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Handout #10.

Signal to Noise Ratio and System Evaluation

Part (I) Signal to Noise Ratio of Cascaded Systems

10.1 Fundamental Statistical Concepts

Signal-to-noise ratio (SNR) is analyzed based on **statistical theory.** A complete description of statistics is beyond the goal of this course. There are, however, several fundamental concepts that are used frequently in the derivation of SNR formulas.
They are reviewed as follows.

(1) Additive events:

❖ Suppose there are two independent random events, whose values are to be added. The expected values (***n***) and variance (**σ²**) add as follows:

$$n_{A+B} = n_A + n_B \qquad (1)$$

$$\sigma^2_{A+B} = \sigma^2_A + \sigma^2_B \qquad (2)$$

(2) Cascaded events:

- Consider a pair of independent sequential events such as the emission of photons and multiplication that occurs at the scintillating screen. The average product and variance of the product are:

$$n_{A\times B} = n_A \times n_B \qquad (3)$$

$$\sigma^2_{A\times B} = n_B^2\sigma_A^2 + n_A\sigma_B^2 \qquad (4)$$

- The variance $\boldsymbol{\sigma^2_{A\times B}}$ is due to the uncertainty of the number of captured x-ray photons and the uncertainty in the number of light photons produced per x-ray photon.
- Note that in radiological imaging, quantum noise obeys Poisson distribution.

(3) Binary process:

- A process is considered **binary** if there are only two possible outcomes (i.e., 0 and 1).
- We characterize the absorption / transmission of an x-ray photon in the scintillating screen as a binary process in which the photon is either stopped or transmitted without interaction.
- If the probability of a photon being stopped is η, the statistical average and variance fit a binomial distribution, where mean and variance are given by:

$$n = \eta \qquad (5)$$

$$\sigma^2 = \eta - \eta^2 \qquad (6)$$

10.2 SNR of a Modern Fluoroscopic Imaging System

(1) The impact of x-ray absorption efficiency (quantum efficiency, η)

- Let us first assume that the average number of x-ray photons falling onto the input phosphor screen of the image intensifier is N_i with a variance of $\sigma_i^2 = N_i$, based on the Poisson statistics.

- We also assume that the absorption efficiency (quantum efficiency) of the screen is **η**. The variance σ^2 of this process is (refer to equation (6)):

$$\sigma^2 = \eta - \eta^2 \qquad (7)$$

- Then the average number of x-ray photons stopped by the screen (N_p) and the corresponding variance (σ_p^2) can be determined by using **equations (3) and (4)**, we understand:

$$n_{A\times B} = N_p, \qquad n_A = N_i, \qquad n_B = \eta$$

$$\sigma_{A\times B}^2 = \sigma_p^2, \qquad \sigma_A^2 = \sigma_i^2 = N_i, \qquad \sigma_B^2 = \sigma^2 = \eta - \eta^2$$

- Therefore:

$$N_p = n_A \times n_B = \eta N_i \tag{8}$$

$$\begin{aligned}\sigma_p^2 &= n_B^2\sigma_A^2 + n_A\sigma_B^2 = \eta^2 N_i + N_i\left(\eta - \eta^2\right) \\ &= \eta \mathrm{N_i}\end{aligned} \tag{9}$$

- Recall Handout # 02, signal noise ratio (SNR), we have:

$$SNR = \frac{CN_p}{\sigma_p} = \frac{C\eta N_i}{\sqrt{\eta N_i}} = C\sqrt{\eta N_i} \tag{10}$$

(2) The impact of x-ray to light conversion ratio (g_1) in the scintillating screen

This is a cascaded process:

- Assuming a x-ray to visible light conversion ratio of $\mathbf{g_1}$ and a corresponding variance of σ_1^2 .

According to Poisson statistics:

$$\sigma_1^2 = g_1$$

- We can estimate the number of light photons ($\mathbf{N_{p1}}$) and corresponding variance ($\boldsymbol{\sigma_{p1}^2}$) that exits from the scintillating screen as follows:

Using **equations (3) & (4),** we understand

$$n_{A\times B} = N_{p1}, \quad n_A = \eta N_i, \quad n_B = g_1$$

$$\sigma_{A\times B}^2 = \sigma_{p1}^2, \quad \sigma_A^2 = \sigma_p^2 = \eta N_i, \quad \sigma_B^2 = \sigma_1^2 = g_1$$

❖ Therefore:

$$N_{p1} = \mathrm{g}_1 \eta \mathrm{N}_\mathrm{i} \tag{11}$$

$$\begin{aligned} \sigma_{p1}^2 &= g_1^2 \sigma_p^2 + \eta N_i \sigma_1^2 \\ &= g_1^2 \eta N_i + \eta N_i g_1 \\ &= g_1^2 \eta N_i \left(1 + \frac{1}{g_1} \right) \end{aligned} \tag{12}$$

❖ The SNR becomes:

$$SNR = \frac{C N_{p1}}{\sigma_{p1}} = \frac{C\sqrt{\eta N_i}}{\sqrt{\left(1 + \frac{1}{g_1} \right)}} \tag{13}$$

(3) The impact of other cascaded process (g_1 and g_2)

- If the imaging system have *two* stages of cascaded processes, the number of quanta output from the 2th stage is N_{p2}, and corresponding variance is σ_{p2}^2, **recall Eq. (3) & (4):**

$$n_{A\times B} = N_{p2},\quad n_A = g_1\eta N_i,\quad n_B = g_2$$

$$\sigma_{A\times B}^2 = \sigma_{p2}^2,\quad \sigma_A^2 = \sigma_{p1}^2 = g_1^2\eta N_i(1+\frac{1}{g_1}),\quad \sigma_B^2 = \sigma_2^2 = g_2$$

- We have:

$$N_{p2} = g_2 \times N_{p1} = g_2 g_1 \eta N_i \tag{14}$$

$$\sigma_{p2}^2 = g_2^2 \times \sigma_{p1}^2 + g_1\eta N_i \times g_2 = g_2^2 g_1^2 \eta N_i (1+\frac{1}{g_1}) + g_1\eta N_i \times g_2$$

$$= g_2^2 g_1^2 \eta N_i (1+\frac{1}{g_1}+\frac{1}{g_1 g_2}) \tag{15}$$

- Therefore, SNR is:

$$SNR = \frac{CN_{p2}}{\sigma_{p2}} = \frac{C\sqrt{\eta N_i}}{\sqrt{\left(1+\frac{1}{g_1}+\frac{1}{g_1 g_2}\right)}} \tag{16}$$

(4) The impact of more cascaded process ($g_1, g_2 \ldots g_k$)

- Similarly, if the imaging system has *k* stages of cascaded processes, assuming the number of quanta output from the kth stage is N_{pk}, and corresponding variance is σ_{pk}^2, we have:

$$N_{pk} = \left(g_1 g_2 \ldots\ldots g_k\right)\eta N_i \tag{17}$$

$$\sigma_{pk}^2 = g_1^2 g_2^2 \ldots\ldots g_k^2 \left(1 + \frac{1}{g_1} + \frac{1}{g_1 g_2} + \ldots + \frac{1}{g_1 g_2 \ldots g_k}\right)\eta N_i \tag{18}$$

$$SNR = \frac{C\sqrt{\eta N_i}}{\sqrt{\left(1 + \frac{1}{g_1} + \frac{1}{g_1 g_2} + \ldots + \frac{1}{g_1 g_2 \ldots g_k}\right)}} \tag{19}$$

(5) The impact of additive noise (N_a)

- Now let us consider additive noise, which results primarily from the image detector or detector related electronics, (although it may also be from the intensifying screen, image intensifier or even a badly designed optical component).
- We assume that the variance of the total additive noise is $\mathbf{N_a^2}$. Note that N_a^2 is independent of x-ray quantum noise.

This is a additive event, recall Eq. (2), we can calculate the variance of the total noise $\boldsymbol{\sigma_T^2}$:

$$\sigma_T^2 = \sigma_{pk}^2 + N_a^2$$

$$= g_1^2 g_2^2 \ldots\ldots g_k^2 (1 + \frac{1}{g_1} + \frac{1}{g_1 g_2} + \ldots + \frac{1}{g_1 g_2 \ldots g_k}) \eta N_i + N_a^2$$

$$= (g_1 g_2 \ldots g_k)^2 \eta N_i \left[(1 + \frac{1}{g_1} + \frac{1}{g_1 g_2} + \ldots + \frac{1}{g_1 g_2 \ldots g_k}) + \frac{N_a^2}{\eta N_i (g_1^2 g_2^2 \ldots\ldots g_k^2)} \right] \quad (20)$$

❖ For the number of quanta output from the kth stage, $\mathbf{N_{pk}}$,

$$N_{pk} = (g_1 g_2 \ldots\ldots g_k)\eta N_i$$

❖ Recall Eq. (10)

$$SNR = \frac{C(g_1 g_2 \ldots g_k)\eta N_i}{\sqrt{(g_1 g_2 \ldots g_k)^2 \eta N_i \left[\left(1 + \frac{1}{g_1} + \frac{1}{g_1 g_2} + \ldots + \frac{1}{g_1 g_2 \ldots g_k}\right) + \frac{N_a^2}{\eta N_i (g_1^2 g_2^2 \ldots\ldots g_k^2)}\right]}}$$

$$SNR = \frac{C\sqrt{\eta N_i}}{\sqrt{\left(1 + \frac{1}{g_1} + \frac{1}{g_1 g_2} + \ldots + \frac{1}{g_1 g_2 \ldots g_k}\right) + \frac{N_a^2}{\eta N_i (g_1 g_2 \ldots\ldots g_k)^2}}} \qquad (21)$$

Discussions about Eq. (21):

- Eq. (21) represents the SNR of a cascaded imaging chain. Both additive and cascaded quantum noises and their effect on the resultant SNR can be analyzed using this equation.
- In cases where $$\frac{N_a^2}{\eta N_i (g_1 g_2 \ldots\ldots g_k)^2} >> 1$$ correspond to a high additive noise fraction, indicating that the system is dominated by additive noise.
- In cases where one of the product terms (g_1, $g_1 \times g_2$, ... ,$g_1 \times g_2 \ldots \times g_k$) is considerably smaller than unity, the SNR of the system is dominated by at least one of the cascaded stages.
- In the "ideal" case, every term of $\frac{1}{g_1 g_2 \ldots\ldots g_k}$ and $\frac{N_a^2}{\eta N_i (g_1 g_2 \ldots\ldots g_k)^2}$ are much smaller than one, so that Eq. (21) reduces to:

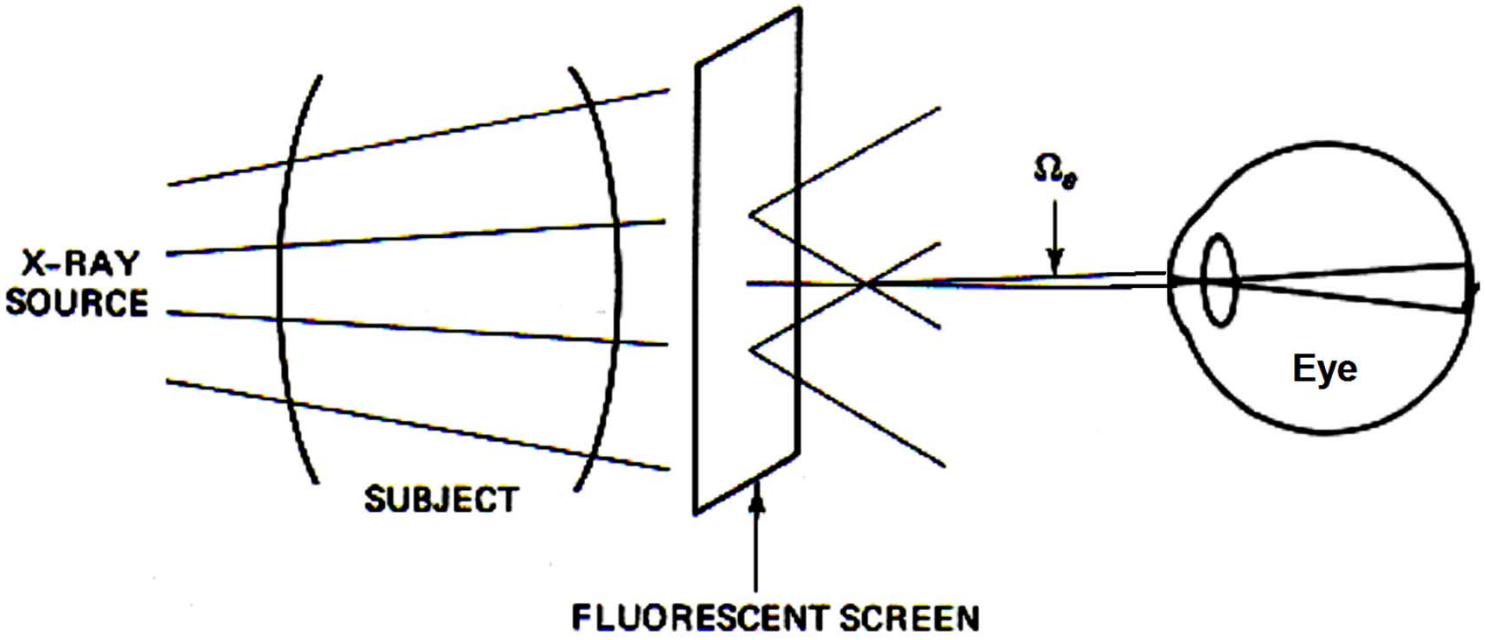
$$SNR = C\sqrt{\eta N_i}$$

which represents a perfect x-ray quantum noise limited, additive noise free imaging system. The SNR is dominated by the number of x-ray photons captured by the x-ray detector (such as the phosphor screen).

10.3 SNR Analysis of Fluoroscopic and Other Cascaded Systems

The previous formulas can be used to analyze the SNR of fluoroscopic and other cascaded x-ray imaging systems:

(1) Conventional fluoroscopy with only a phosphor screen



Quantum gain

η: Absorption efficiency (quantum efficiency) of the phosphor screen, (assume 50%).

g_1 : Gain of the phosphor screen (x-ray to light conversion), (assume 1000 light photons / x-ray photon).

g_2 : Collection efficiency of the eye

$$g_2 = \frac{T_e \Omega_e}{4\pi} = \frac{T_e A}{4\pi r^2}$$

where Ω_e**:** the small solid angle intercepted by the pupil

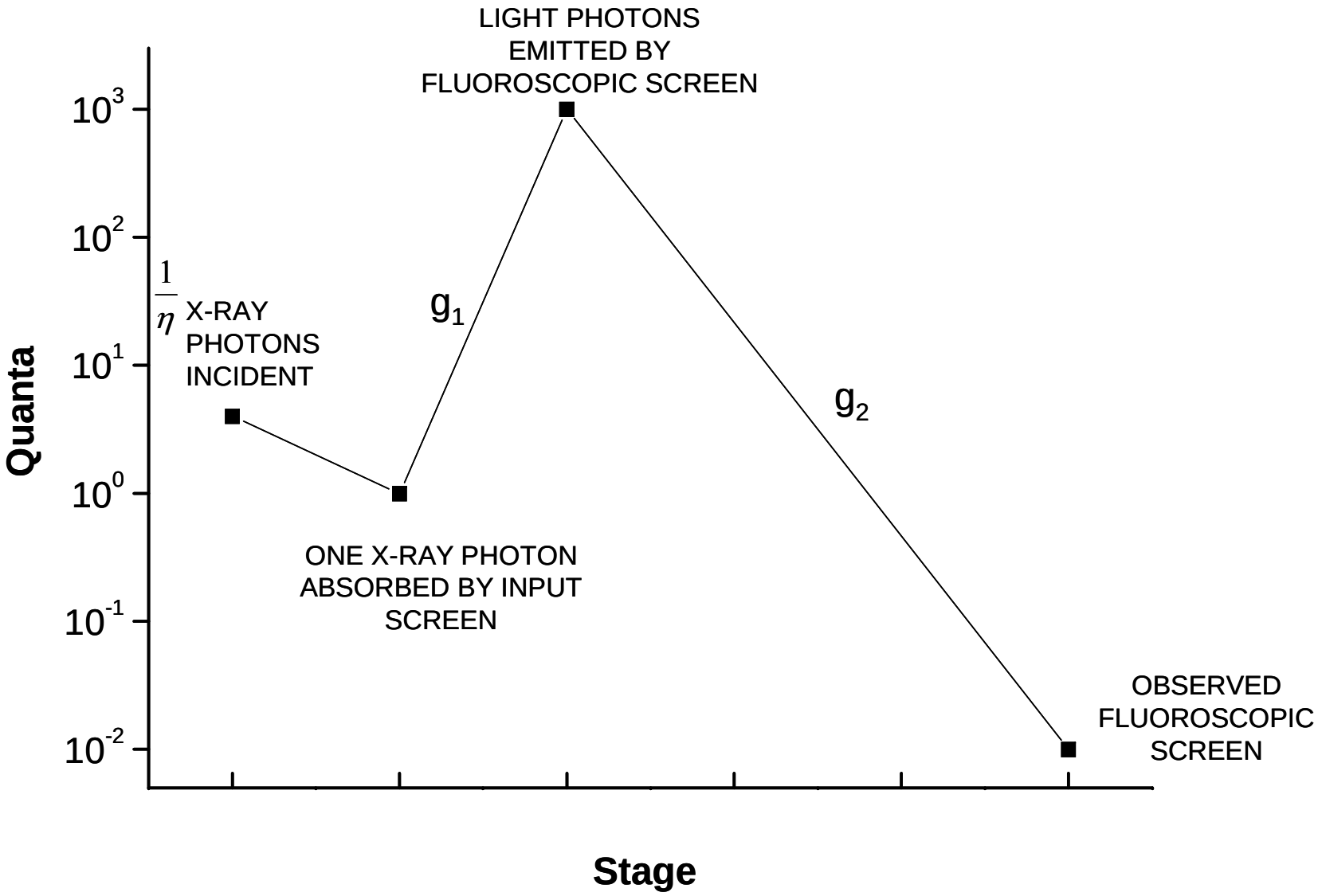
T_e: is the light transmission to the retina, which is about 0.1,

A: is the pupil area, usually is 0.5cm^2

r: is the distance of the eye from the screen, the closest reasonable viewing distance is about 20 cm.

Therefore,

$$g_2 = \frac{T_e \Omega_e}{4\pi} = \frac{T_e A}{4\pi r^2} = \frac{0.1 \times 0.5}{4\pi \times 20^2} \approx 10^{-5}$$


LIGHT PHOTONS
EMITTED BY
FLUOROSCOPIC SCREEN
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
$\frac{1}{\eta}$ X-RAY
PHOTONS
INCIDENT
g_1
g_2
ONE X-RAY PHOTON
ABSORBED BY INPUT
SCREEN
OBSERVED
FLUOROSCOPIC
SCREEN
Quanta
Stage

Example:

g_1=1000 light photons / x-ray photon

g_2=10^{-5}

A total quantum gain:

$$g = g_1 g_2 = 1000 \times 10^{-5} = 10^{-2} = 0.01$$

For one x-ray photon absorbed by the phosphor, about 1000 light photons are emitted by the phosphor, but only about 10^{-2} light photons are collected by the observer's eye (total quantum gain of 10^{-2}).

How would this low efficiency affect SNR?

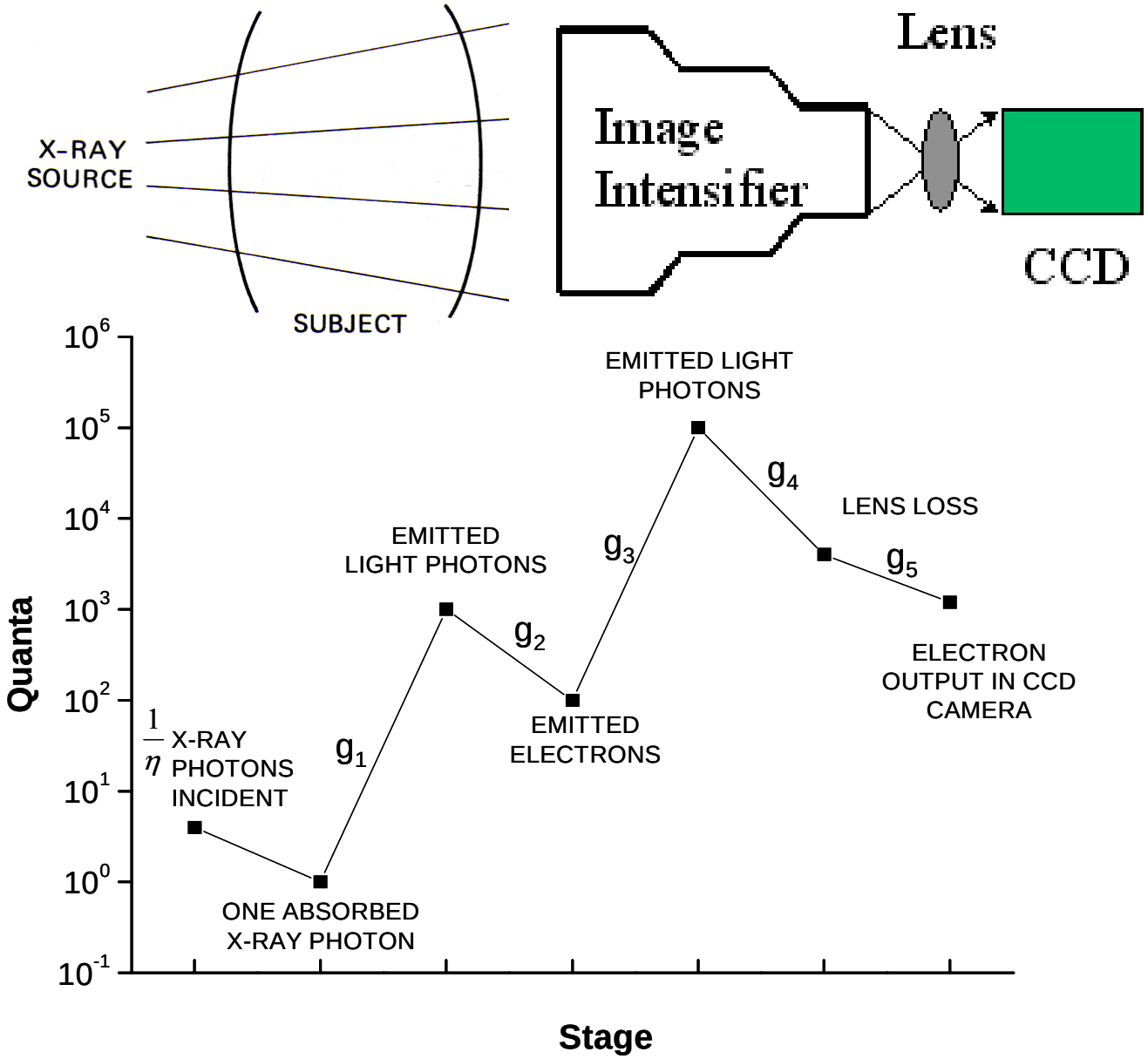
Recall Eq. (19):

$$SNR = \frac{C\sqrt{\eta N_i}}{\sqrt{\left(1 + \frac{1}{g_1} + \frac{1}{g_1 g_2}\right)}} = \frac{C\sqrt{\eta N_i}}{\sqrt{\left(1 + \frac{1}{1000} + \frac{1}{0.01}\right)}}$$

$$\approx \frac{C\sqrt{\eta N_i}}{10}$$

This is certainly not a "radiation efficient" system. The poor quantum gain reduced the image quality (SNR) some 9 times as one would achieve with an x-ray quantum noise limited system at the same radiation exposure to the patient.

(2) Fluoroscopy systems with image intensifier



The example on the previous slide demonstrates the following:

η: Absorption efficiency (quantum efficiency), (assume 50%).

$\mathbf{g_1}$: the gain of the input scintillating phosphor of the image intensifier (light photons per absorbed x-ray photon), (say 1000 light photons / x-ray photon);

$\mathbf{g_2}$: the efficiency of the photocathode in electrons per light photon, (about 10%);

$\mathbf{g_3}$: the gain of the output phosphor of the image intensifier in light photons per electron. (The electrons are accelerated to an energy of about 25 keV so as to produce about 1000 visible photons per electron).

$\mathbf{g_4}$: the efficiency of the loss in the optics lens system, (usually about 1%);

$\mathbf{g_5}$: the quantum efficiency of the CCD camera in electrons per light photon; (usually about 0.3).

Example: g_1=1000 light photons / x-ray photon

g_2=10%=0.1 $\quad g_1g_2=100$

g_3= 1000 $\quad g_1g_2g_3 = 10^5$

g_4= 1%=0.01 $\quad g_1g_2g_3g_4 = 1000$

$g_5 = 0.3$

The total quantum gain is calculated as follows:

$$g = g_1g_2g_3g_4g_5 = 1000 \times 0.1 \times 1000 \times 0.01 \times 0.3 = 300$$

Recall Eq. (19):

$$SNR = \frac{C\sqrt{\eta N_i}}{\sqrt{\left(1+\frac{1}{g_1}+\frac{1}{g_1g_2}+\frac{1}{g_1g_2g_3}+\frac{1}{g_1g_2g_3g_4}+\frac{1}{g_1g_2g_3g_4g_5}\right)}}$$

$$= \frac{C\sqrt{\eta N_i}}{\sqrt{\left(1+\frac{1}{1000}+\frac{1}{100}+\frac{1}{10^5}+\frac{1}{1000}+\frac{1}{300}\right)}}$$

$$\approx \frac{C\sqrt{\eta N_i}}{1.0076} \approx C\sqrt{\eta N_i}$$

This is an x-ray quantum noise limited system.

(3) An optically coupled CCD digital radiography system

η: Absorption efficiency (quantum efficiency), (assume 65%).

g_1 : is the gain of the input scintillating screen (light photons per absorbed x-ray photon), (assume 1000 light photons / x-ray photon);

g_2 : the efficiency of the optical fiber taper (assume: 10%);

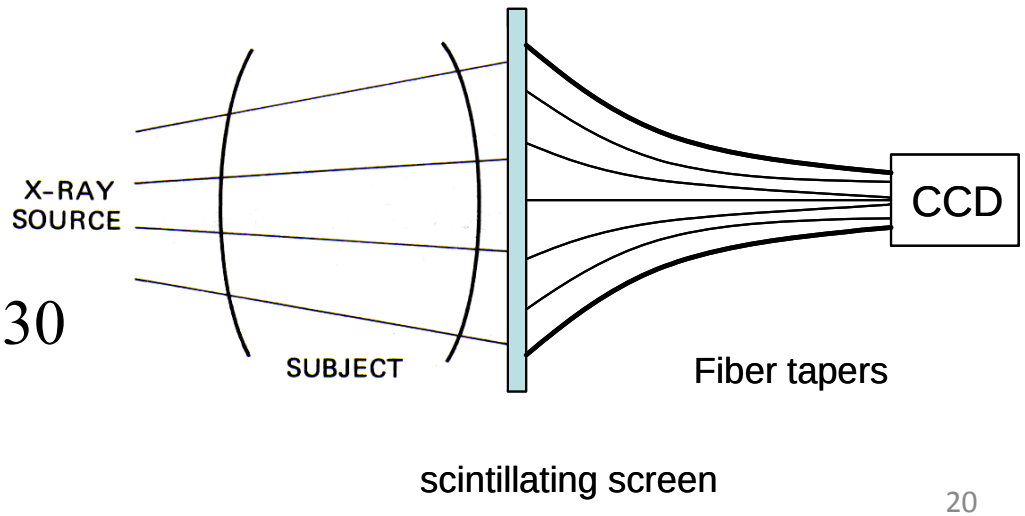
g_3 : the quantum efficiency of the CCD camera in electrons per light photon; (assume 30%).

N_i : the average number of x-ray photons falling onto the input phosphor screen (assume 10,000 x-ray photons)

N_a: total additive noise (assume a readout noise of 10 electrons)

A total quantum gain:

$$g = g_1 g_2 g_3 = 1000 \times 0.1 \times 0.3 = 30$$



Recall Eq. (21):

$$SNR = \frac{C\sqrt{\eta N_i}}{\sqrt{\left(1+\frac{1}{g_1}+\frac{1}{g_1 g_2}+\frac{1}{g_1 g_2 g_3}\right)+\frac{N_a^2}{\eta N_i (g_1 g_2 g_3)^2}}}$$

$$= \frac{C\sqrt{\eta N_i}}{\sqrt{\left(1+\frac{1}{1000}+\frac{1}{100}+\frac{1}{30}\right)+\frac{10^2}{0.65\times 10^4 \times (30)^2}}}$$

$$= \frac{C\sqrt{\eta N_i}}{1.021} \approx C\sqrt{\eta N_i}$$

This is an x-ray quantum noise limited system.

(4) A digital radiography system with a indirect flat panel detector

η: Absorption efficiency (quantum efficiency), (assume: 50%).

g_1: is the gain of the input scintillating screen (light photons per absorbed x-ray photon), (assume 1000 light photons / x-ray photon);

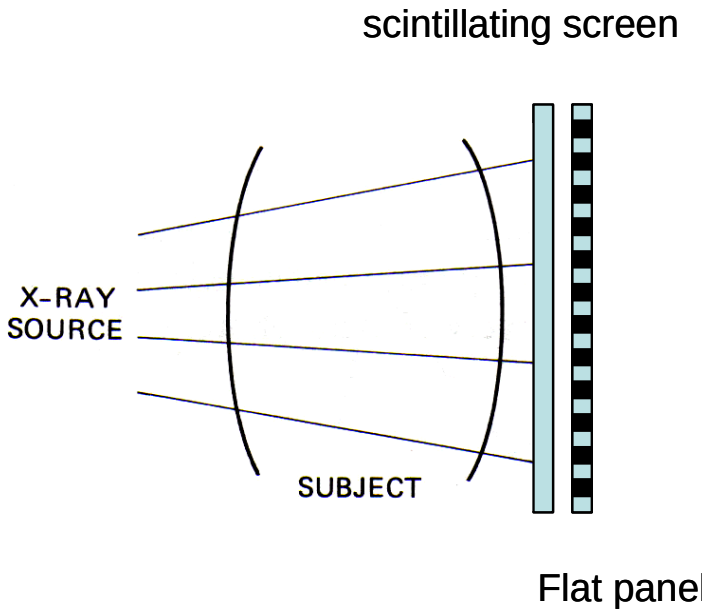
g_2: the quantum efficiency of the flat panel detector in electrons per light photon (assume: 30%).

N_i: the average number of x-ray photons falling onto the scintillating screen (assume: 10,000 x-ray photons)

N_a: total additive noise (assume a readout noise of 6000 electrons)

A total quantum gain:

$$g = g_1 g_2 = 1000 \times 0.3 = 300$$



Recalling Eq. (21):

$$SNR = \frac{C\sqrt{\eta N_i}}{\sqrt{\left(1+\frac{1}{g_1}+\frac{1}{g_1 g_2}\right)+\frac{N_a^2}{\eta N_i (g_1 g_2)^2}}}$$

$$= \frac{C\sqrt{\eta N_i}}{\sqrt{\left(1+\frac{1}{1000}+\frac{1}{300}\right)+\frac{6000^2}{0.50\times 10^4 \times (300)^2}}}$$

$$= \frac{C\sqrt{\eta N_i}}{1.041} \approx C\sqrt{\eta N_i}$$

This is an x-ray quantum noise limited system.

Handout #10
Signal to Noise Ratio and System Evaluation

Part (II) System Evaluations

How is the performance of medical devices evaluated?

- In the following, we will take medical imaging systems as an example, although the basic principle and techniques described here applies to many other medical devices and/or systems.

10.4 Objective Evaluation and Subjective Evaluation

- **Objective evaluation**

  Physics and engineering parameters, such as the modulation transfer function (MTF), signal to noise ratio (SNR), detective quantum efficiency (DQE) et al, provide **objective data** to describe the performance of imaging systems.

- **Subjective evaluation**

  Parameters involving observer's perception of medical images, provides a more **subjective** measure to evaluate the ability of imaging systems/techniques/procedures to reveal a certain pathology.

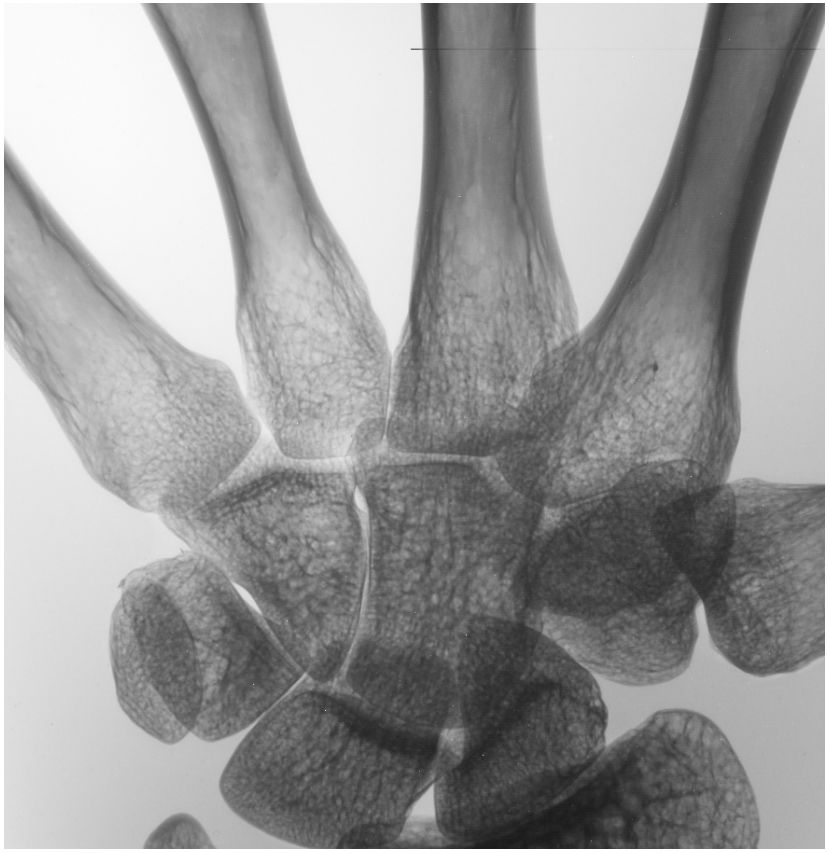
10.5 Subjective Evaluation of Medical Images

- The end products of a medical imaging system are images;
- The goal of acquiring medical images is for observers to read them;
- The bottom line of subjective evaluation is through the observers perception.

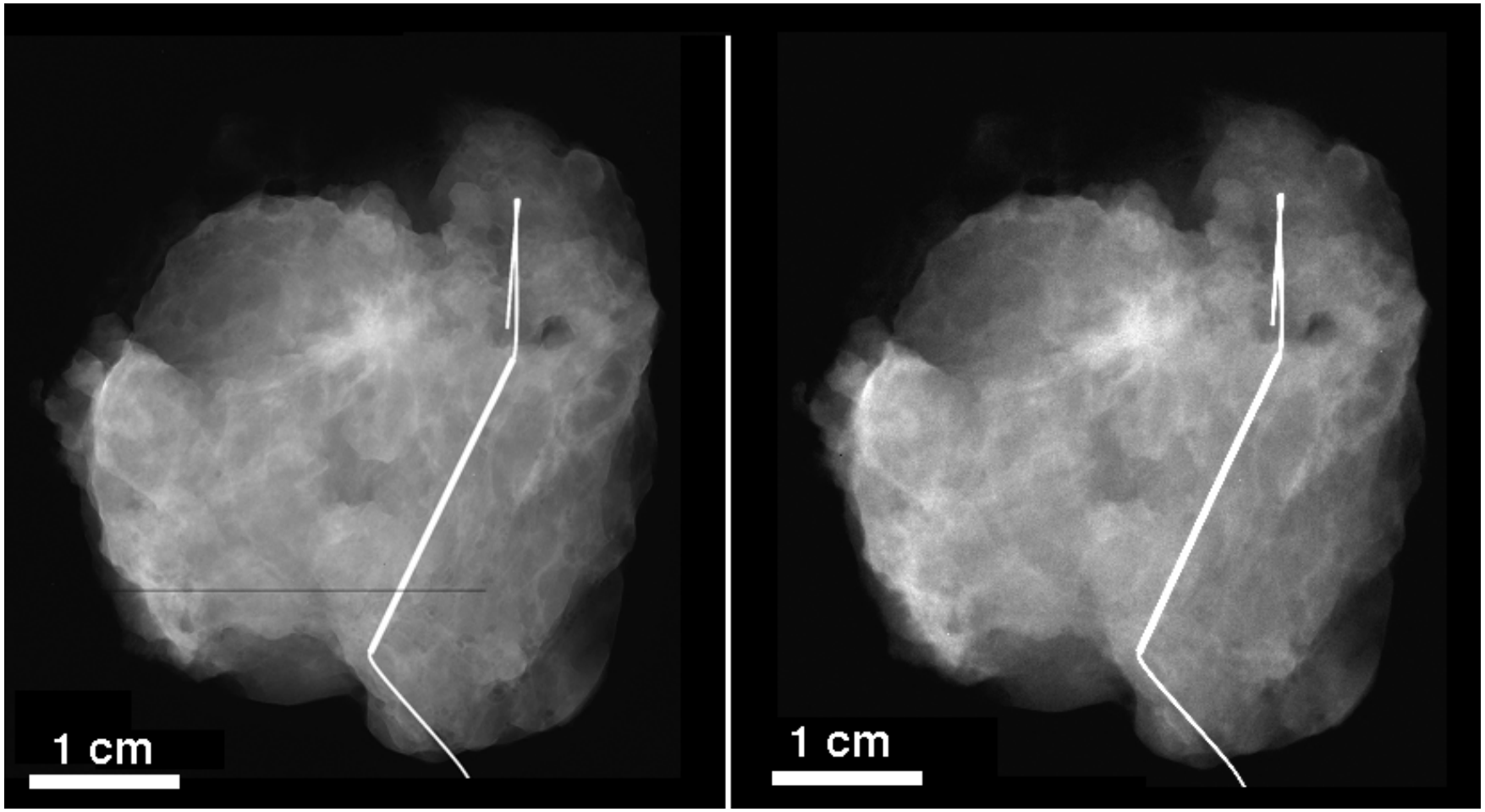
Some Examples:

A. Mammogram

B. Two X-ray images



C. Human breast lumpectomy specimen



40 kVp, 7 mm focal spot
SID = 1.78 m, M = 2.7

40 kVp, 7 mm focal spot,
SID = 1.78 m, M = 1

10.6 Perception of Phantom Images

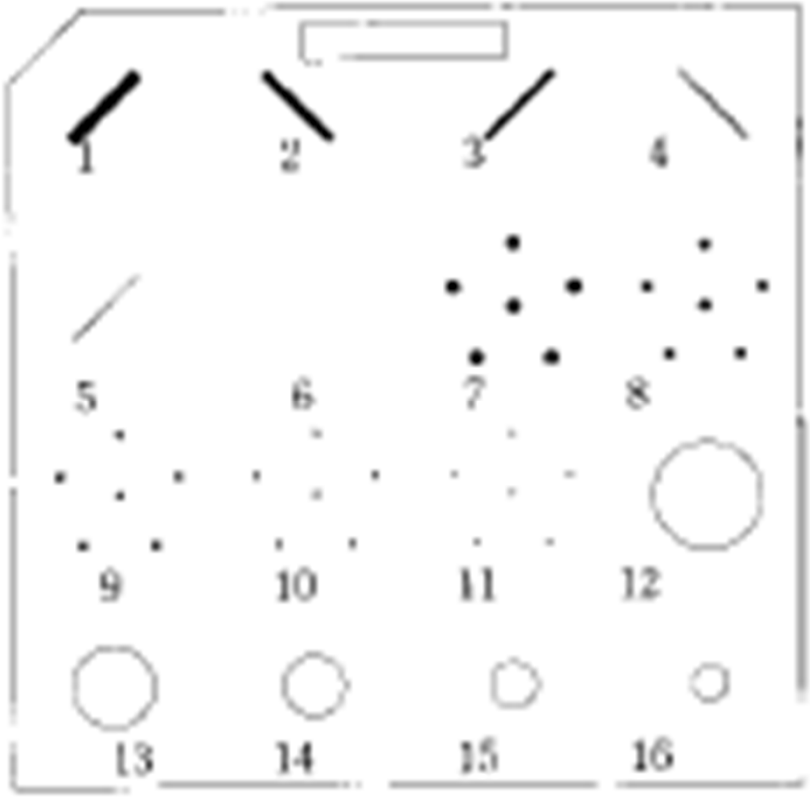
Procedures:

(1) Design or select phantom to simulate "clinical" conditions

- ❖ Similar attenuation coefficients
- ❖ Similar scatter characteristics
- ❖ Similar thickness, field size, etc

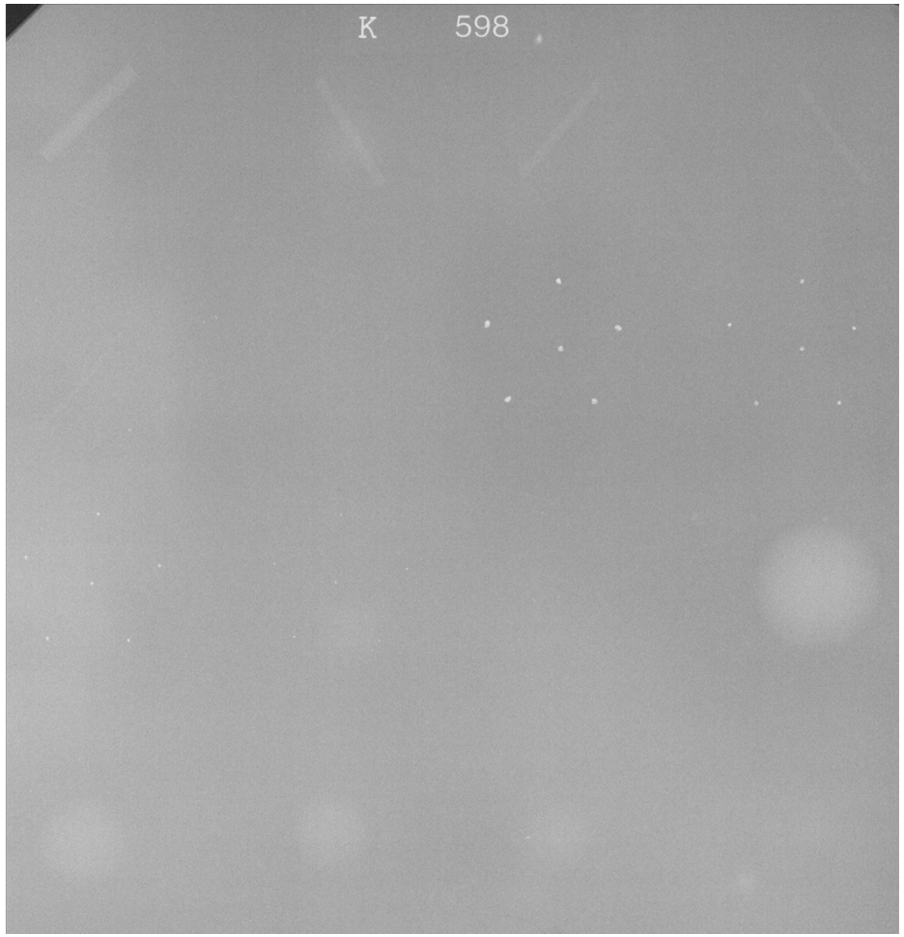
Simple phantoms, like the ACR phantom used for mammography, demonstrate several different types of features:

- ❖ Rows of radio-opaque bars to simulate fibrous calcifications in ducts
- ❖ Small dot groups to simulate microcalcifications
- ❖ Spheres of several sizes and densities to simulate masses.



Other phantoms exist which are designed to be more anthropomorphic, which include normal bone and tissue structures in addition to simulated anomalies.

(2) Acquire phantom images under "clinical" conditions



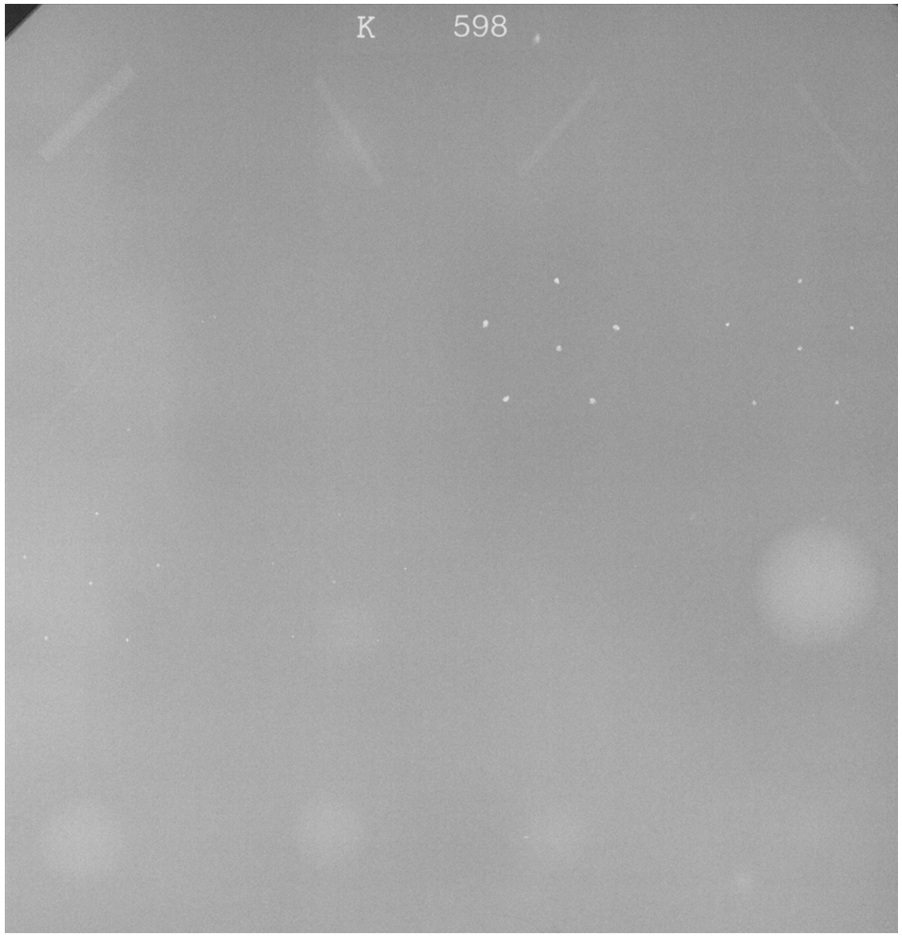
ACR Phantom Image taken at 60 kVp, 0.166 mA, 30sec and M=2.7

(3) Review the phantom images by a observer or a group of observers

The method to **score** the ACR mammography phantom is as follows:

The images of the phantom are viewed by observers.

- If the full length of a fiber is visible, it is counted as 1 point.
- If not all but more than half of a fiber was visualized, it is counted as 0.5 point.
- Similar scoring is also given to the other patterns with the phantom (specks and masses).



10.7 Contrast-detail-dose Analysis (CDD)

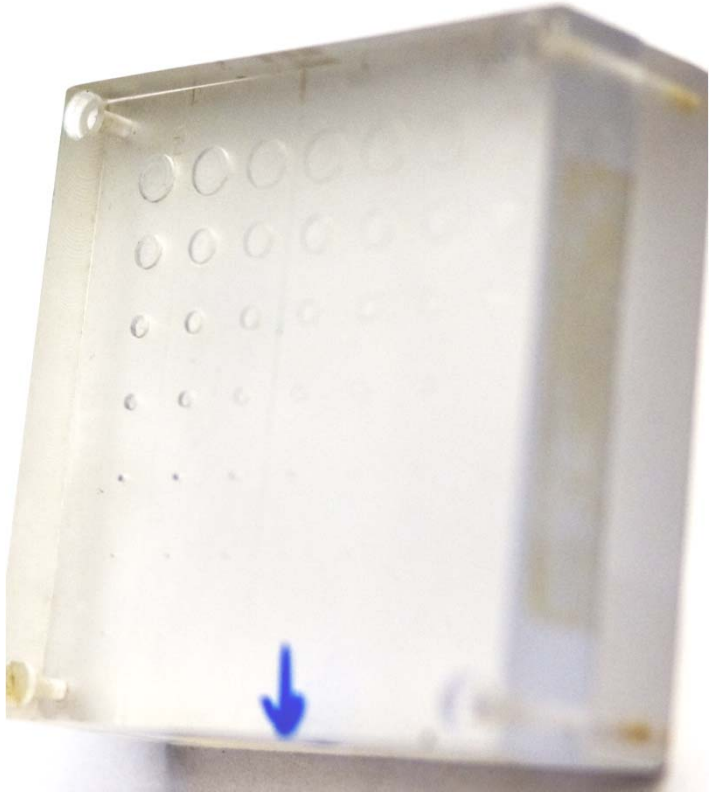
- This method combines contrast, resolution, noise, radiation to the patient and the capabilities of the observer (eye) together.

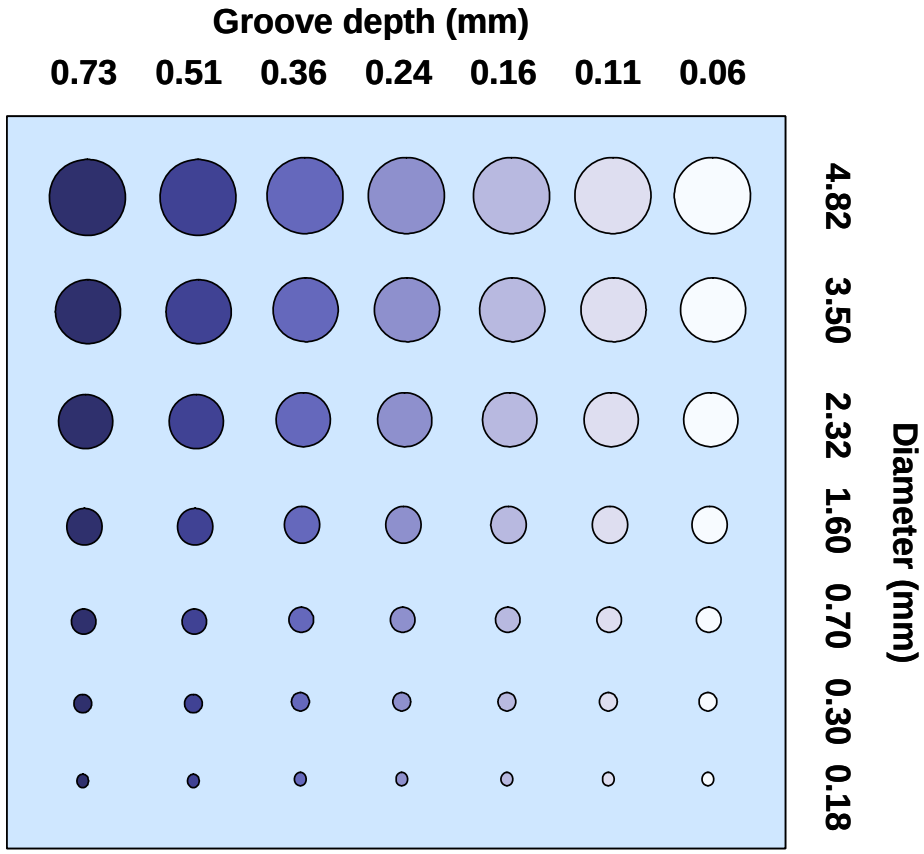
- It serves as an overall figure of clinical utility of images or imaging systems.

- Contrast-detail-dose analysis is an experimental technique for evaluating detectability at the threshold of human visibility in a medical image.

Procedure:

(1) Select or build a phantom:





(2) Acquire phantom images under pre-determined conditions

- ❖ Beam quality, quantity of exposure, etc

(3) Review the images

- The resulting images are examined by a group of observers who determine the minimal perceptible object (the threshold contrast) for each detail diameter.

(4) Generating contrast detail curves

- The contrast-detail detectability is expressed graphically as a contrast-detail curve, which relates the threshold contrast necessary to perceive an object as a function of the object's diameter.
- When threshold contrast is displayed on the y axis as a function of detail (object diameter) on the x axis, a typical contrast-detail curve begins at the upper left corner of the graph(i.e., high contrast, small detail) and declines asymptotically toward the right lower corner (low contrast, large detail) in the shape of a hyperbola.

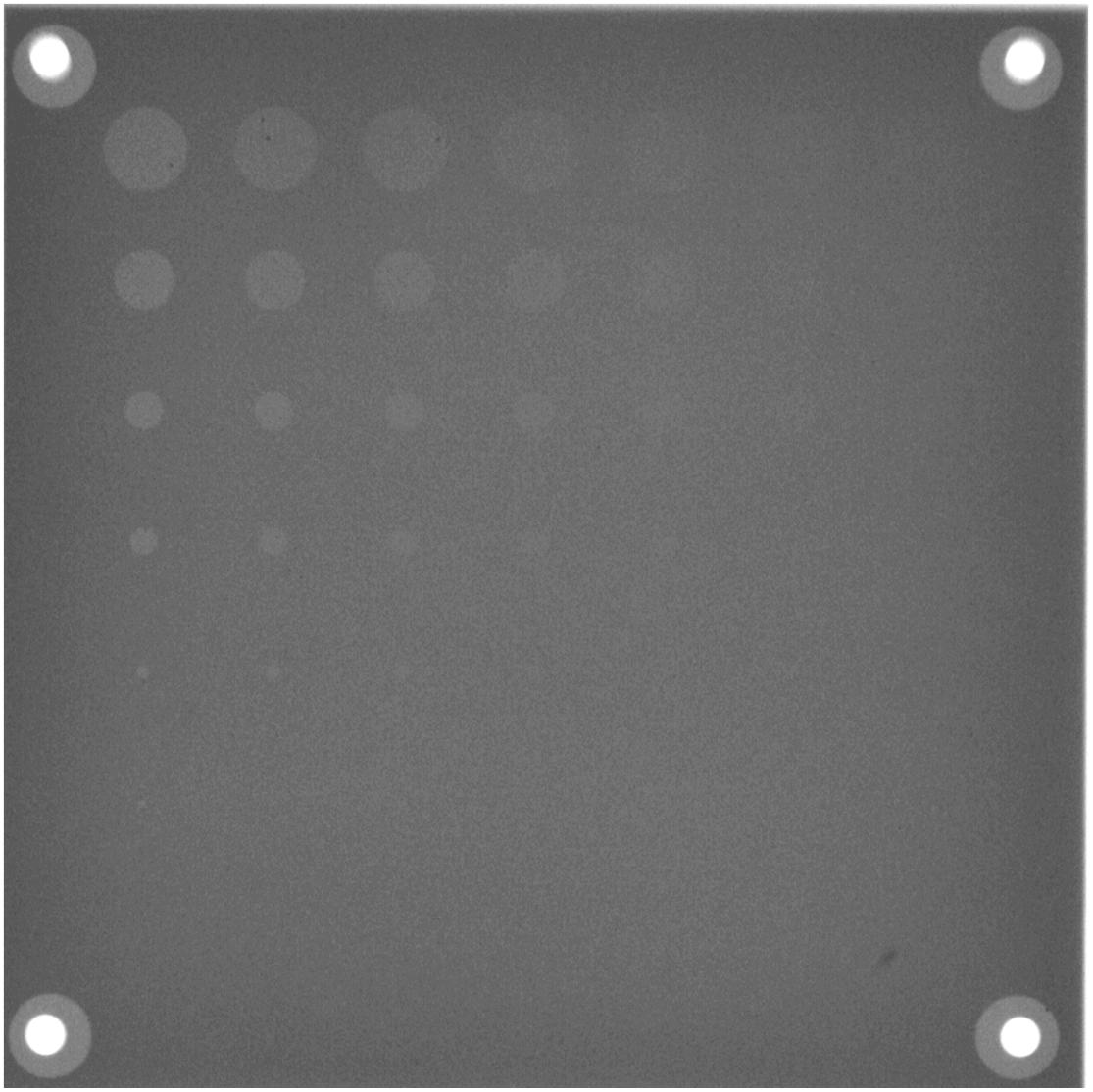
(5) System comparisons

- System comparisons are performed by generating contrast-detail curves that illustrate which system or radiation dose is better at producing images for detecting noise-limited objects at low contrast.

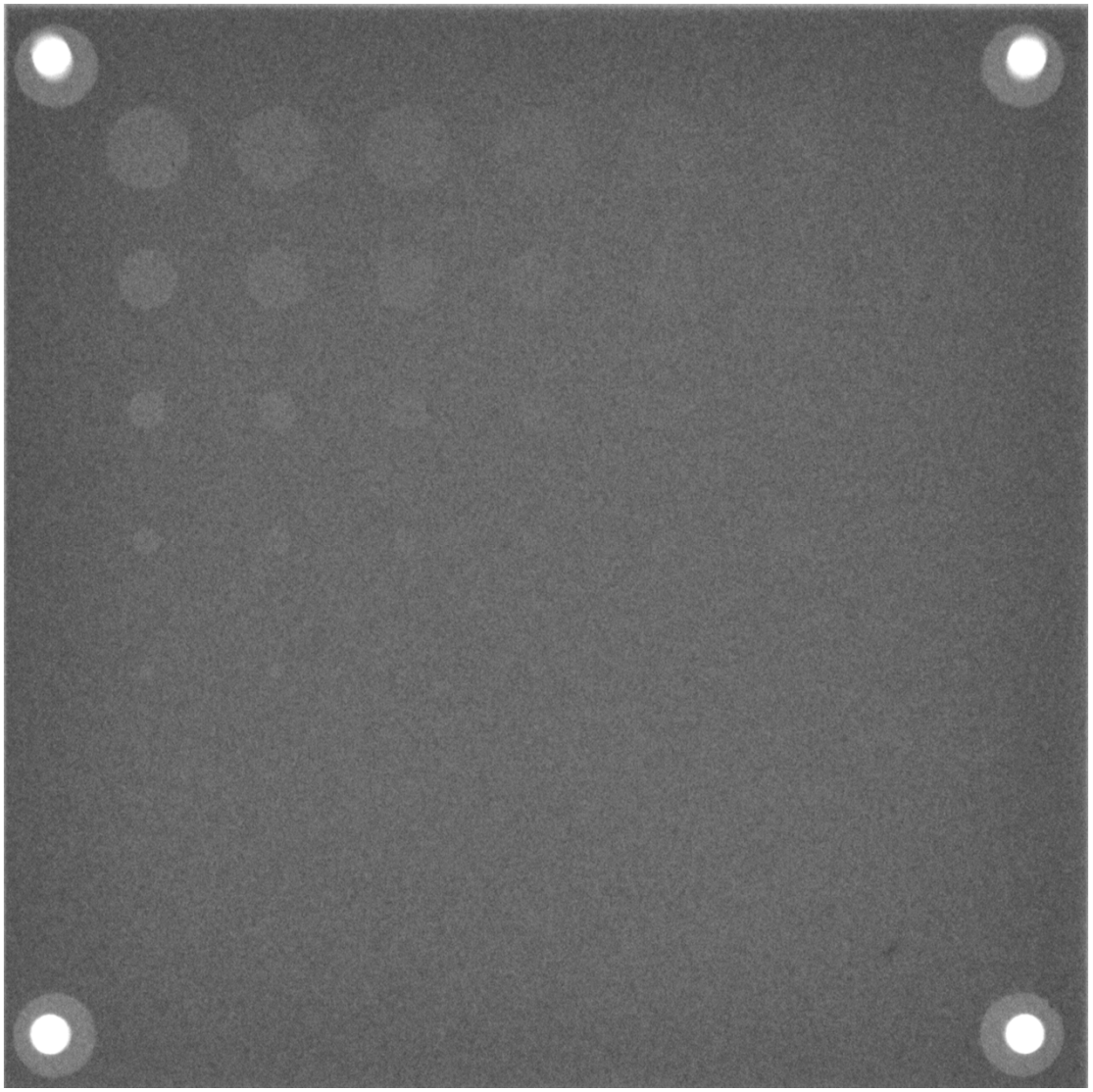
- Contrast-detail curves can also be generated to compare images acquired under different conditions, or reviewed by different group of observers, etc.

The following slides provide a few examples:

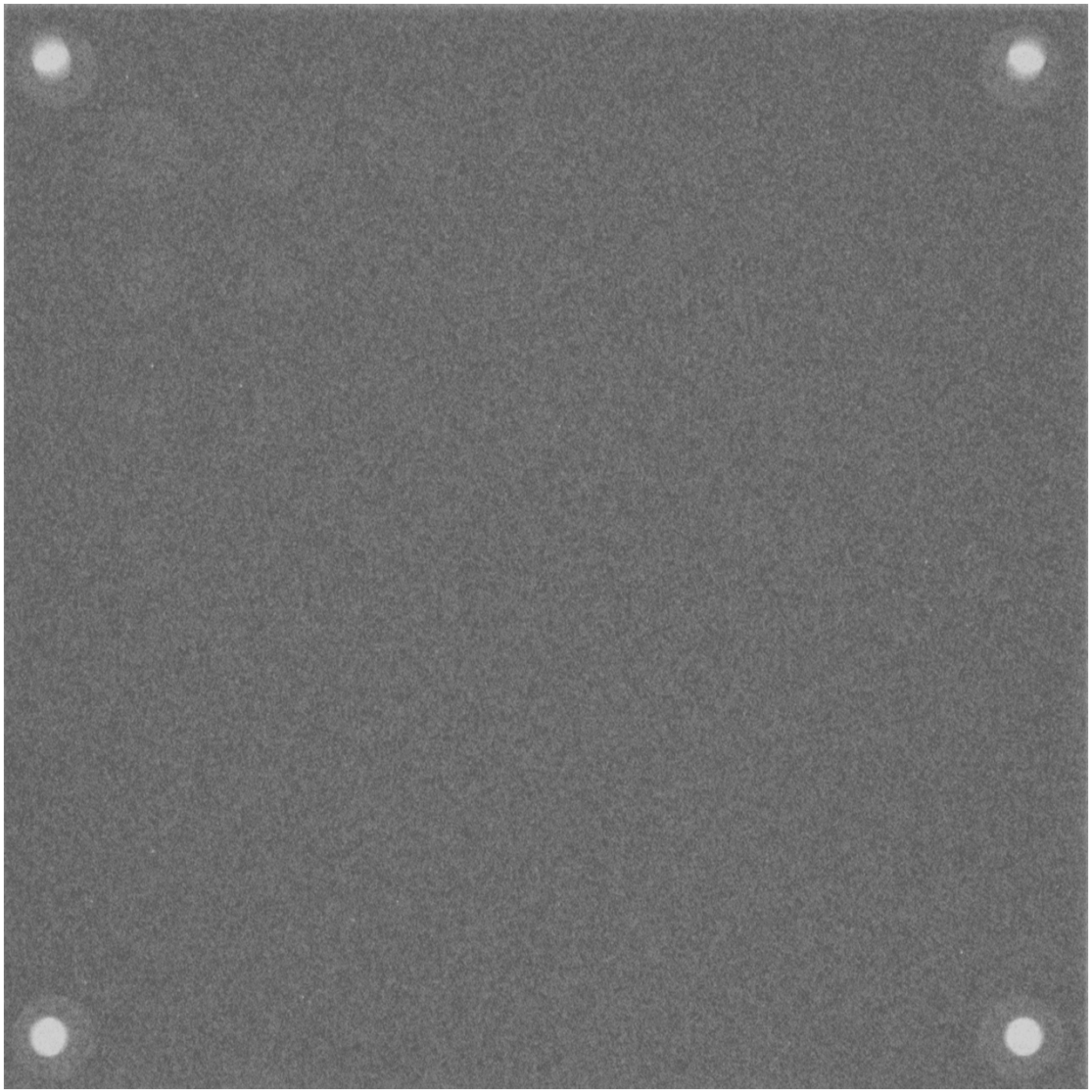
Contrast Detail Phantom Image taken at 40 kVp, 0.25 mA, 32 s



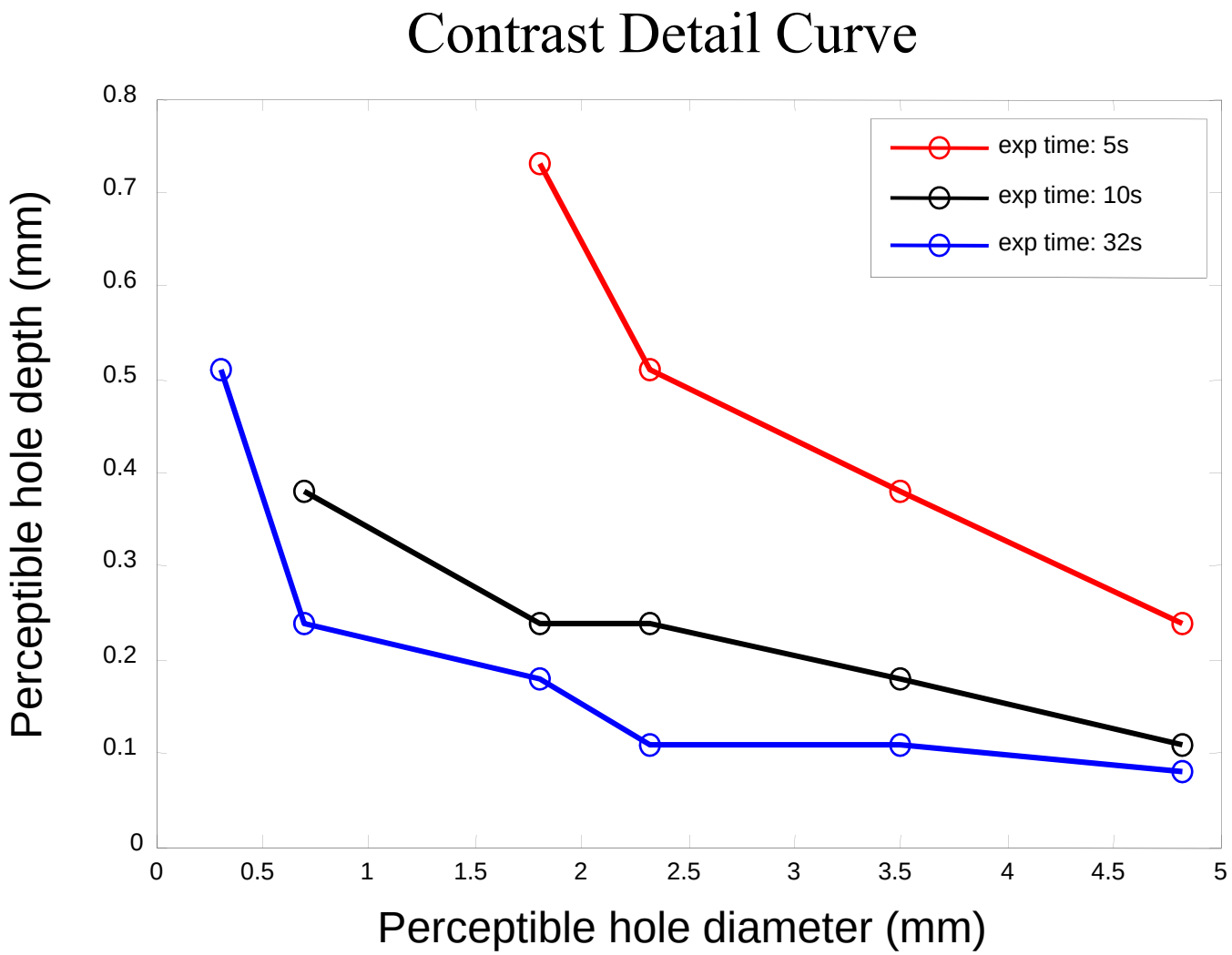
Contrast Detail Phantom Image taken at 40 kVp, 0.25 mA, 10 s



Contrast Detail Phantom Image taken at 40 kVp, 0.25 mA, 5 s



❖ Contrast detail curve determined from the reading of the above 3 CD phantom images



Example:

- ❖Twelve experienced observers independently reviewed 21 phantom images, indicating the threshold contrast (hole depth) detected for each detail diameter and the minimum perceptible diameter for each hole depth.
- ❖All unexposed film areas were masked with a black opaque overlay, leaving only the phantom image visible.
- ❖All images were viewed on conventional light boxes, and viewing sequences were randomized among modalities and x-ray exposures.

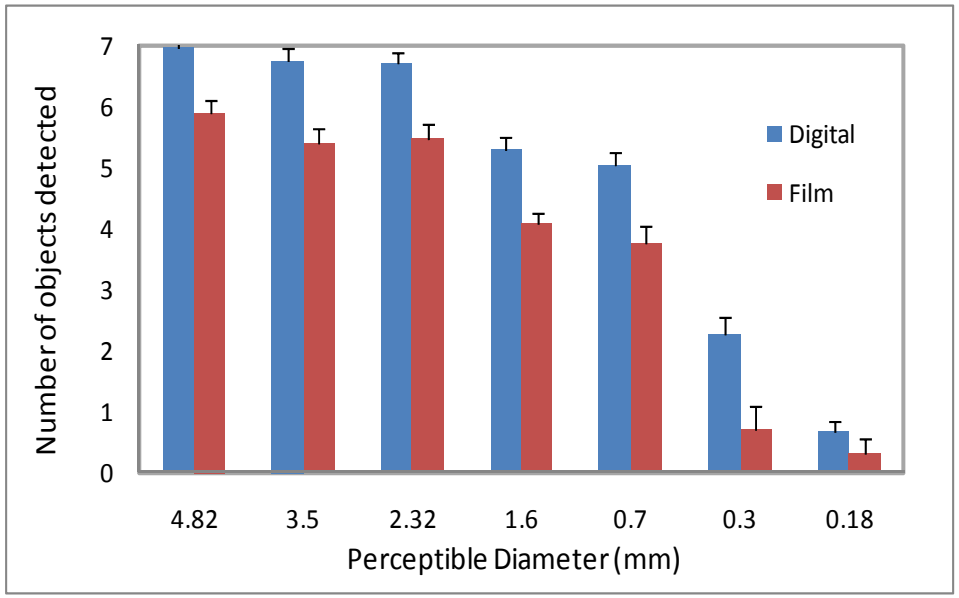


Figure: Detectabilities of the analog (Red bars) and digital (blue bars) systems expressed as the number of objects detected by 12 observers as a function of the minimal perceptible detail-diameter. Data are for readers' performance with phantom images obtained at the intermediate range of the seven mean glandular doses studied (digital image at 131mrad [1,310µGy] and analog image at 137mrad [1,370µGy]), which approximates the usual clinical exposure dose. Interobserver errors were calculated as the standard error of means and are represented by the error bars.

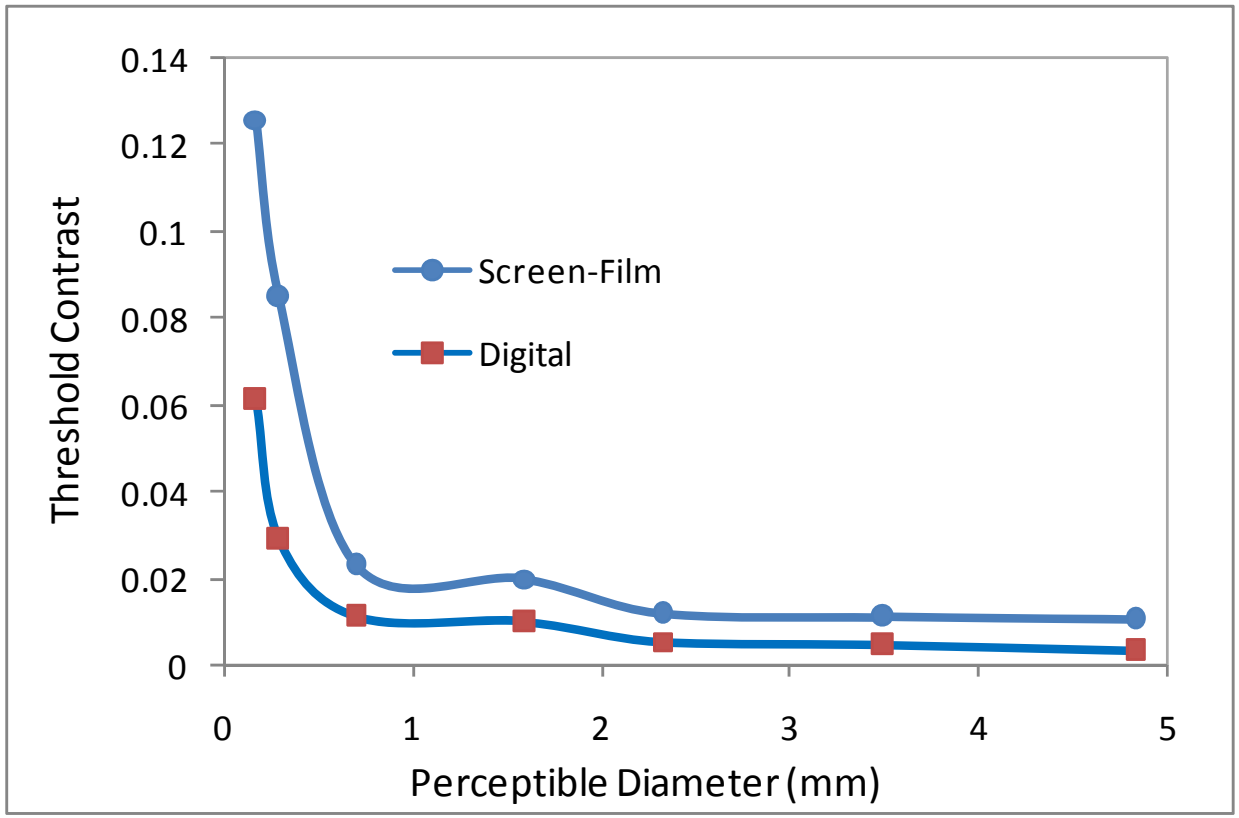


Figure: Contrast-detail curves for the digital and screen-film systems. The digital image was acquired at a mean glandular dose of 131 mrad (1,310 µGy), and the analogy image was acquired at a mean glandular dose of 137 mrad (1,370 µGy).

H. Liu, et al, Academic Radiology, Vol. 4, No.3, p197-203, 1997

Summary:

Parameters utilized to evaluate image quality or the performance of imaging systems include:

Objective parameters:

- Resolution, contrast, MTF,
- Noise, noise power spectrum (NPS), SNR,
- Efficiency, detective quantum efficiency (DQE), etc.

These parameters provide a physics/engineering "standard" for the images or systems;

Objective parameters may also be used to guide the design trade-offs in system development.

Subjective parameters:

- ❖ Phantom image perception,
- ❖ Contrast-detail-dose analysis,
- ❖ ROC analysis-to be discussed in next lecture

There is a fair amount of human judgment involved in the evaluation.

The subjective parameters provide a direct measure to evaluate the ability of imaging systems/techniques/procedures to reveal a certain pathology.

Example: How do you evaluate the quality of a new type of cookies? (Do you like these cookies?)

Objective measures:	Type, brand, ingredients, etc
Subjective:	Taste it !!!

Homework #9

1. An exercise in contrast-detail analysis

A Contrast-detail phantom was used to acquire images to be evaluated in this project. This phantom consists of two Lucite slabs with holes of different depths and diameters. There are seven hole-depths for each of the seven hole-diameters. The holes range in diameter from 0.18 to 4.82 mm and in depth from 0.06 to 0.73 mm (Fig 1). The total thickness of the phantom is 23mm. Under standard diagnostic x-ray exposure, the different hole-depth produces different subject contrasts (Table 1).

Digital images were acquired under 28KVp-0.3mA-3seconds (Fig.2), and 28KVp-0.3mA-9seconds (Fig.3), respectively. The subject contrasts produced by each of the hole-depth under the given x-ray beam quality are listed in the following table.

Please determine the impact of these two x-ray techniques to human observer's detectability (hint: You may want to review the images, derive a contrast detail curve from each image, and compare these two curves). The Table and Figures are given in the following slides.

Table 1. Hole-depth and corresponding subject contras

Hole depth (mm)	Subject Contrast (under the given condition)
0.06	0.4%
0.11	0.73%
0.16	1.1%
0.24	1.6%
0.36	2.4%
0.51	3.5%
0.73	5.0%

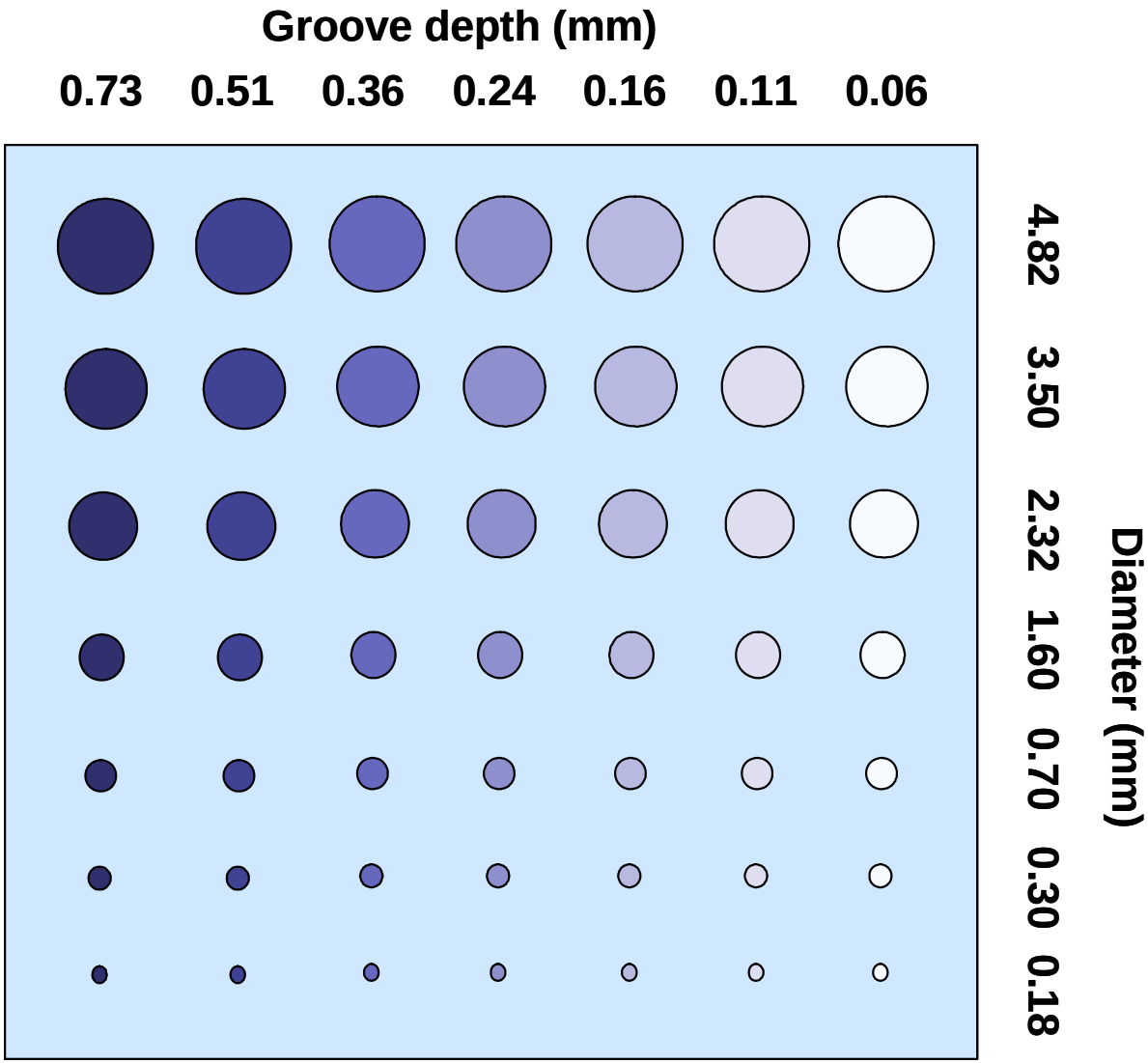


Figure 1. A contrast-detail phantom.

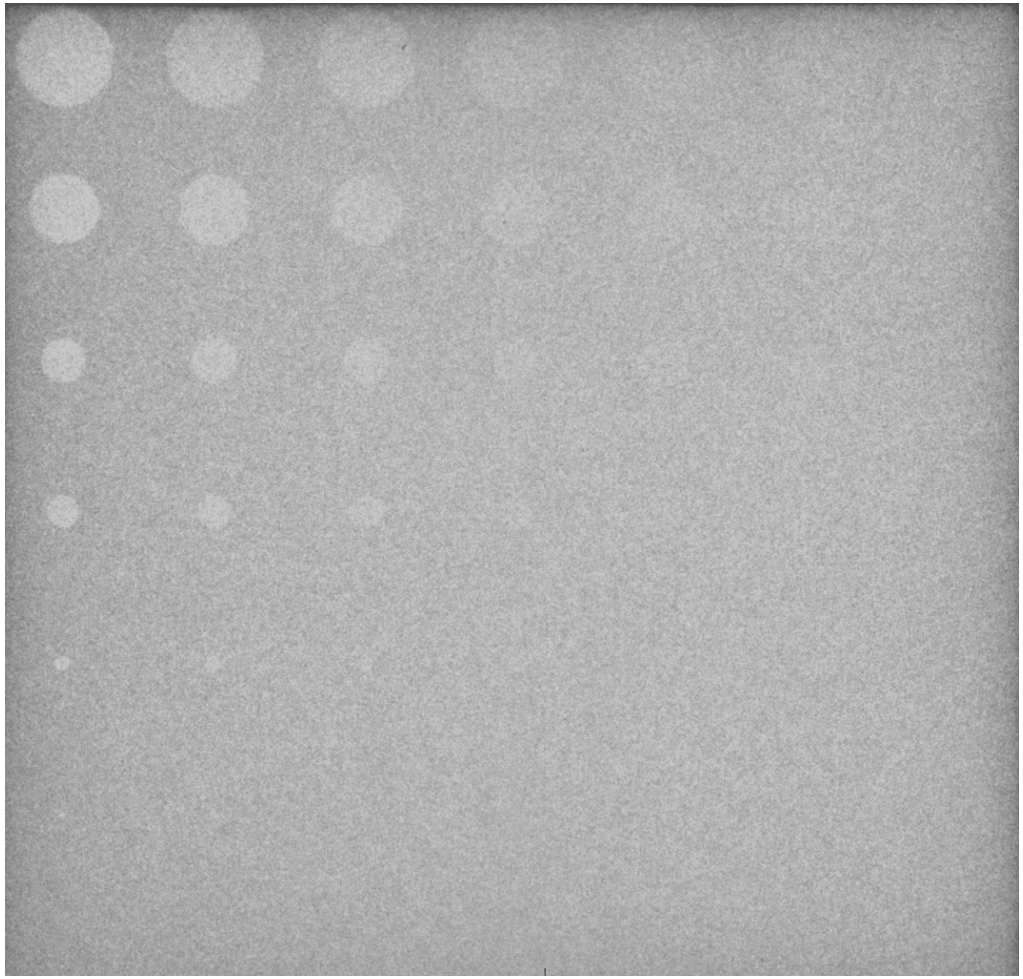


Fig.2: This image was acquired under 28 kVp, 0.3 mA and exposure time of 3 seconds.

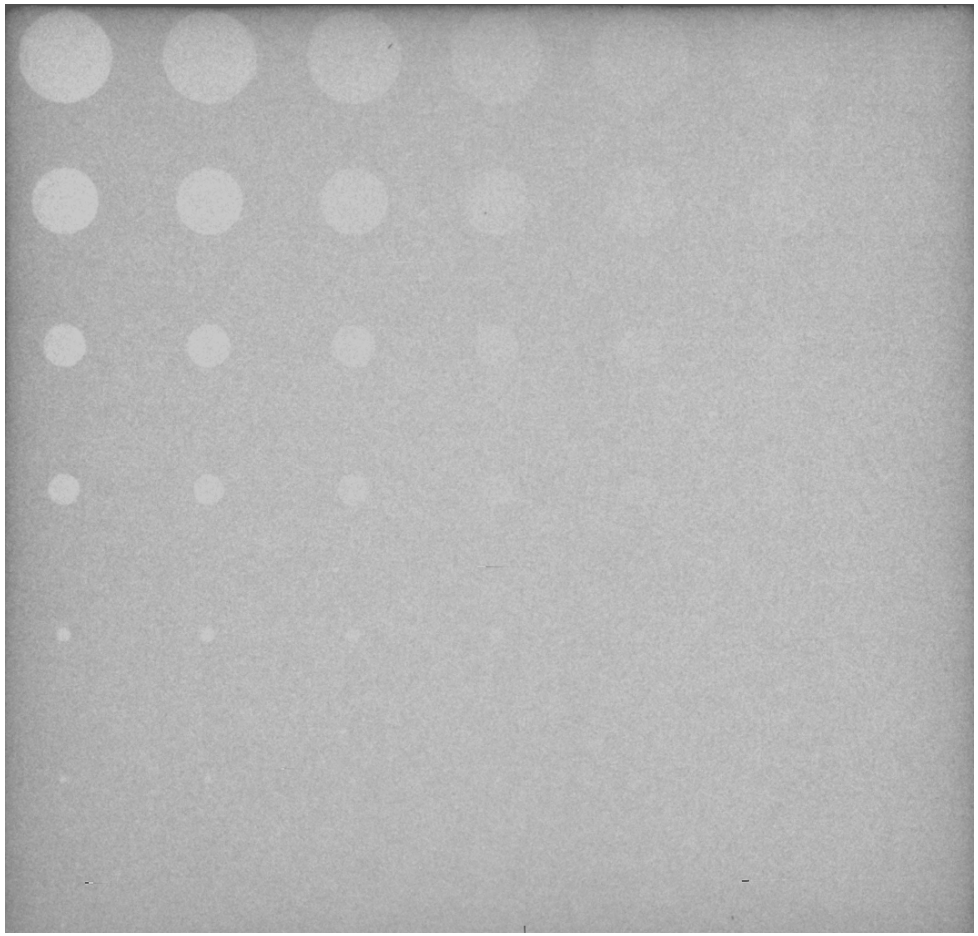
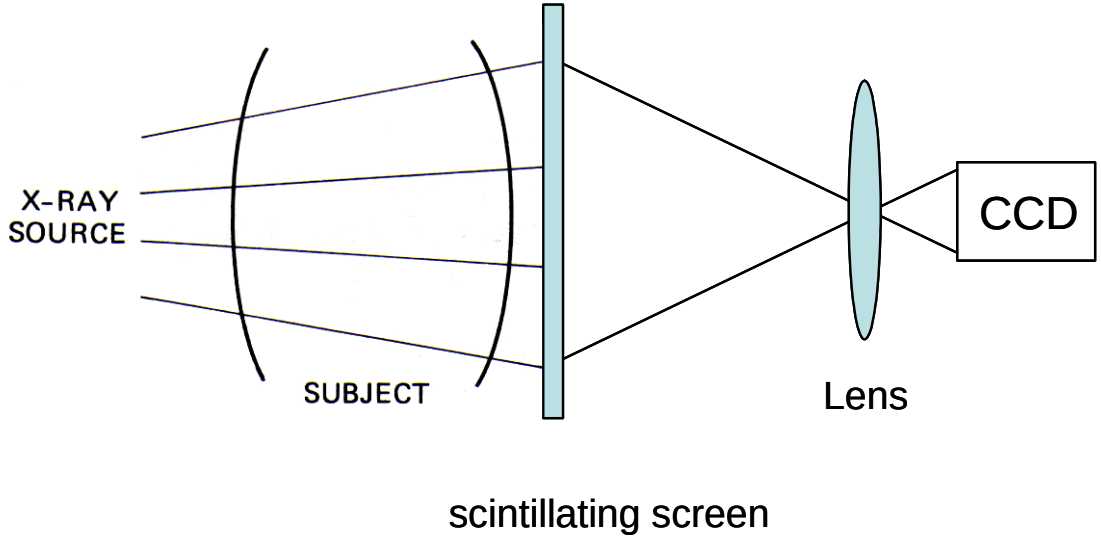


Fig. 3: This image was acquired under 28 kVp, 0.3 mA and exposure time of 9 seconds

2. A lens coupled CCD digital radiography is schematically shown, and its technical parameters are given as follows.



η: Absorption efficiency (quantum efficiency) of the scintillating screen, (assume 65%).

g_1: is the gain of the scintillating screen (light photons per absorbed x-ray photon), (assume: 500 light photons / x-ray photon);

g_2: the efficiency of the optical lens system, (assume 1%);

g_3: the quantum efficiency of the CCD camera in electrons per light photon; (assume: 35%).

N_i: the average number of x-ray photons falling onto the input phosphor screen (assume: 5,000 x-ray photons)

N_a: total additive noise (a readout noise of 200 electrons for CCD detector)

Is this system a radiation efficient, x-ray quantum noise limited system? If yes, why? if no, how much more radiation the patient will have to be exposed in order to achieve the same image quality (SNR) as if an x-ray quantum noise limited system is used.