levels of access
  - Operator
  - Service Technician and Applications

Clinical programme setup (example)

- Nephrostomy exam presets
  - BOLD means it's the start up mode for the system!
- Great detail of flexibility

- Similar parameter sets are programmed for all acquisition and fluoro on the system…



(Siemens interface)

Jones *et al* 2014 Medical imaging using ionizing radiation…Med Phys41, 014301

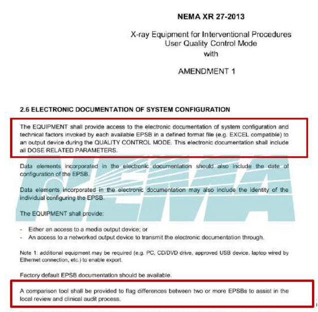
Clinical programme setup

- But, its possible to select from a large number of parameters
- It is impossible for the MP to ensure that these settings are appropriate or 'optimized'…

Clinical programme setup

- Standards to help optimisation and comparisons:
  - National Electrical Manufacturers Association (NEMA)
  - XR27 User Quality Control Mode for interventional procedures

- To have access to the technical factors of each protocol
  - To export settings to USB (Excel or .csv format)
  - Comparison tool provided to review, audit, optimize



NEMA XR 27-2013

X-ray Equipment for Interventional Procedures
User Quality Control Mode
with

AMENDMENT 1

2.6 ELECTRONIC DOCUMENTATION OF SYSTEM CONFIGURATION

The EQUIPMENT shall provide access to the electronic documentation of system configuration and technical factors invoked by each available EPSB in a defined format file (e.g. EXCEL compatible) to an output device during the QUALITY CONTROL MODE. This electronic documentation shall include all DOSE RELATED PARAMETERS.

Data elements incorporated in the electronic documentation should also include the date of configuration of the EPSB.

Data elements incorporated in the electronic documentation may also include the identity of the individual configuring the EPSB.

The EQUIPMENT shall provide:

- Either an access to a media output device; or
- An access to a networked output device to transmit the electronic documentation through.

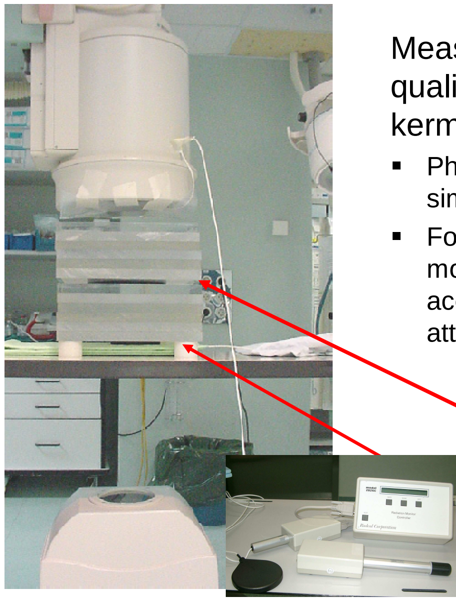
Note 1: additional equipment may be required (e.g. PC, CD/DVD drive, approved USB device, laptop wired by Ethernet connection, etc.) to enable export.

Factory default EPSB documentation should be available.

A comparison tool shall be provided to flag differences between two or more EPSBs to assist in the local review and clinical audit process.

Note 2: the comparison tool can be external to the EQUIPMENT and not be classified as a medical device.

Commissioning: image quality & dose



Measure of phantom image quality and entrance surface air kerma rate (ESAK rate):

- Phantom (PMMA or water) to simulate clinical conditions
- For a selected imaging mode, AEC modulates technical factors according to geometry and attenuation

Test object to measure image quality, at the isocenter

Flat ionisation chamber to measure phantom entrance surface air kerma rate (K_e)

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Interventional Radiological Equipment - Selection and Installation

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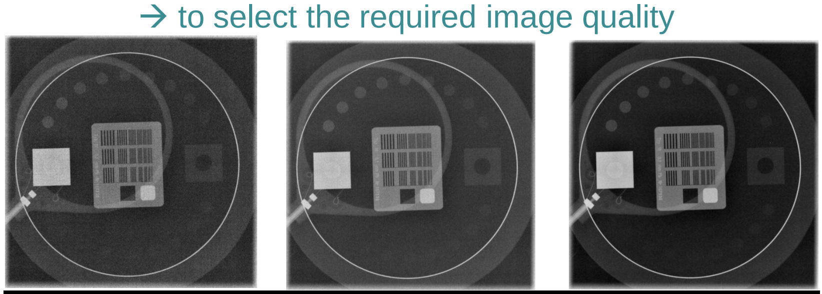
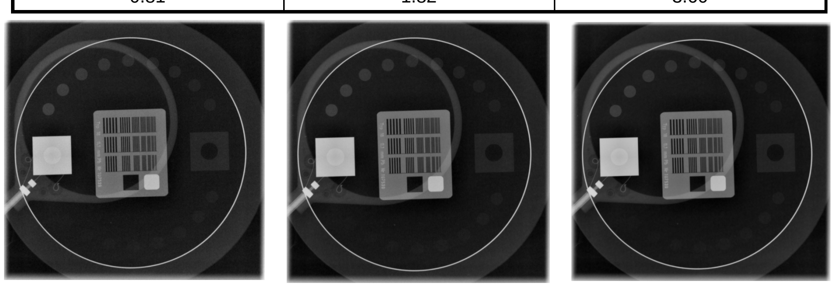
Image quality vs. detector air kerma/image (0.1 – 3.6 µGy/image) → to select the required image quality

(example: fluorography mode)



0.10 µGy/image *	0.20	0.36
0.81	1.82	3.60



(*) incident air kerma at the entrance of the imaging detector (without anti-scatter grid) – IEC

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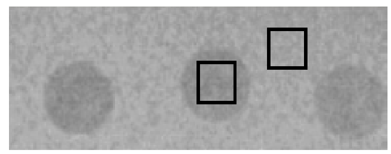
Image quality: Contrast to Noise Ratio (CNR)

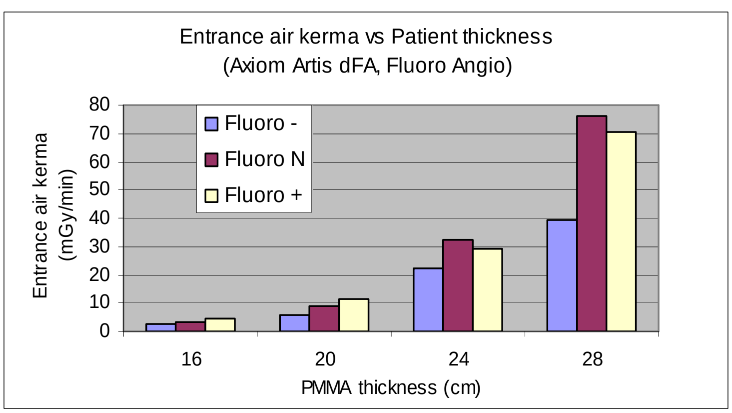
- With a stored digital image an objective quantitative evaluation can be assessed
- Example of CNR measurement using a contrast-detail image phantom)



$$CNR = \frac{PV_{BKG} - PV_{D}}{SD_{BKG}}$$

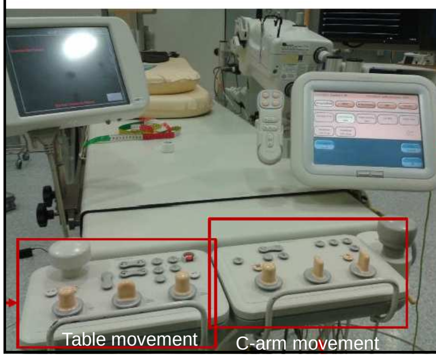
Commissioning:
Entrance air kerma rates vs. patient thickness

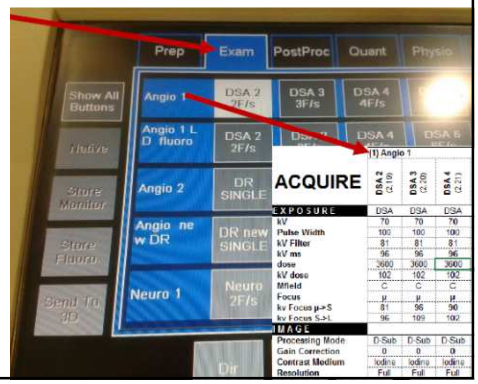
- This information should be made available for <u>each imaging mode and protocol</u>



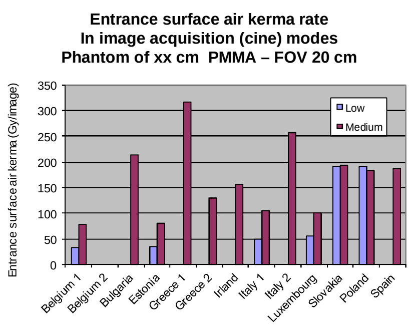
Commissioning: clinical protocols

- The optimised protocols for the defined clinical protocols will be available at the equipment console and at the patient table





Optimisation: Angiographic equipment setup



Large variability in equipment set-up and performances:

-dose rates:

- cine low: ratio max/min 4
- cine normal : ratio max/min 4

SENTINEL European survey (2007)

Optimisation → Equipment should be setup (air kerma/image at the entrance of the imaging detector, processing parameters, etc.) to provide the necessary image quality for the different imaging modes and clinical tasks

Team: radiologist, technologist, medical physicist and manufacturer

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Summary

- Interventional radiology systems are very flexible
- Make sure you are requesting the system answering to the clinical needs
- The commissioning stage is crucial for this, as well as for setting baselines for QC tracking
- QC: You cannot test every program –make sure you are testing the relevant programs
- Get to know the system, what the buttons do, how they are organized
- 12 monthly QC alone is not sufficient – we need more frequent QC'
- Patient dose monitoring (dose archives) is very important (mainly) for complex and long procedures (high dose)