AAPM Annual Meeting 2006

Abstract ID: 26-5971-9361

Digital Fluoroscopic Imaging: Acquisition, Processing and Display

Barry Belanger, PhD

Disclosure: GE Healthcare Employee

Outline

X-Ray Clinical Imaging Applications: Variety & Key Considerations

Performance Metrics for Clinical Imaging

Modern X-Ray Imaging System Design:
- Acquisition, Processing and Display

Key Points to Consider in the Purchasing Process

Implementing Quality Assurance & Pitfalls to Avoid

Fluoro X-ray Systems under discussion

Cardiovascular: **R&F "fluoro"**

X-Ray Clinical Imaging Applications: Variety & Key Considerations:

<u>Anatomy/object of interest</u>: radiographic attenuation, size, motion:
- Bone: spine: vertebroplasty, needle placement
- GI tract with barium contrast
- Blood vessel or Heart chamber with iodine contrast
- Guidewire, catheter, stent

- <u>Background anatomy</u>: attenuation variations, motion
  - Thorax: large attenuation variations, rapid cardiac motion
  - Abdomen: more uniform attenuation, less motion
  - Cranium: large attenuation variations, little motion

- <u>Attenuation range</u>: from pediatric to obese adult.
  - AP thorax: 6cm (ped) to 32cm (large adult) and growing, equivalent to ~9HVLs of ~3cm, ~500:1 difference in attenuation.
  - LAT thorax presents greater range and challenge

Range of Needs and Conditions is huge:
>> Need for Flexibility, Automation, Preset Protocols

Performance Metrics for Clinical Imaging:

- **Imaging Dose Efficiency:**
  - X-Ray Source Efficiency
  - Image Detector Efficiency
- **Dynamic Range**
- **Temporal Response**
- **Image Artifacts**

A Comprehensive Set of Relevant IQ Measures

Performance Metrics: Clinical Image Quality & Dose

Optimization Problem Statement:

$$\frac{\text{Benefit}}{\text{Cost}} = \frac{\text{Clinical Objective}}{\text{Risk}} \cong \frac{\text{Clinical Image Quality}}{\text{Dose}} = \text{Imaging Dose Efficiency}$$

Objectives:

- Maximize Imaging Dose Efficiency: Best clinical image quality for any dose level clinician chooses to use, tailored to intended application.
- Provide range of Dose/IQ selections to operator to fit application needs and preferences of clinicians.
- Provide Dose Readout/Feedback: clinician awareness for decision making.
- Automate the process as much as possible.

Caveat:

- Dose = Dose Rate x Time, alternately Dose/Exposure x Number of Exposures.
- ➢ Need to consider impact of Image Quality on fluoro time, number of exposures required to achieve clinical goals

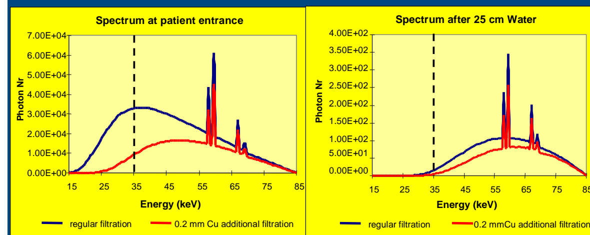
Consistent with ALARA (As Low As Reasonably Achievable) Dose Principle

Performance Metrics for Clinical Imaging:

Requirement	Clinical Benefits
X-Ray Source Efficiency: High continuous power capability, range of spectral filters	• High Dose Efficiency • High fluoro penetration capability for large patients
Image Detector Efficiency (DQE): High X-Ray Conversion Efficiency, Low Readout Noise	• High Image Quality: Object detectability • High Dose Efficiency
Wide Dynamic Range: High min/max signal range from image detector plus specialized image processing to present information effectively on display.	• Visualize contrast differences from thin to dense anatomy. • No Blooming in thin anatomy: robust, forgiving to difficulties with positioning, collimation, contour filters, etc.
Temporal Response: Fast Readout, low lag, range of frame rates & exposure times	• High definition of moving objects • Good rendering of dynamic events

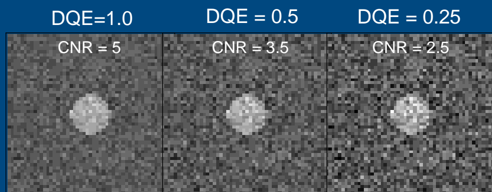
A Comprehensive Set of Relevant IQ & Dose Efficiency Measures

Performance Metrics: XRT: Spectral Filtration



- Softer radiation does not contribute significantly to image
- Spectral filtration eliminates this radiation before it reaches the patient
- Requires higher XRT power to be effective

Performance Metrics: Detector: Importance of DQE



Options enabled by higher DQE:
- Better Image, Same Dose
- Same Image, Lower Dose

DQE (Detective Quantum Efficiency) is judged the best index of object detectability in contrast & dose-limited imaging, as in real clinical imaging.

Performance Metrics: Temporal Response: Value

Pediatric Imaging Protocol

4 msec max pulse width

30 Frames/Sec

Modern X-Ray Imaging System Design

- XRT/Source Assembly
- Image Detector
- Automatic Exposure Control
- Imaging modes: fluoro, dynamic record, Digital Spot, DSA, Rotational/3D
- Image processing & Display
- Procedure Protocol Driven Customization and Control

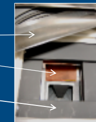
X-Ray Source Assembly: X-Ray Tube & Collimator

X-Ray Tube:

- 3200 Watt continuous fluoro capability
- Metal envelope for reduced off focus radiation
- **0.3**, **0.6**, **1.0** Focal Spot (0.3 for DSA)

Collimator with variable Spectral Filtration:

- Contour Filters
- 0.1, 0.2, 0.3, 0.6 & 0.9mm Copper filters
- Rectangular Blades



Detectors: Image Intensifier/TV >> Flat Panel

Image Intensifier Chain

Image Intensifier | Optical Iris | Camera | Analog Processing & A/D

Digital Flat Panel Detector

DFP Benefits:

"Birthright"

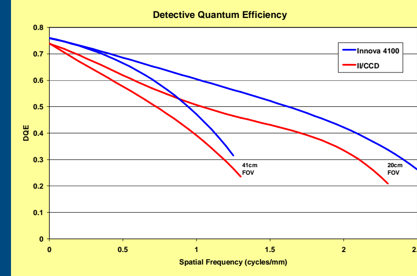
- **Brightness & MTF Uniformity Across Entire Image**
- ***No* Veiling Glare**
- ***No* Geometric Distortion**
- ***No* Earth Field Distortion**

Design-Dependent:

- **5-10x Improvement in Dynamic Range: depends on imaging mode and DFP & Electronics Design**
- **Radiographic DQE: Typically better**
- **Fluoro DQE: Depends on Detector & Electronics Design**

Detector DQE: Flat Panel vs II/CCD

- **200u Pixel 40x40cm Flat Panel**
- **State of the Art 40cm Image Intensifier + 1k x 1k CCD**



40cm Flat Panel has Significant Advantage in DQE

Detector: DFP: Binning in Larger FOVs

Native 200 x 200 micron photodiodes

Summed 400 x 400 micron pixel (in blue)

Binning Principle:

- Scan Adjacent Lines in Pairs → Scan
- Digitally add adjacent columns in pairs

Performance Implications:

- 4X signal/pixel: better SNR
- Limiting Spatial Resolution 1.25 instead of 2.5 lp/mm (comparable to II/Video)
- Good DQE at lower doses used in LFOV imaging, exceeding II/Video chain
- Reduced image processing, storage and display requirements.

amp amp amp amp

A/D A/D A/D A/D

\+ \+

Binning Enables LFOV Imaging at Required Rates

Detector DQE: X-Ray Detector/Imaging Chain

To understand how well an image chain works we must consider:

- **The DQE curve of the image chain**
- **The spatial frequency content of the object being imaged**

Innova 2100 Fluoro DQE @ 1 uR/Fr

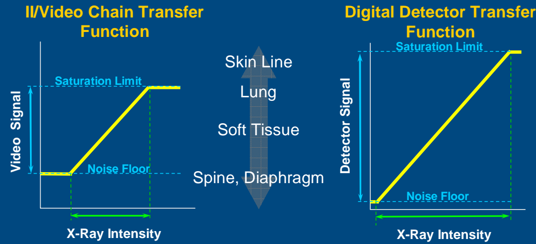
DQE(f) at ***fluoro level*** radiation exposure of 8 nGy/Fr (1 uR/Fr)

Spatial frequency content of a stent.

Note that there is progressively less signal at higher frequencies, particularly beyond 2 lp/mm.

- The spectrum of the stent extends over a wide range of spatial frequencies.
- Therefore, the DQE response over this same range of spatial frequencies is important to determining the quality of the image.
- Response at a single spatial frequency, e.g., spatial resolution limit, doesn't tell the story.

Detector Dynamic Range: DFP Versus II/TV



- DFP Provides 5-10x Improvement in Dynamic Range of Captured X-ray Information.
- Display Dynamic Range Must Be Addressed Independently (later in this presentation)
- Higher Dynamic Range Can Reduce Retake Rates (no burnout/blackout) and is More Forgiving to Errors, Hence it is Dose Conservative

Modern X-Ray Imaging System Design

- XRT/Source Assembly
- Image Detector
- Automatic Exposure Control
- Imaging modes: fluoro, dynamic record, Digital Spot, DSA, Rotational/3D
- Image processing & Display
- Procedure Protocol Driven Customization and Control

Automatic Exposure Control Systems

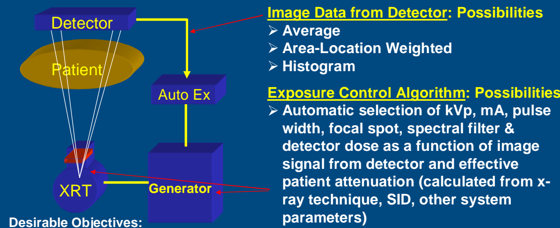


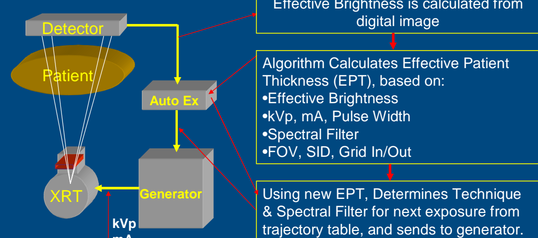
Image Data from Detector: Possibilities
- Average
- Area-Location Weighted
- Histogram

Exposure Control Algorithm: Possibilities
- Automatic selection of kVp, mA, pulse width, focal spot, spectral filter & detector dose as a function of image signal from detector and effective patient attenuation (calculated from x-ray technique, SID, other system parameters)

Desirable Objectives:
- Maximize Imaging Dose Efficiency: Best clinical image quality for any dose level clinician chooses to use, tailored to intended application, capitalizing on component characteristics.
- Provide range of Dose/IQ selections to operator to fit application needs and preferences of clinicians.
- Provide Dose Readout/Feedback: clinician awareness for decision making.
- Automate the process as much as possible.

Exposure	Skin Dose	DAP
On	Rate	Total
Off	Total	Total

Automatic Exposure Control Systems: "Trajectory" Table-Based



Effective Brightness is calculated from digital image

Algorithm Calculates Effective Patient Thickness (EPT), based on:
- Effective Brightness
- kVp, mA, Pulse Width
- Spectral Filter
- FOV, SID, Grid In/Out

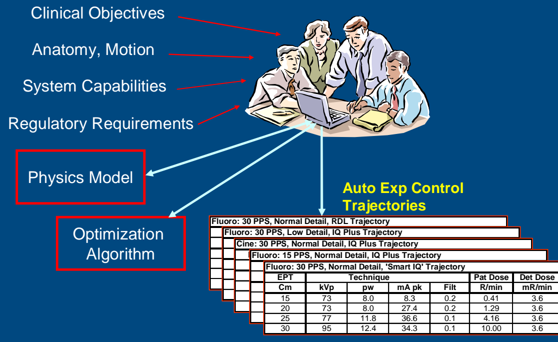
Using new EPT, Determines Technique & Spectral Filter for next exposure from trajectory table, and sends to generator.

Fluoro: 30 PPS, Normal Detail, 'Smart IQ' Trajectory

EPT	Technique				Pat Dose	Det Dose
Cm	kVp	pw	mA pk	Filt	R/min	mR/min
15	73	8.0	8.3	0.2	0.41	3.6
20	73	8.0	27.4	0.2	1.29	3.6
25	77	11.8	36.6	0.1	4.16	3.6
30	95	12.4	34.3	0.1	10.00	3.6

Benefits: Flexibility, Optimization, Upgradeability

Automatic Exposure Control Systems: "Trajectory" Table-Based: Trajectory Design Process



Fluoro: 30 PPS, Normal Detail, 'Smart IQ' Trajectory

EPT	Technique				Pat Dose	Det Dose
Cm	kVp	pw	mA pk	Filt	R/min	mR/min
15	73	8.0	8.3	0.2	0.41	3.6
20	73	8.0	27.4	0.2	1.29	3.6
25	77	11.8	36.6	0.1	4.16	3.6
30	95	12.4	34.3	0.1	10.00	3.6

Automatic Exposure Control Systems: "Trajectory" Table-Based: Typical Optimization Criteria

Object Contrast: Difference in x-ray intensity due to the presence of the stent or other device, iodine in artery, barium in colon, etc.

Background Noise: Normal statistical variation in background intensity due to finite number of x-rays used to image

$$\text{Image Quality} = \frac{\textbf{Contrast} \text{ (more is better)}}{\textbf{Noise} \text{ (less is better)}} = \text{CNR}$$

Cost = Patient Skin Dose

Design Strategy: One of several possibilities:

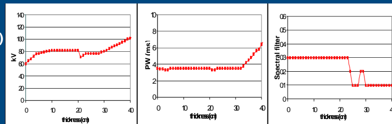
- **Maintain near-constant CNR over range of patient thickness (within limits)**
  - **Significant dose savings on small patients & shallow angles**
- **Provide several levels of CNR (and therefore dose) to Operator:**
  - **Operator chooses level of IQ required for procedure: via protocols, tableside control, initial system setup (trajectory family)**
- **Minimize patient dose required to achieve selected CNR by optimizing x-ray technique and filtration.**
- **Pediatric: Limit Pulse width to 4 mSec max in fluoro and digital cardiac record**

Consistent with ALARA (As Low As Reasonably Achievable) Dose Principle

Automatic Exposure Control Systems: "Trajectory" Table-Based: Sample Trajectories for One Operating Mode of Pediatric Angiography

Independent control of:

- **kVp**
- **mA**
- **Pulse Width (primary & Grid)**
- **Spectral Filter**
- **Focal Spot**
  - **Within limits of:**
  - **XR Tube: filament, power, etc.**
  - **Generator: Power, control ranges**
  - **Regulations**



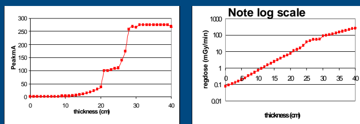
kVp (upper left), Pulse Width (upper middle), Spectral Filter thickness (upper right), mA (lower left) and patient entrance dose as a function of EPT in cm of PMMA for one fluoro AutoEx trajectory.

Patient Thickness Control Range:

- **From 0 cm (bare table) to >40cm of PMMA effective patient thickness (EPT)**

Target Values:

- **kVp: 60-80 kVp for Iodine imaging**
- **Pulse Width: 4 mSec max for peds**



Automatic Exposure Control: "Trajectory" Table-Based: Trajectory "Family" Options Example

Typical Dose Levels: Fluoro (mGy/min), Cardiac & Innova Chase (µGy/fr) and DSA (mGy/fr)

Lower Dose ↓

	Fluoro 30fps	Cardiac	Dyn 5 fps	DSA
Mode Selection 1	Normal : 21.8 Low : 9.4	Normal : 91.2 Low : 32.4	Normal : 293 Low : 146	Normal : 2.0 Low : 1.0
Mode Selection 2	Normal : 25.2 Low : 10.4	Normal : 91.2 Low : 35.2	Normal : 293 Low : 146	Normal : 2.0 Low : 1.0
Mode Selection 3	Normal : 14.9 Low : 5.7	Normal : 91.2 Low : 32.4	Normal : 293 Low : 146	Normal : 2.0 Low : 1.0
Mode Selection 4	Normal : 18.7 Low : 7.7	Normal : 32.4 Low : 14.3	Normal : 293 Low : 146	Normal : 1.0 Low : 0.5
Mode Selection 5	Normal : 9.7 Low : 4.0	Normal : 32.4 Low : 14.3	Normal : 293 Low : 146	Normal : 1.0 Low : 0.5

Test conditions:

- Patient Entrance Dose
- 20 cm FOV
- 20 cm PMMA phantom
- Reference: Operator Manual

- Fluoro Levels : 5:1 range in dose rate, @ 30 fps: (20:1 with 15 and 7.5 fps)
- Mode 2 and Mode 5 Trajectories have 5R/min limit in Fluoro Low Mode.
- Cardiac Record Levels : 6:1 range in dose/frame
- Dynamic 5 fps: 2:1 range in dose/frame
- DSA: 4:1 range in dose/frame

Automatic Exposure Control: Options for Dose Change with Frame Rate

Two Options Seen on Current Systems:

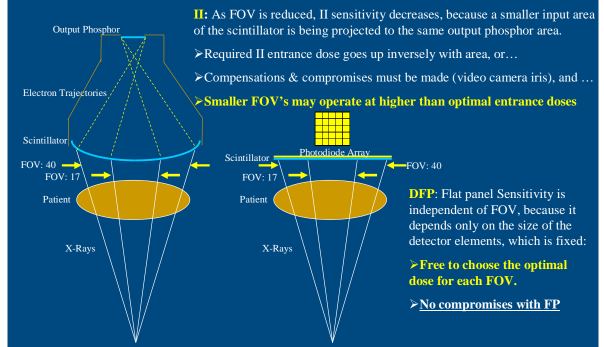
1. Balanced Dose/IQ : Follows "Aufrichtig" or "Square Root" Scale: Maintains static object detectability.
2. Minimize Dose: Dose rate drops directly with fluoro frame rate.

Frame Rate	Balanced Dose/IQ	Minimize Dose	Balanced Dose/IQ	Minimize Dose
30	100%	100%	10.4	10.4
15.0	75%	50%	7.8	5.2
7.5	50%	25%	5.2	2.6

Data for GE Innova 2100 in mGy/min

Best choice may depend upon application and user:
- Select lowest frame rate tolerated by user for application
- Select lowest usable dose at selected frame rate

Automatic Exposure Control: Options for Dose Change with Field of View: DFP vs II

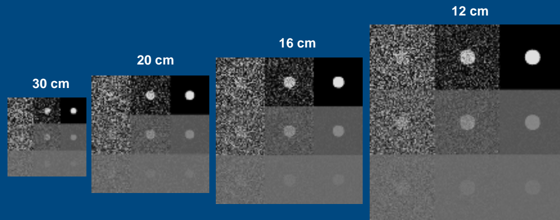


II: As FOV is reduced, II sensitivity decreases, because a smaller input area of the scintillator is being projected to the same output phosphor area.
- Required II entrance dose goes up inversely with area, or…
- Compensations & compromises must be made (video camera iris), and …
- **Smaller FOV's may operate at higher than optimal entrance doses**

DFP: Flat panel Sensitivity is independent of FOV, because it depends only on the size of the detector elements, which is fixed:
- **Free to choose the optimal dose for each FOV.**
- **No compromises with FP**

Automatic Exposure Control: Options for Dose Change with Field of View

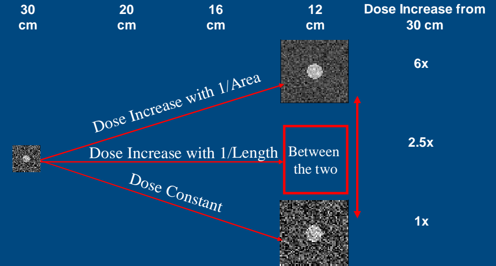
Illustration of FOV Change without Dose Change



How much does IQ improve with magnification alone?

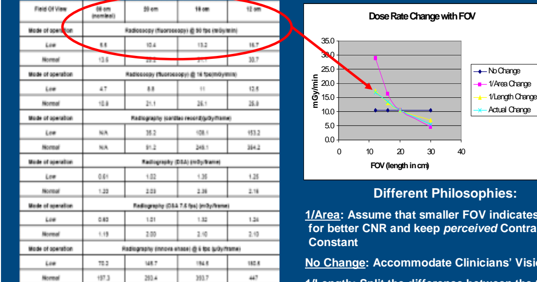
Automatic Exposure Control: Options for Dose Change with Field of View

Illustration of FOV Change with Dose Change

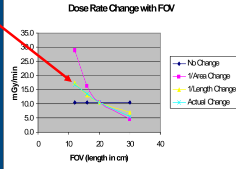


How much does IQ improve with magnification + dose?

Automatic Exposure Control: Options for Dose Change with Field of View



Field Of View	[illegible] cm (nominal)	20 cm	16 cm	12 cm
Mode of operation	Radioscopy (fluoroscopy) @ 30 fps (mGy/min)			
Low	5.5	10.4	15.2	16.7
Normal	13.6	[illegible]	[illegible]	30.7
Mode of operation	Radioscopy (fluoroscopy) @ 15 fps(mGy/min)			
Low	4.7	8.8	11	12.5
Normal	10.8	21.1	26.1	25.8
Mode of operation	Radiography (cardiac record)(µGy/frame)			
Low	N/A	35.2	108.1	153.2
Normal	N/A	91.2	249.1	394.2
Mode of operation	Radiography (DSA) (mGy/frame)			
Low	0.61	1.02	1.35	1.25
Normal	1.23	2.03	2.36	2.16
Mode of operation	Radiography (DSA 7.5 fps) (mGy/frame)			
Low	0.83	1.01	1.32	1.24
Normal	1.19	2.00	2.10	2.10
Mode of operation	Radiography (innova chase) @ 6 fps (µGy/frame)			
Low	73.2	148.7	194.8	180.6
Normal	197.3	293.4	393.7	447



Different Philosophies:

1/Area: Assume that smaller FOV indicates need for better CNR and keep *perceived* Contrast/Noise Constant

No Change: Accommodate Clinicians' Vision Only

1/Length: Split the difference between the two above

GE Philosophy is Close to 1/Length.

Most manufacturers change less than 1/Area with FOV

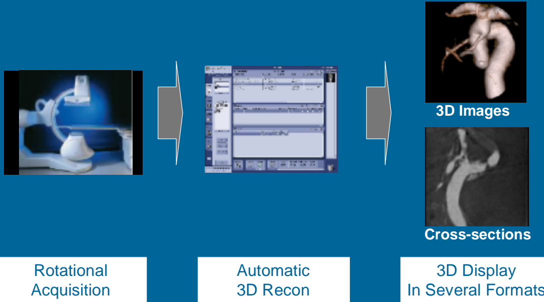
Modern X-Ray Imaging System Design

- XRT/Source Assembly
- Image Detector
- Automatic Exposure Control
- Imaging modes: Fluoro, Dynamic Record, Digital Spot, DSA, Subtracted Bolus Chase, Rotational Angio/3D/CT
- Image processing & Display
- Procedure Protocol Driven Customization and Control

AAPM 2006: Digital Fluoroscopic Imaging: Acquisition, Processing and Display. Abstract ID: 26-5971-9361. Belanger

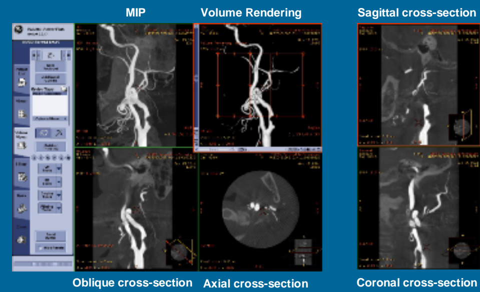
Rotational Angio/3D/CT on Flat Panel Angiography Systems

Vascular, bone and soft tissue 3D imaging in the intervention suite



AAPM 2006: Digital Fluoroscopic Imaging: Acquisition, Processing and Display. Abstract ID: 26-5971-9361. Belanger

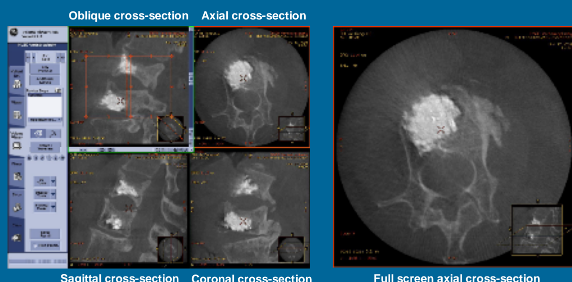
Rotational Angio/3D/CT on Flat Panel Angiography Systems



Both 3D views and cross-sections Can be automatically created at 3D volume loading

AAPM 2006: Digital Fluoroscopic Imaging: Acquisition, Processing and Display. Abstract ID: 26-5971-9361. Belanger

Rotational Angio/3D/CT on Flat Panel Angiography Systems



Both 3D views and cross-sections
Can be automatically created at 3D volume loading

Rotational Angio/3D/CT on Flat Panel Angiography Systems

Acquisition and Reconstruction Protocols

"Classical"

- ~5 second acquisition
- One or two spins (for subtracted)
- ~200° at 35-40°/s
- ~150 frames
- 3D recon in 256^3 and/or 512^3
- Display: MIP, VR, MPVR, etc.

Vascular, bone and soft-tissue 3D imaging

"CT" Mode

- ~5, 10 & 20 second acquisition
- One single non-subtracted spin
- ~200° at ~40, 20 and 10°/s
- ~150, 300 or 600 frames
- 3D recon in 256^3 or 512^3
- Display: MPVR (+ MIP, VR, etc.)

Increased contrast senstivity for bone and soft-tissue imaging

Evolution toward better "CT" Capabilities:

- Longer effective exposure times than CT in some cases
- Higher spatial resolution *capability* than CT
- Low contrast sensitivity less than CT

Rotational Angio/3D/CT on Flat Panel Angiography Systems

Typical Reconstruction Algorithm Elements and Attributes:

- Full cone-beam tomographic reconstruction
- Based on Feldkamp algorithm
- Compensation/calibration for "Open Gantry" *dynamic mechanical behavior*
- Processing of *truncated* views
- Beam hardening correction
- Ring artefacts removal
- Parallel implementation
- Reconstruction time depends primarily on matrix, e.g., 256^3, 512^3.

Your CT knowledge should be transferrable!

Modern X-Ray Imaging System Design

- XRT/Source Assembly
- Image Detector
- Automatic Exposure Control
- Imaging modes: fluoro, dynamic record, Digital Spot, DSA, Rotational/3D
- Image processing & Display
- Procedure Protocol Driven Customization and Control

Image Processing: Dynamic Range Management

Classic Contrast/Latitude Tradeoff

Desired Behavior

Breaking the Contrast/Latitude Constraint

Image Processing: Dynamic Range Management

➢ ***Digital Spot Example: Simple Display LUT***

Digital detector dynamic range covers the entire range of exposure levels; more than can be displayed without processing!

Image Brightness
Soft Tissue
Lung, Skin Line
Spine, Diaphragm
X-ray Detected

…or a Bone Look

But one LUT can't do it all at once.

Image Processing: Dynamic Range Management

➢ ***Digital Spot Example: Multiresolution Processing***

Raw Input

Decompose
•Spatially filter

Transform
•Select Weights

A1
A2
...
An

Reconstruct
•Weighted Addition

Processed Image

Get all the desired information in one image

Image Processing: Dynamic Range Management

➢ **Realtime Processing in Peripheral Runoff Sequence**

Bolus Chase: Unsubtracted

- No contour/bolus filters used
- Manually pan table to follow contrast bolus.
- AutoEx automatically adjusts technique on the fly.
- DRM handles wide dynamic range of image data from detector

Wide Dynamic Range + DRM:

- More diagnostic info in one run
- Robust: fewer retakes?

Image Processing: Fluoro Noise Reduction

Advanced Fluoro Noise Reduction (FNR)

What is it?
- Temporal averaging of image data to reduce quantum noise (fluoro-only application)

What is advanced?
- Motion compensation is integrated into the algorithm: reduces lag effects in the presence of anatomical motion
- Level of filtering is matched to frame-rate

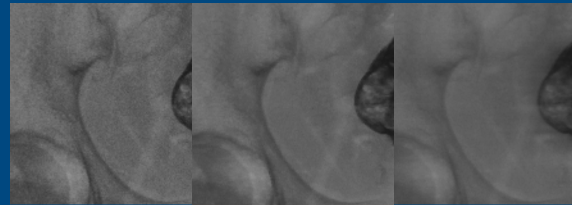
Results:
- Significant improvement in clincial image quality > opportunity to reduce dose.
- Sufficient noise reduction to allow (in certain cases) use of a last-image hold in lieu of acquiring a spot image

AAPM 2006: Digital Fluoroscopic Imaging: Acquisition, Processing and Display. Abstract ID: 26-5971-9361. Belanger

Image Processing: FNR Motion Compensation

Impact of Motion Compensation at 30 fps

none	*16 frame recursive averaging with motion compensation*	*16 frame recursive averaging no motion compensation*



Motion Compensation is a Clear Benefit

AAPM 2006: Digital Fluoroscopic Imaging: Acquisition, Processing and Display. Abstract ID: 26-5971-9361. Belanger

Modern X-Ray Imaging System Design

- XRT/Source Assembly
- Image Detector
- Automatic Exposure Control
- Imaging modes: fluoro, dynamic record, Digital Spot, DSA, Rotational/3D
- Image processing & Display
- Procedure Protocol Driven Customization and Control

AAPM 2006: Digital Fluoroscopic Imaging: Acquisition, Processing and Display. Abstract ID: 26-5971-9361. Belanger

Procedure Protocol-Driven Customization and Control

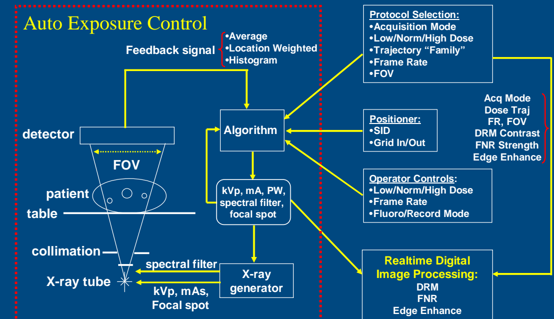


Image Processing Can Use Protocol & Exposure Information for Optimization:
➢Beware of Interactions when Testing

AAPM 2006: Digital Fluoroscopic Imaging: Acquisition, Processing and Display. Abstract ID: 26-5971-9361. Belanger

Procedure Protocol-Driven Customization and Control

➢System Features for Dose Reduction

Pre-defined Procedure Protocols (fit dose & technique to procedure)

Automatic Spectral Filters

Pulsed, Variable Frame Rate Fluoro (linked to Procedure Protocols)

Virtual Collimation, Virtual Panning

Adjustable Contour (Wedge) Filters in Collimator

Last Image Hold

Fluoro Loop Replay & Store (with DICOM & DVD Record)

Auto or Manual Grid removal

Patient Contouring (Automatic Minimization of patient-detector distance)

Dose reporting

The More Automatic/Programmable, the Better

Key Points to Consider in the Purchasing Process

- Applications breadth required by clinical department, both today and looking out ~5 years.
- Procedure/protocol capability/flexibility/performance provided by equipment
- Imaging/Dose performance provided by equipment

Implementing Quality Assurance & Pitfalls to Avoid

- Prioritize by key clinical procedural needs.
- Work with Supplier's Field Service Engineer ***and*** Applications Specialists through installation and customer training to fully understand capabilities and optimize to clinical needs and preferences.
- Perform full verification test set at installation
  - Consider "standardized" procedures:
    - Manufacturer's
    - IEC 61223-3-1
    - SCA&I?/NEMA XR-21 (Cardiac)
- Perform key functional & performance checks at periodic intervals.

Thank You!