Display processing is used to transform digital radiography data to display values for presentation using a workstation or film printer.

(A) Subject contrast (B) is recorded by the detector (C) and transformed to display values (D) that are sent to a display device (E) for presentation to the human visual system.

- Introduction (4)
  1. Preprocessing (12)
  2. Generic Image Processing (2)
     A. Grayscale rendition (10) 
     B. Exposure recognition (7)
     C. Edge restoration (20)
     D. Noise reduction (10)
     E. Contrast enhancement (14)
  3. Commercial Implementations (23)

1. Understand how recorded signals are conditioned to produce image data for processing.
2. Understand the approaches used to improve the visibility of structures in radiological images.
3. Survey current commercial implementations and distinguish essential similarities / differences.
The presenter is a designated principal investigator on research agreements between Henry Ford Health System and the following companies (alphabetical):

* Agfa Medical Systems
* Brown & Herbranson Imaging
* Eastman Kodak Company
* Shimadzu Medical Systems
* Roche Pharmaceuticals
* Gammex-RMI
* Vidar Systems Corp.

The presenter has provided consulting services over the last 12 months with the following companies (alphabetical):

* Advanced AIRS
* Vidar Systems Corp.

* Drilled DR image processing

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1. Course Outline

1. Preprocessing
2. Generic Image Processing
3. Commercial Implementations

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For CR and DR systems, radiation energy deposited in the detector is converted to electrical charge. Preamplifier circuits then convert this to a voltage which is digitized using analog to voltage converter (ADC) to produce RAW image values.
RAW data from the detector is pre-processed to produce an image suitable for processing.

- Bad pixels
  - Pixels with high or low values or with excessive noise
  - Values corrected by interpolation from neighbors
  - There are presently no requirements to report bad pixel statistics as a part of DR system purchase.

- New bad pixels can develop in DR panels that are in service.
- Frequent gain calibration can help detect newly developed problems.
- The defects shown to the right were reported by the radiologist interpreting the study.

- Dark image
  - The signal recorded when no x-rays are incident on the detector is referred to as the dark image or offset image.
  - Most detectors produce a signal that linearly increases from the offset value of each pixel as x-ray incident exposure is increased.
  - Dark image values are susceptible to drift and often have high thermal dependence.
The linear gain may slightly differ from pixel to pixel. These variations produce fixed pattern noise.

**Uniform radiation exposure**

**Dark Image** ($I_D$) obtained by averaging many images obtained with no x-ray input to the detector.

**Gain Image** ($I_G$) obtained by averaging many images obtained with a uniform x-ray fluence.

Uniformity correction is performed subtracting the dark offset and adjusting for gain differences.

$$I_{COR} = (I_{RAW} - I_D) (k/ (I_G - I_D))$$

Log transformation using a Log look-up table allows this to be performed with a subtraction.

$$I_{COR} = \log(I_{RAW} - I_D) - \log(I_G - I_D) - K$$

The recorded signal recorded is approximately proportional to the exponent of the attenuation coefficient line integral:

$$I(x,y) = I_o \exp(-P(x,y))$$

The log of the recorded signal is proportional to the line integral.

$$\ln(I(x,y)) = -P(x,y) - \ln(I_o)$$

Small perturbations cause the same image value change whether in high or low transmission regions.

For $I_o$ values stored as a 12 bit number (0 - 4095), a convenient format has a change of 1000 for every factor of 10 change in exposure.

$$I_{COR} = 1000 \log_{10}(mR) + 2000$$
One major manufacturer uses internal I_{FP} values that are proportional to the square root of exposure.

The relative noise of the I_{FP} values is constant for all incident exposures, however the tissue contrast is not.

\[ I_{FP} = 1250 \text{ mR}^{1/2} \]

For this system, this structure is used only for data stored in a multi-scale Agfa format used by Agfa products. Data exported using DICOM exchange (for processing) can be sent in a log exposure format.

Normalized For Processing Pixel Values (INFP)

"For-processing pixel values, I_{FP}, that have been converted to have a specific relation to a standardized radiation exposure (E_{STD}), ..."

\[ I_{INFP} = 1000 \log_{10} \left( \frac{E_{STD}}{E_0} \right), \quad E_{STD} \text{ in micro-Gray units, } E_0 = 0.001 \text{ micro-Gray}, \]

### Course Outline

1. Preprocessing
2. Generic Image Processing
3. Commercial Implementations
Grayscale Rendition:
- Convert signal values to display values
- Exposure Recognition: Adjust for high/low average exposure
- Edge Restoration: Sharpen edges while limiting noise
- Noise Reduction: Reduce noise and maintain sharpness
- Contrast Enhancement: Increase contrast for local detail

Exposure Recognition
Spatial Processes
Edge Restoration
Noise Reduction
Contrast Enhance
Grayscale (VOI-LUT)

Grayscale LUTs
For Processing data values are transformed to presentation values using a grayscale Look Up Table.

Grayscale Value of Interest (VOI) Look Up Table (LUT) transforms For Processing values to For Presentation Values.
- Monitors and printers are DICOM calibrated to display presentation values with equivalent contrast.
- The VOI-LUT optimizes the display for radiographs of specific body parts.

The VOI-LUT may be applied by the modality, or sent to an archive and applied by a viewing station.
- When the transformation is linear, the VOI LUT is described by the Window Center (0028,1050) and Window Width (0028,1051).
- When the transformation is non-linear, the VOI LUT is described by VOI LUT Sequence (0028,3010).
When communicating images to a PACS systems, it can be beneficial to send the VOI-LUT sequence for application at display. PACS workstations should be capable of translating or stretching the VOI-LUT to make contrast and brightness changes.

Presently, many systems send images to a PACS system as scaled P values with the VOI-LUT already applied to the processed data. PACS workstations cannot adjust the VOI-LUT to demonstrate contrast in over or under penetrated regions.

The applied VOI-LUT produces good contrast for the primary tissues of interest. For the full range of P values, contrast is limited in the toe and shoulder regions.
Shifting the Window Level (WL) to inspect highly penetrated regions renders gray levels with a poorly shaped portion of the VOI LUT.

The ability to shifting the VOI-LUT at the display workstation permits regions of secondary interest to be viewed with good radiographic contrast.

Signal Range:
A signal range of up to 10^4 can be recorded by digital radiography systems. Unusually high or low exposures can thus be recorded. However, display of the full range of data presents the information with very poor contrast. It is necessary to determine the values of interest for the acquired signal data.
Exposure Recognition:

All digital radiographic systems have an exposure recognition process to determine the range and the average exposure to the detector in anatomic regions. A combination of edge detection, noise pattern analysis, and histogram analysis may be used to identify Values of Interest (VOI).

VOI LUT Level and Width:

The values of interest obtained from exposure recognition processes are used to set the level and width of the VOI LUT. Areas outside of the collimated field may be masked to prevent bright light from adversely affecting visual adaptation.

Tissue region

Advanced image segmentation algorithms are used in some systems to identify the region where tissue attenuation has occurred. This provides information on the values of interest for presentation.

DR systems report a metric indicating the detector response to the incident radiation exposure.

- The methods used to deduce this metric are all different:
  - The regions from which exposure is measured vary.
  - Reported exposure may increase proportionally to the log of exposure or may vary inversely with exposure.
  - The scale of units varies widely with factor of 2 changes in exposure associated with changes varying from 0.15 to 300.

- Fuji: \( S = \frac{200}{E_{\text{in}}} \) 80 kVp, unfiltered
- Agfa: \( \log(M) = 2.22 + \log(E_{\text{in}}) + \log(S/200) \) 75 kVp, 1.5 Cu (mm)
- Kodak: \( EI = 1000 \log(E_{\text{in}}) + 2000 \) 80 kVp, 0.5 Cu 1.0 Al
**Indicated Equivalent Air Kerma (K_{IND})** [IEC, Exposure Index]

- An indicator of the quantity of radiation that was incident on regions of the detector for each exposure made.
- The region may be defined in different ways.
- The value should be reported in units of microgray.

**Relative Exposure (E_{REL})**

- An indicator as to whether the detector response for a specific image, K_{IND}, agrees with K_{IND}(b,v).
- Relative exposures are to be reported as:
  \[ E_{REL} = \log_{10} \left( \frac{K_{IND}(b,v)}{K_{IND}^{\text{ref}}(b,v)} \right) \]
- \( E_{REL} \) is intended as an indicator for radiographers and radiologists as to whether the technique used to acquire a radiograph was correct.

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**MTF**

Radiographs with high contrast details input high spatial frequencies to the detector.

- For many systems, the detector will blur this detail as indicated by the MTF.
- Enhancing these frequencies can help restore image detail.
- However, at sufficiently high frequencies, there is little signal left and the quantum mottle (noise) is amplified.
- The frequency where noise exceeds signal is different for different body parts/views.

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**Lateral Knee View**

- Lateral knee view with equalization but no edge restoration as indicated by the filter strength.
Edge restoration applied using a filter equal to 1/MTF with slight noise reduction at frequencies above 0.7 of the maximum.

Exposure of 100 speed film.
High DQE iDR systems can restore edges without producing excessive noise.

- **Edge restoration:** Lung tissue typically produces low frequency signals and the chest radiograph has high quantum noise. Thus, very modest edge restoration should be used.
- **Quantum mottle in the abdomen:** Low exposure and thick tissue result in significant quantum mottle below the diaphragm. Inverse MTF filters need to be damped at high frequency to prevent excessive noise (Wertz filter).

**Skeletal Processing**
- Edge restoration may be extended to high frequencies particularly if high resolution screens are used. Noise is generally not problematic for extremely clear.
- Restoration versus enhancement: U'W'TT edge processing as shown restores object detail to that which would be recorded with a perfect detector. The term restoration is recommended rather than enhancement.

**Spatial Processes**
- Exposure Recognition
- Edge Restoration
- Noise Reduction
- Contrast Enhancement

**GrayScale Rendition**
- Convert signal values to display values

**Exposure Recognition**
- Adjust for high/lower average exposure.

**Noise Reduction**
- Reduce noise and maintain sharpness

**Contrast Enhancement**
- Increase contrast for local detail
Radiograph of a hand phantom demonstrates uniform noise in the lucite ‘tissue’ and detailed human bone features. Noise reduction is shown using a zoom view of the mcp joint.

Vertical profiles of the mcp joint in an AP radiograph show the effects of noise reduction.

Conceptual method (Simoncelli):
A common technique for noise reduction is known as ‘coring’. An image signal is split into two or more bands; the highpass bands are subjected to a threshold non-linearity that suppresses low-amplitude values while retaining high-amplitude values.

Statistical significance (Simoncelli):
Removal of noise from images relies on differences in the statistical properties of noise and signal. The classic Wiener solution utilizes differences in power spectral density, a second-order property. The Bayesian estimator described provides a natural extension for incorporating the higher-order statistical regularity present in the point statistics of sub-band representations.
2D – adaptive non-linear coring

Couwenhoven, 2005,
SPIE vol 5749, pg318

- High Frequency sub-band
- Coring function
  \[ P = P(1 + wP^2) \]
- Adaptation
  - Signal amplitude
  - Signal to noise

High frequency sub-band Coring function

Adaptation

\[ P = \frac{P}{1 + wP^2} \]

Signal amplitude

Signal to noise

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2E – Contrast Enhancement

- Grayscale Rendering: Convert signal values to display values
- Exposure Recognition: Adjust for high/low average exposure
- Edge Restoration: Sharpen edges while limiting noise
- Noise Reduction: Reduce noise and maintain sharpness
- Contrast Enhancement: Increase contrast for local detail

Grayscale Rendering

Exposure Recognition

Edge Restoration

Noise Reduction

Contrast Enhancement

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2E – Contrast Enhancement

- A wide range of log(S) values is difficult to display in one view.
- Lung detail is shown here with low contrast.

Contrast Enhancement: Enhancement of local detail with preservation of global latitude.

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2E – Unsharp Mask

- A highly blurred image can be used to adjust image values.
- The Unsharp Mask can be obtained by large kernel convolution or low pass filter.
- Note that the grayscale has been reversed.
The difference between the image and the unsharp mask contains detail. This is added to the image to enhance detail contrast.

The contrast enhanced image has improved lung contrast and good presentation of structures in the mediastinum.

Detail enhancement is obtained by adding the scaled subtracted detail to the image.

In practice, the amount of contrast enhancement can be selected by first defining a grayscale rendition that achieves the desired latitude, and then applying a filter that enhances detail contrast. The enhancement gain is adjusted to amplifying the contrast of local detailed tissue structures.

Methods using large kernel of equal weight have poor frequency response characteristics.

For a specific grayscale rendition, detail contrast can be progressively enhanced:

- Latitude – the range of the unenhanced LUT.
- Detailed Contrast – the effective slope of the enhanced detail at each grey level.
- Gain – the increase in LUT local slope.
5 thoracic radiologists at 3 medical centers preferred a gain of 2.4 for the interpretation of PA chest radiographs of any latitude.

SPIE 4319, 2001

Contrast enhancement of wide latitude
Musculoskeletal views improves visualization
Course Outline

1. Preprocessing
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An optional software applicable for all types of FCR imaging. MIP is an enhanced version of Fujifilm’s proprietary Multifrequency Processing (MIP) and uses frequency enhancement to provide greater diagnostic information from a single exposure image.

FNC (Fast Noise Control)

Through separation of the noise and signal of an image, it is possible to selectively decrease the noise level.

Maximum selective exclusion of unnecessary information translates into easier diagnosis.

A series of proceedings articles describes the image processing approaches used by Eastman Kodak Company.
3B – EKC Signal Equalization (Kodak EVP)

\[ E'(i,j) = \alpha \cdot \{ E(i,j) \ast K \} + (1 - \alpha) \cdot E_{mid} + \beta \cdot \{ E(i,j) - (E(i,j) \ast K) \} \]

\[ D(i,j) = \rho [E'(i,j)] \]

3B – EKC Multi-Frequency Processing

Wang, AAPM '06, CE

3B – EKC control variables

Couwenhoven, RSNA Informed 2005

1st World Congress Thoracic Imaging 2005

GXR, Th. Rohse, November 2005

PHILIPS

UNIQUE

Image Quality Enhancement
**UNIQUE Principle**

Multi-Resolution Decomposition

Original Image

Processed Image

**3D – Agfa MUSICA**


**Non-linear transfer**

Non-linear transfer functions alter the contrast in each frequency band to amplify small signal contrast while controlling noise.
The recently released Musica-2 provides a more unified approach to the processing of all bodyparts. In general, Musica-2 has the ability to provide more aggressively processed appearance.

Multi Frequency Adjustment Window

Narrowed Signal Range

Increased Detail Contrast
In General

- Linear Filters
  Linear filters implemented with Fourier transforms or convolution with large area, variable amplitude kernels can achieve equalization and edge restoration with full control of the frequency transfer characteristics.
- Multi-scale Filters
  Multi-scale filters have coarse control of frequency transfer characteristics but can apply non-linear transformations to achieve noise reduction and prevent high contrast saturation.
3 - Commercial Implementation of DR Processing

- Image processing is provided by all CR/DR suppliers under a variety of trade names.
- While the computation approaches differ, the effect on the radiograph is similar.
- The processed digital image can appear very much different than a traditional screen film radiograph.
- It is possible to set up systems from different suppliers to provide similar appearance (but difficult). Harmonized processing is needed.

3 - Body Part & View

- Processing parameters for equalization, grayscale rendition, and edge restoration are set specifically for each body part / view that may be done.
- This requires close cooperation between the user and the supplier to set up tables that conform to the body part-view used in a department.
- Dependence on body part size complicates processing.
- New industry developments may provide processing software that automatically selects the proper parameters from the image data and makes adjustments for body part size.