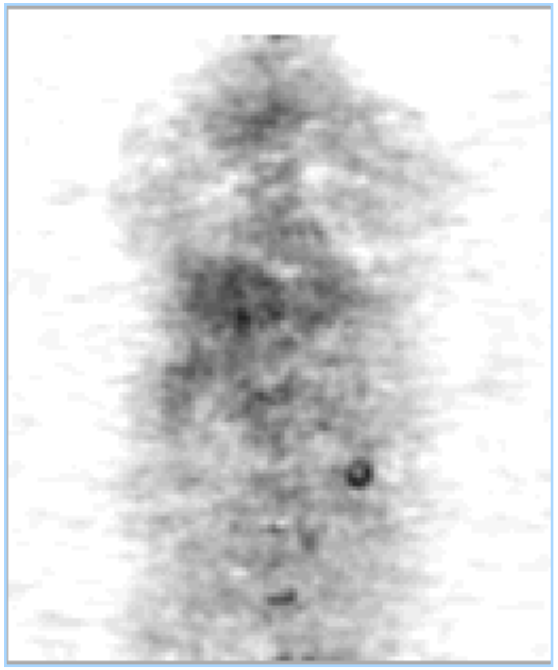
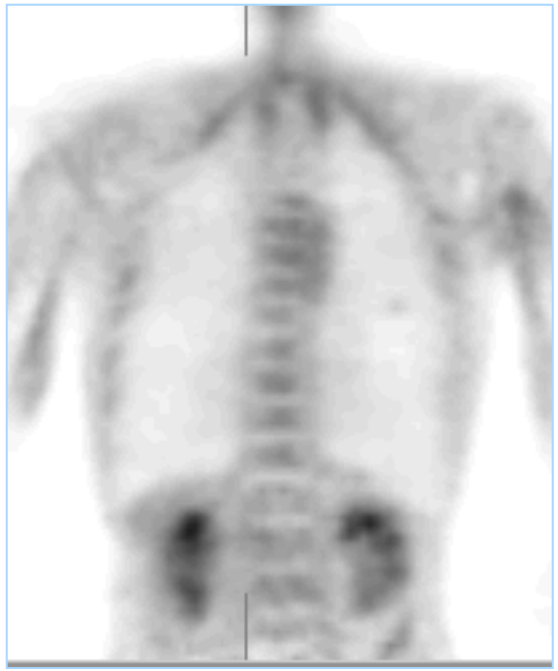
Image Quality

Image quality assessment





Question: which is a better image?

Answer: what are you trying to do?

Image Quality

Image quality, for the purposes of medical imaging, can be defined as the ability to extract desired information from an image

- Harrison H. Barrett *PNAS, 1993*

- "Task-based" definition of Image quality

Methods of determining imaging quality

- Six important factors
  1. Contrast
  2. Resolution
  3. Noise
  4. Accuracy
     a) quantitative accuracy
     b) diagnostic accuracy
  5. Artifacts
  6. Distortion

Contrast

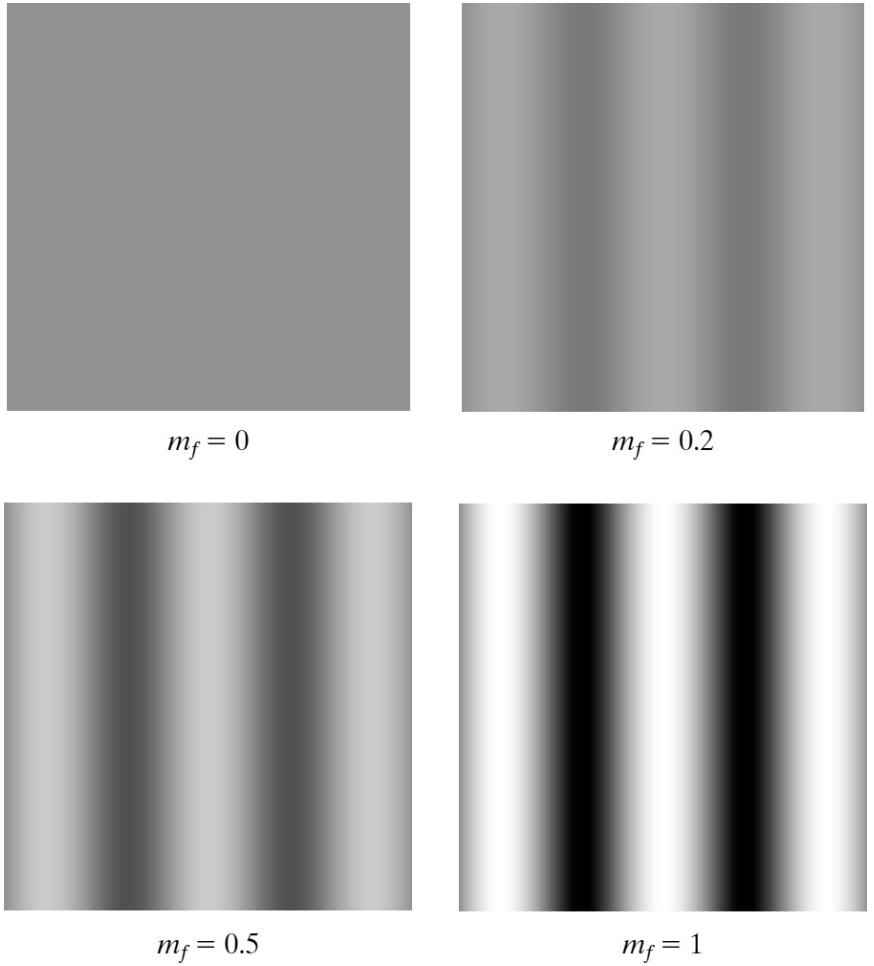
- Define modulation $$m_f = \frac{f_{\text{MAX}}(x,y) - f_{\text{MIN}}(x,y)}{f_{\text{MAX}}(x,y) + f_{\text{MIN}}(x,y)}$$

- Suppose

$$f(x,y) = A + B\sin(2\pi u_0 x)$$

$$\text{if } A \geq B > 0, \text{ then } m_f = \frac{B}{A}$$

- Increasing modulation = increasing contrast

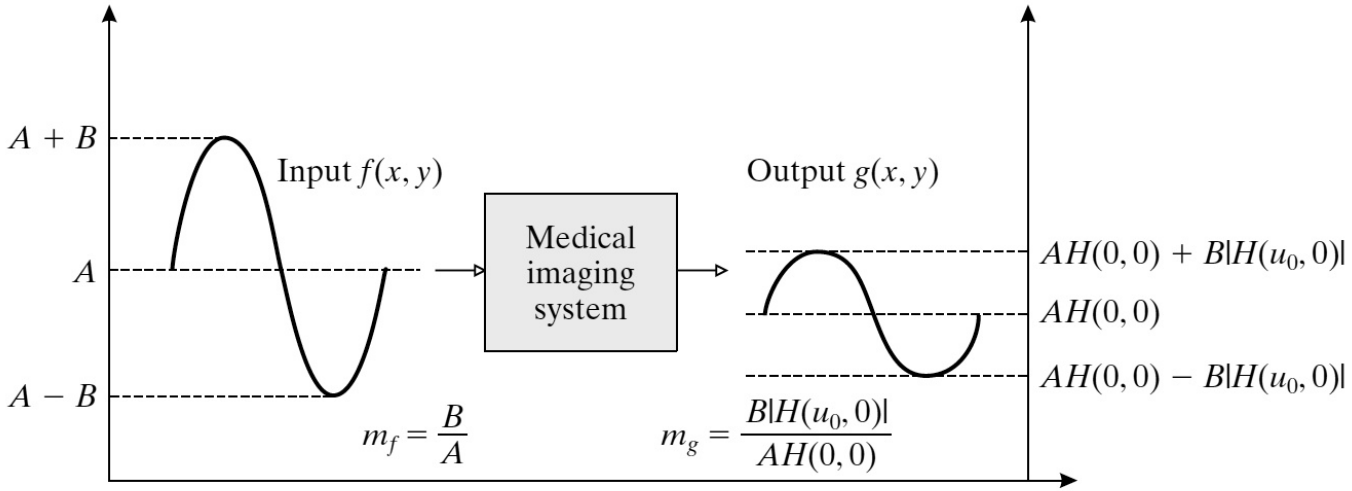


Modulation Transfer Function

- For a linear shift-invariant (LSI) system, define the Modulation Transfer Function (MTF) as the ratio of the output modulation to the input modulation

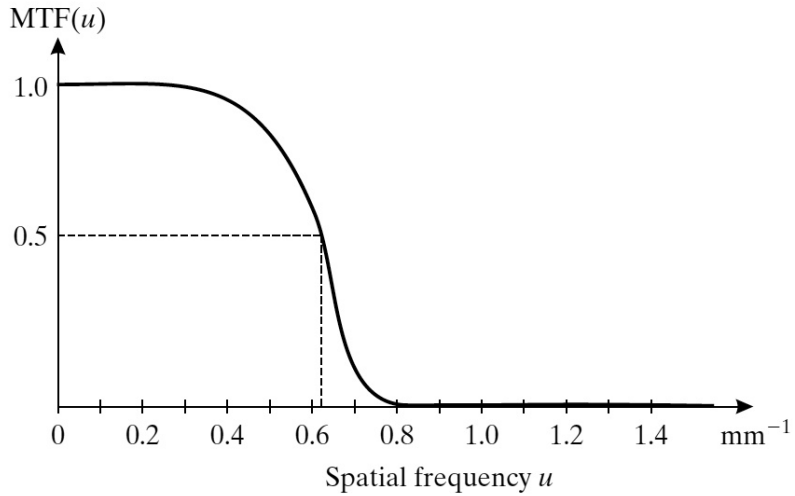
$$\mathrm{MTF} = \frac{m_g}{m_f}$$

- If the PSF is $h(x,y) = \mathcal{F}_{2\mathrm{D}}^{-1}\{H(u,v)\}$
- Then $\mathrm{MTF}(u,v) = \dfrac{m_g}{m_f} = \dfrac{|H(u,v)|}{H(0,0)}$



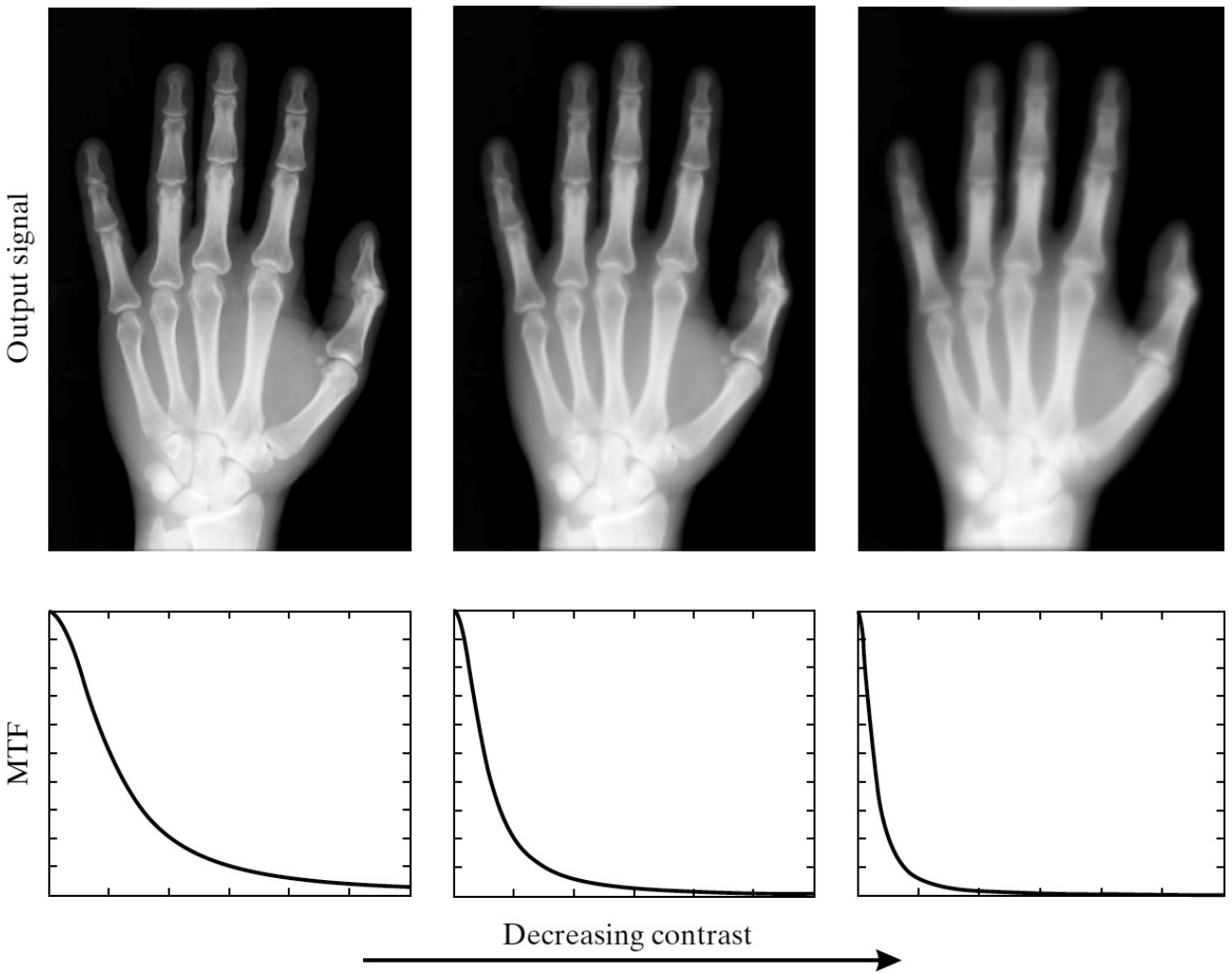
Modulation Transfer Function

- The Modulation Transfer Function quantifies the degradation in contrast as a function of frequency
- Typically $0 \leq \mathrm{MTF}(u,v) \leq \mathrm{MTF}(0,0) \leq 1$
- I.e. as frequency increases there is less contrast information transferred



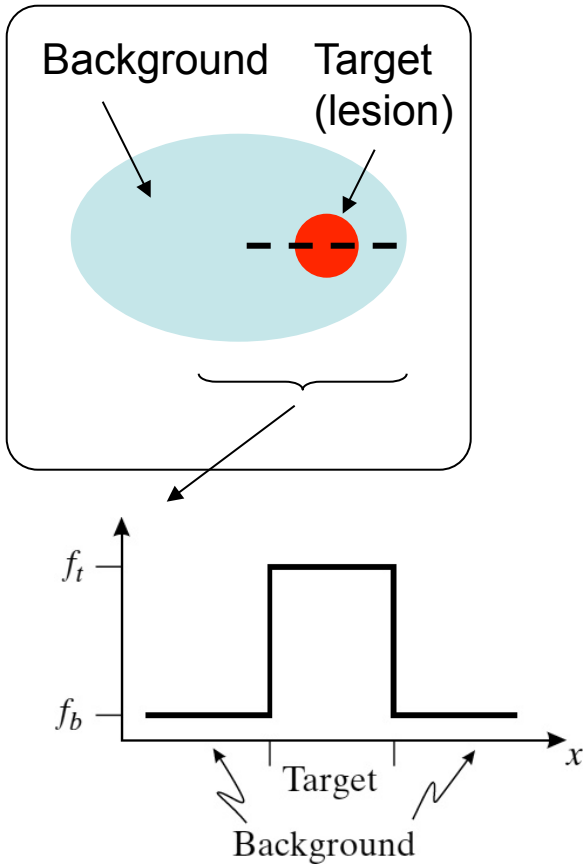
Modulation Transfer Function

- Loss of contrast at higher frequencies is equivalent to blurring



Local Contrast

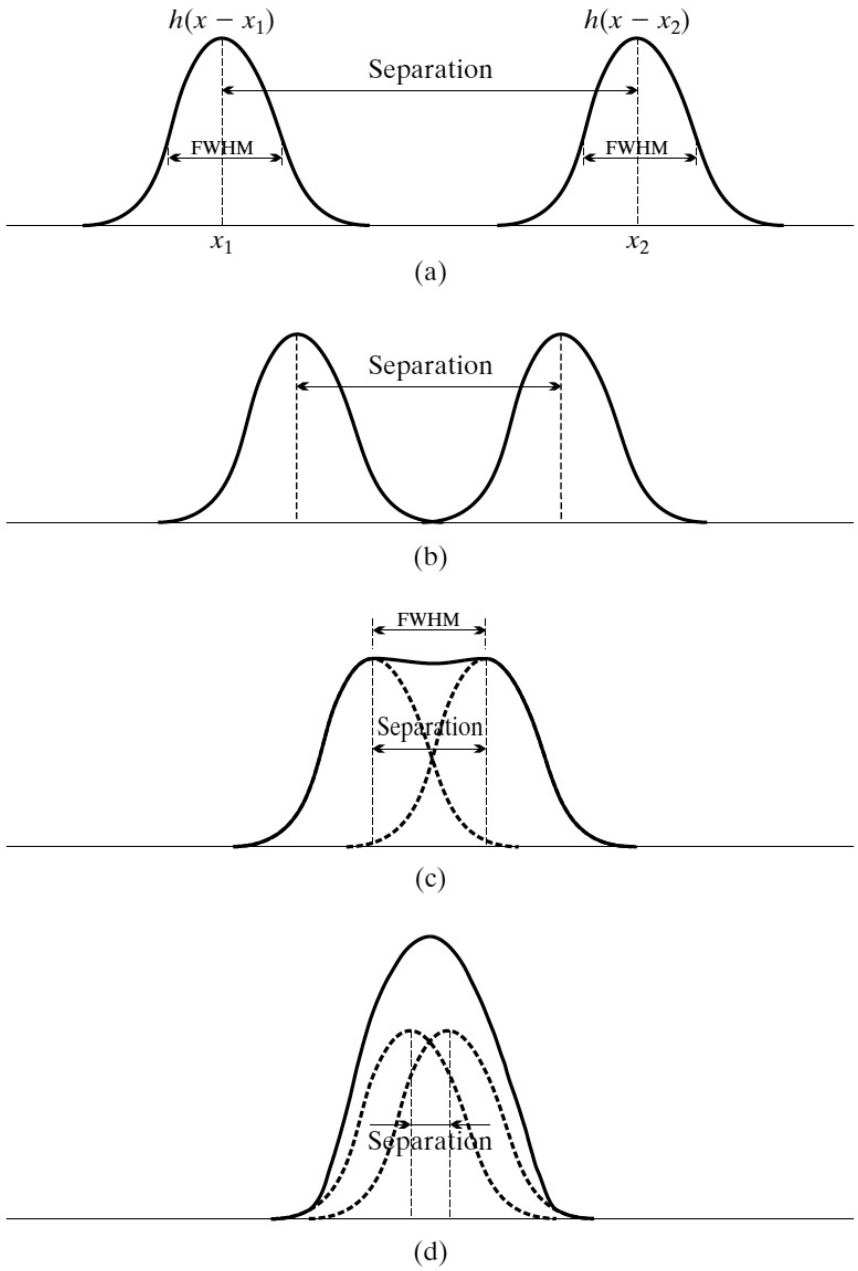
- MTF is valid for sinusoidal objects
- For localized objects, we can use local contrast



$$C = \frac{f_T(x,y) - f_B(x,y)}{f_B(x,y)}$$

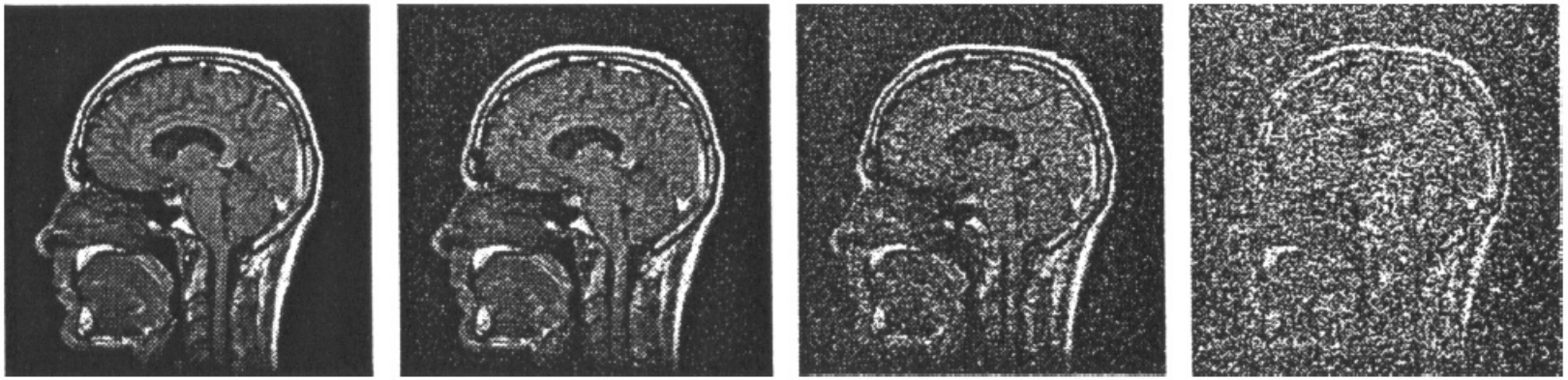
Resolution

- Defined as the ability to accurately depict two distinct events in space, time, or frequency as separate
- The full-width at half-maximum (FWHM) is the minimum distance for the two points to be separable
- A decrease in FWHM is an increase in resolution



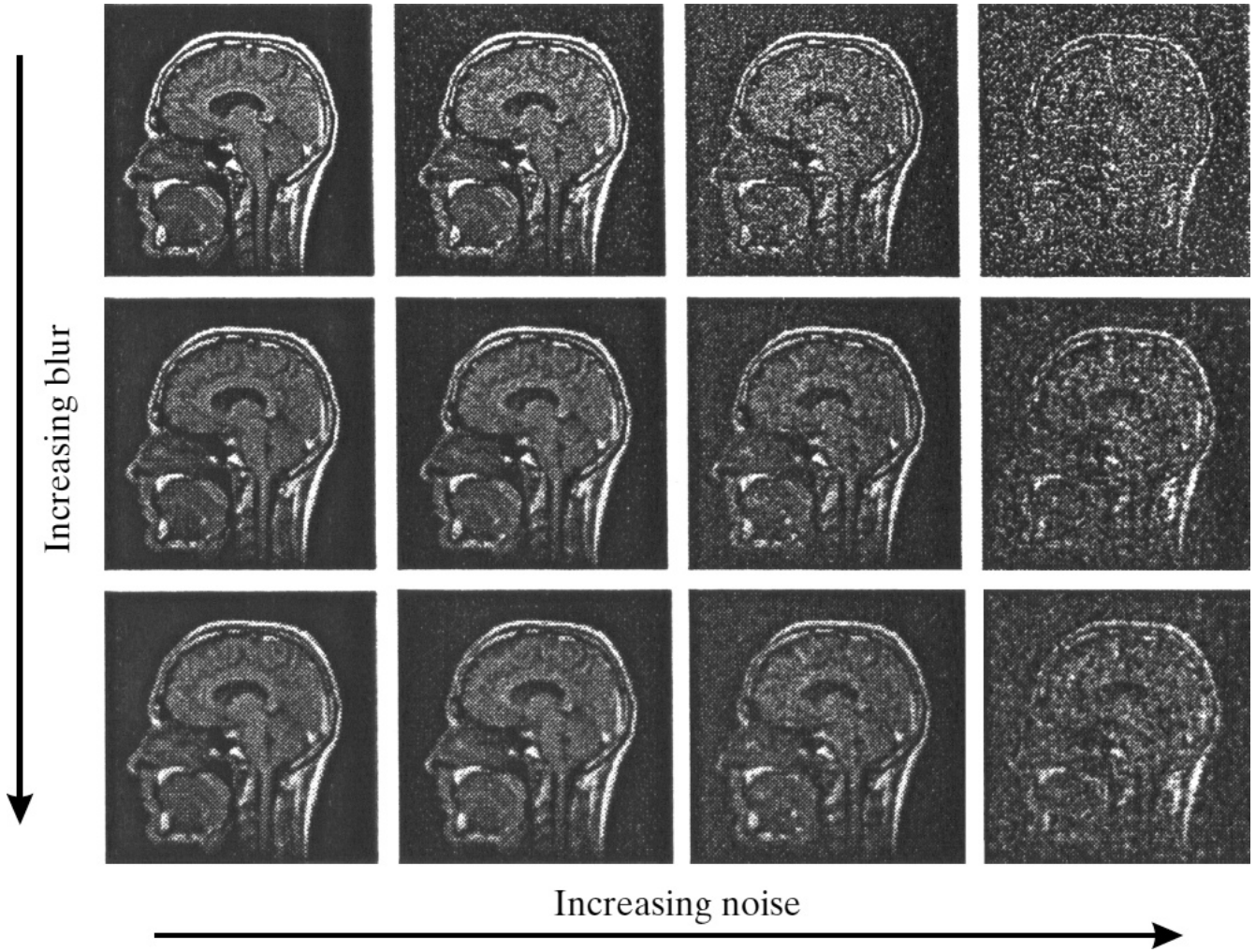
Noise

- Source and type of noise depends on the physics of the imaging system
- Noise is a degrading effect



Signal to Noise Ratio

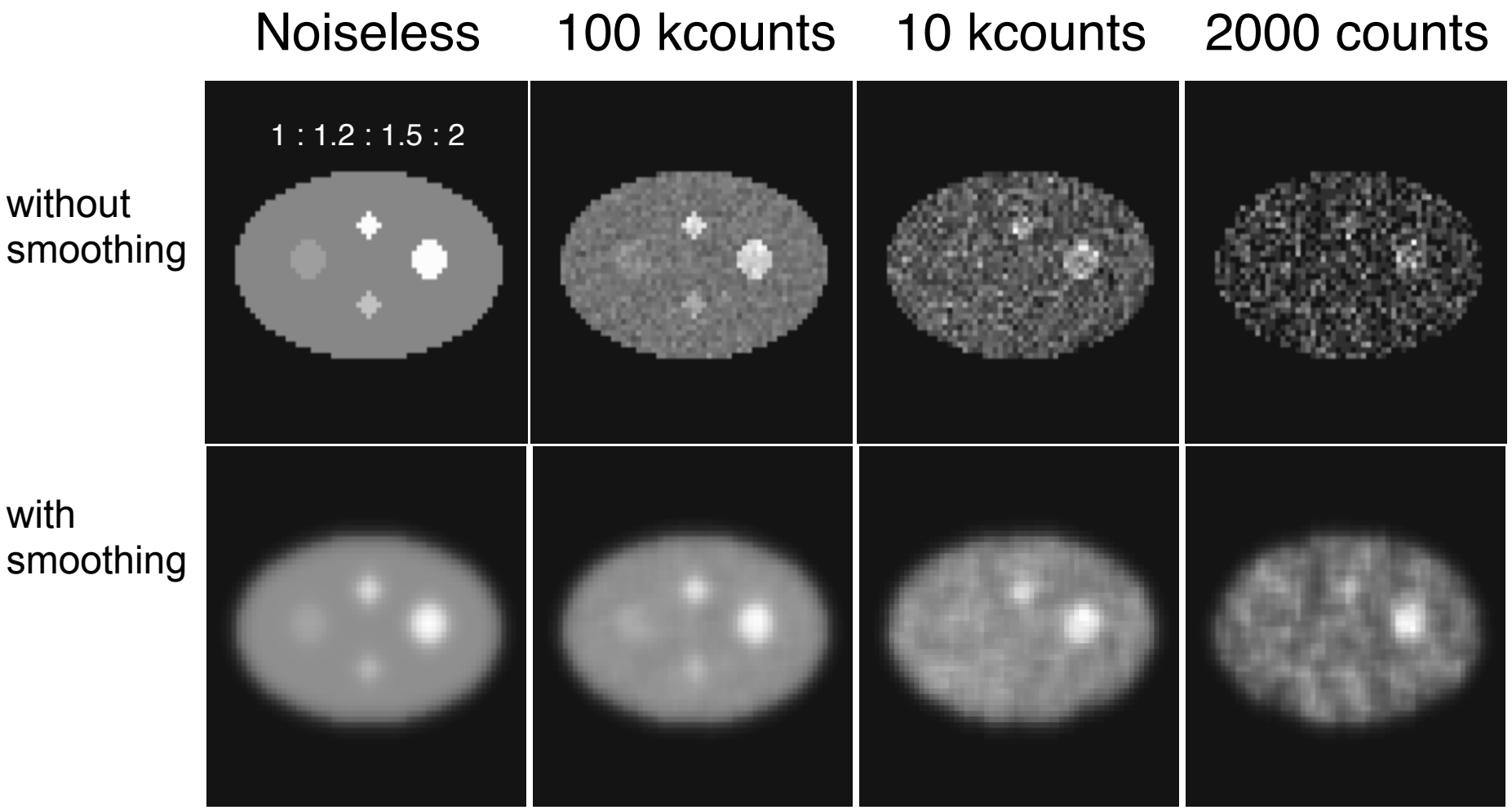
- When we reduce noise, we reduce contrast (or resolution)
- Evaluate overall effect through the signal-to-noise ratio (SNR)



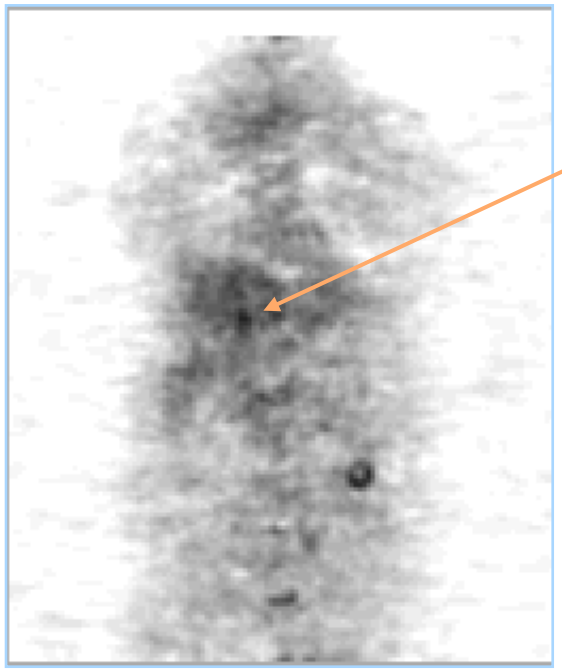
Signal to Noise Ratio

- Exact form of SNR depends on the physics of the imaging system (since noise does)
- Two common forms:
  - Amplitude SNR $$SNR_A = \frac{\text{Amplitude}\{f(x,y)\}}{\text{Amplitude}\{N(x,y)\}}$$
  - Power SNR $$SNR_P = \frac{\text{Power}\{f(x,y)\}}{\text{Power}\{N(x,y)\}}$$

Detectability: Is it there?



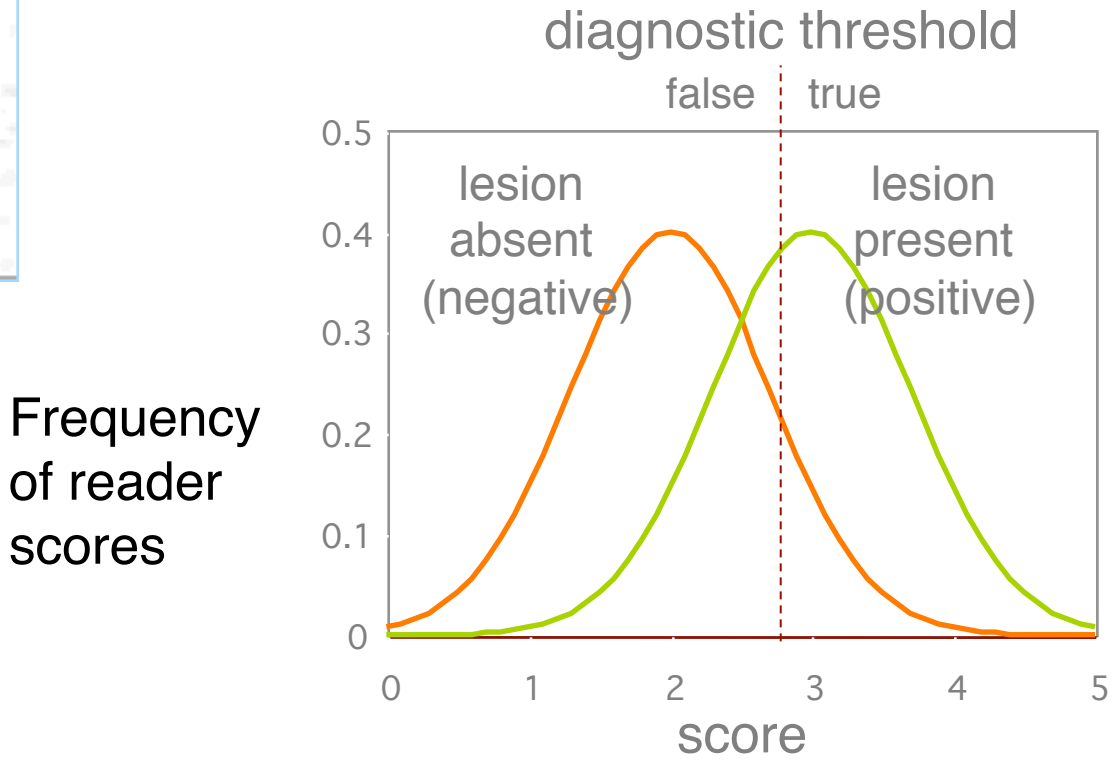
Quantifying Detection Performance



?

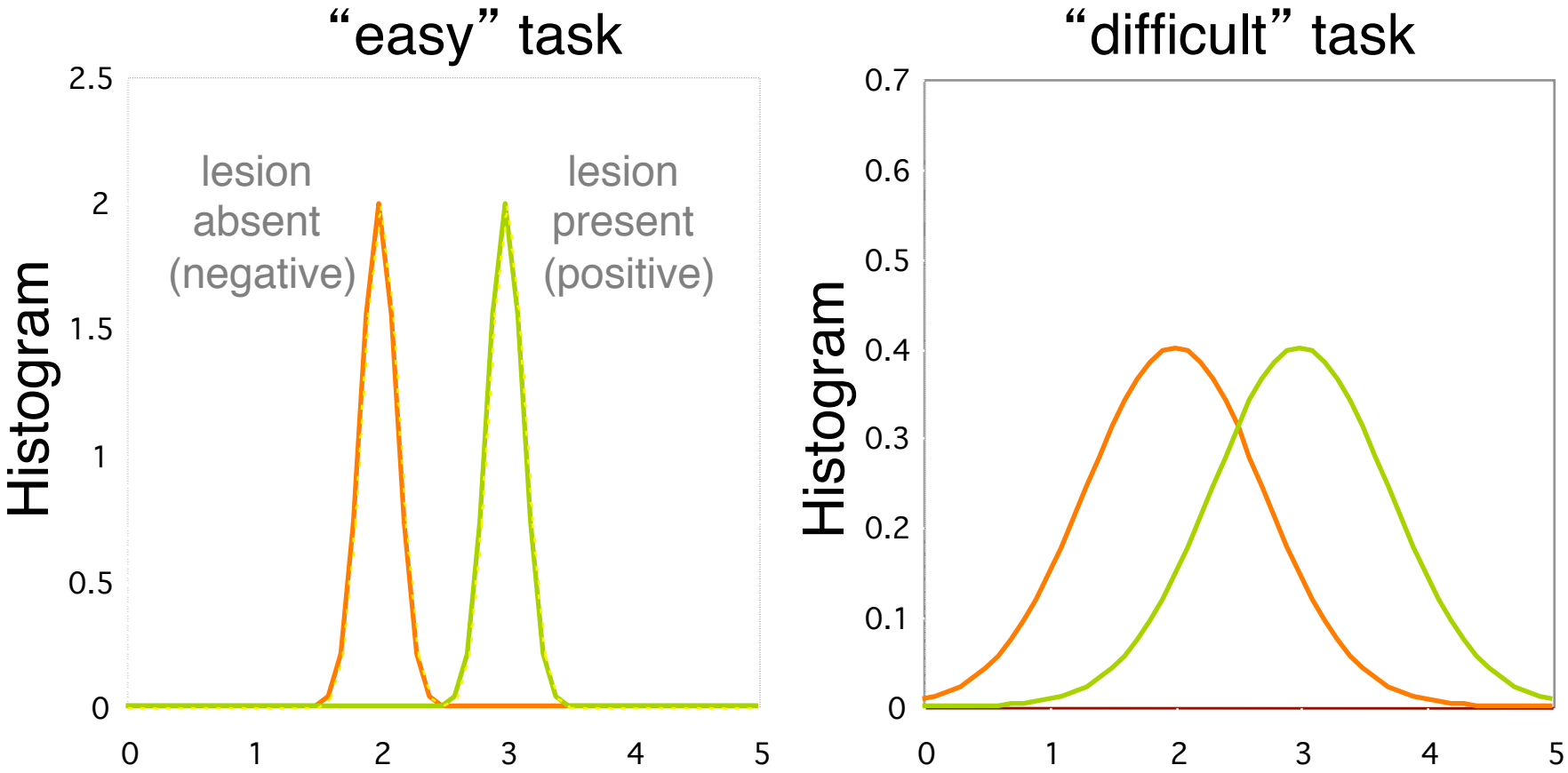
Possible method of reader scoring:

1 = confident lesion absent
2 = probably lesion absent
3 = possibly lesion absent
4 = probably lesion present
5 = confident lesion present



Frequency of reader scores

Class Separability (e.g. detectability)



Reader score (1 = confident lesion absent, 5 = confident lesion present)

Quantifying Detection Performance

Does the observer say the object is present?	Is the object present? Positive	Is the object present? Negative
True	True Positive (TP)	False Positive (FP)
False	False Negative (FN)	True Negative (TN)

Key concepts

- Sensitivity: True positive fraction

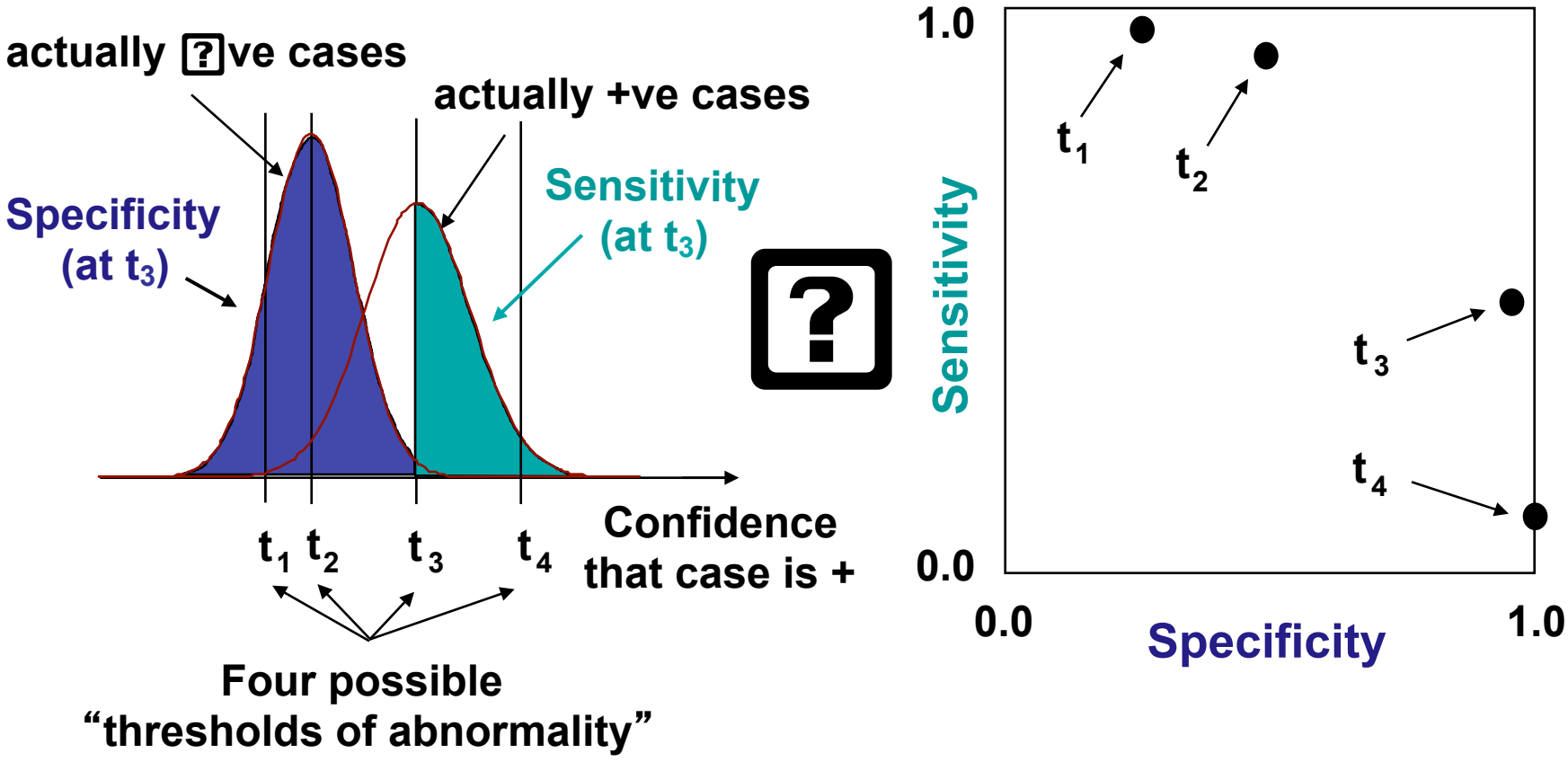
  (TPF) = TP/(TP + FN) = TP/P
- Specificity: True negative fraction

  (TNF) = TN/(TN + FP) = TN/N
- Accuracy = (TP + TN) / (P + N)

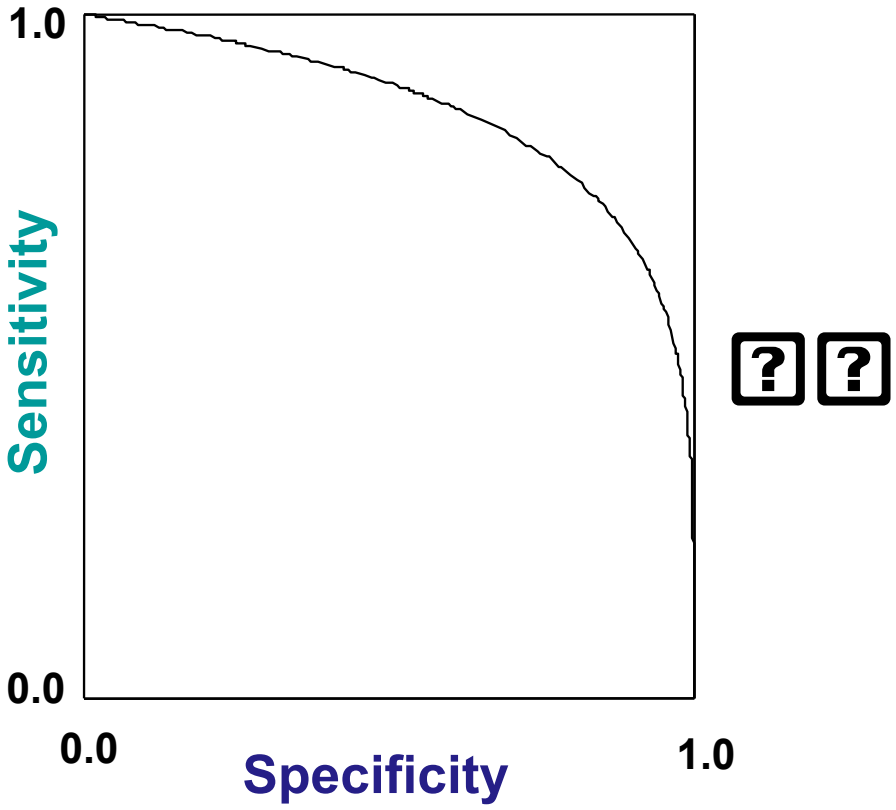
Is the object present?

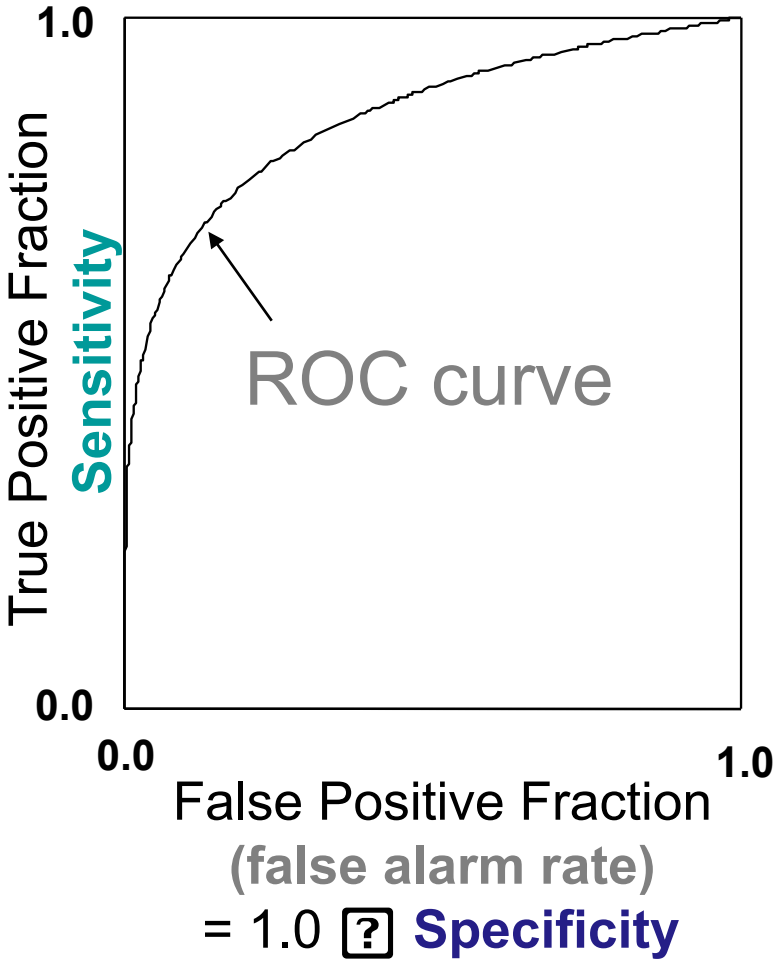
	Positive	Negative
True	True Positive (TP)	False Positive (FP)
False	False Negative (FN)	True Negative (TN)

Dependence of Sensitivity and Specificity on “threshold of abnormality”:

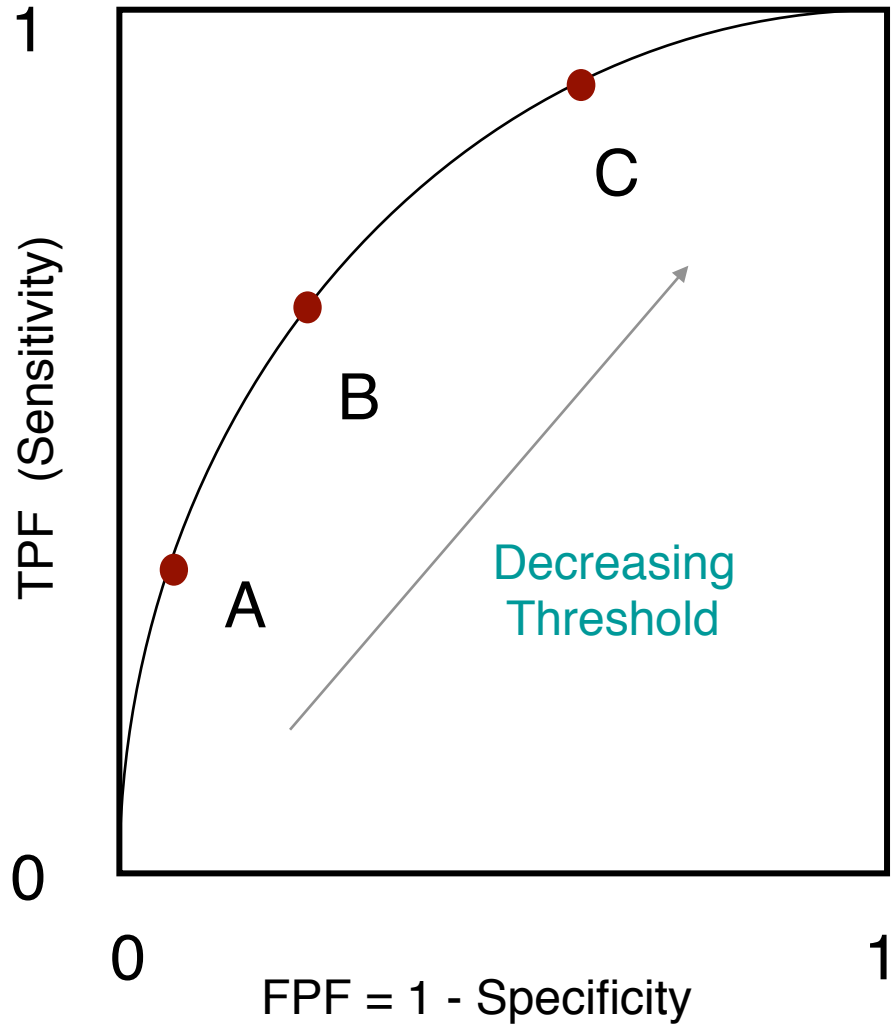


Reciever Operating Characteristic (ROC) Curve



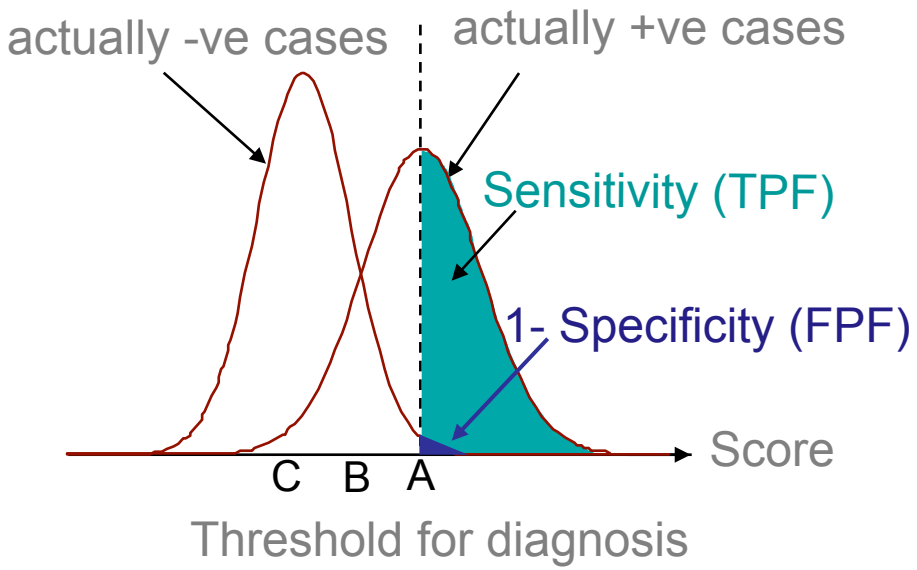


The ROC Curve

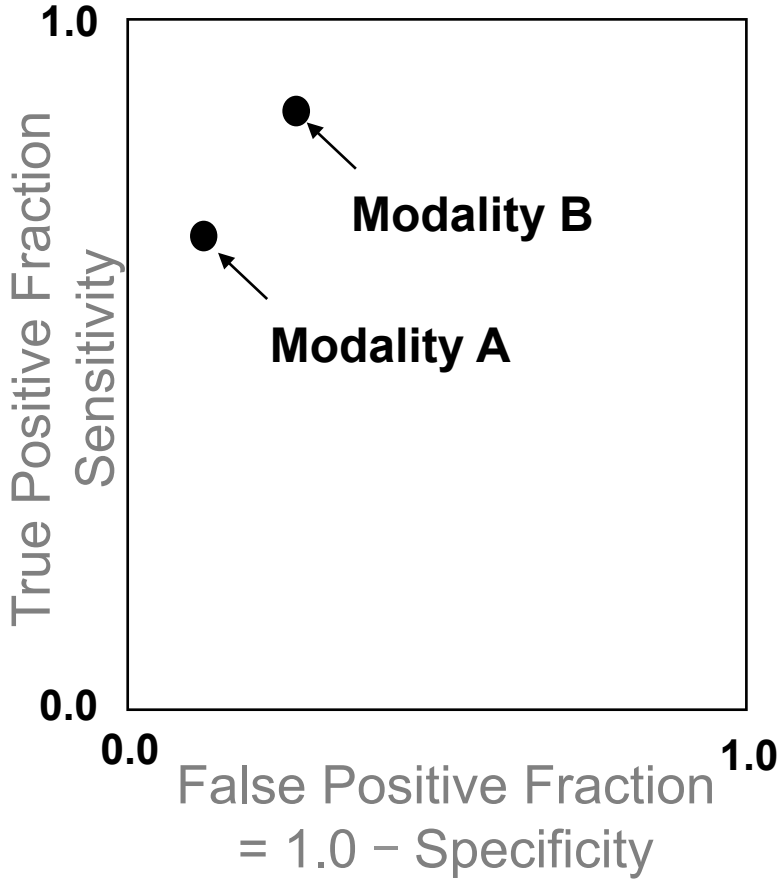


Points A, B, & C correspond to different thresholds

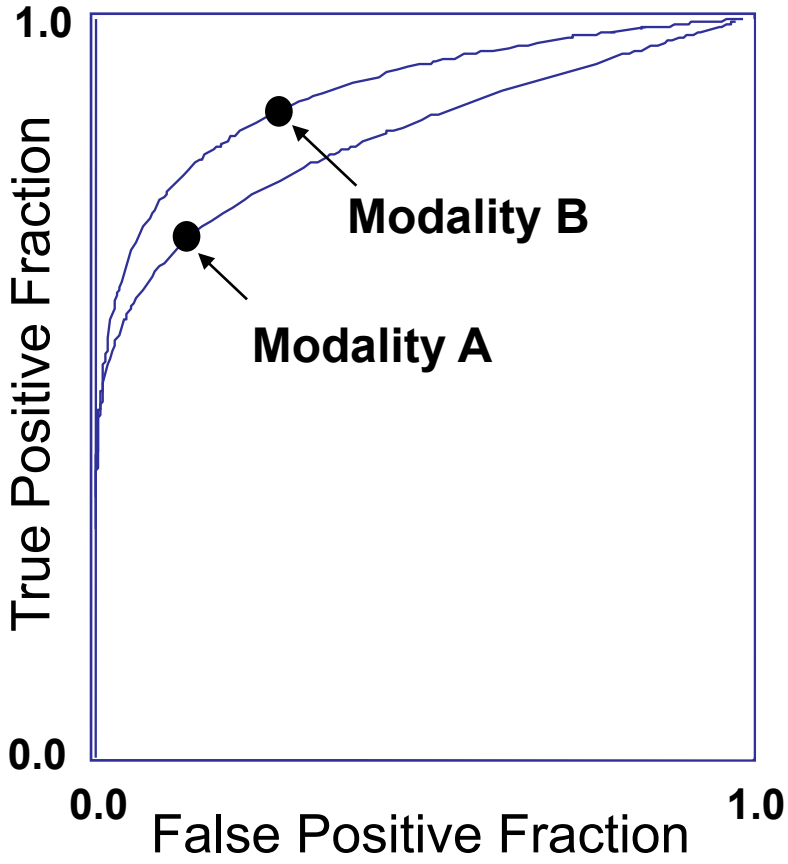
Note, for example, it is always possible to make sensitivity = 1 if the threshold is low enough!



A dilemma: Which modality is better?



The dilemma is resolved after ROCs are determined (one possible scenario):

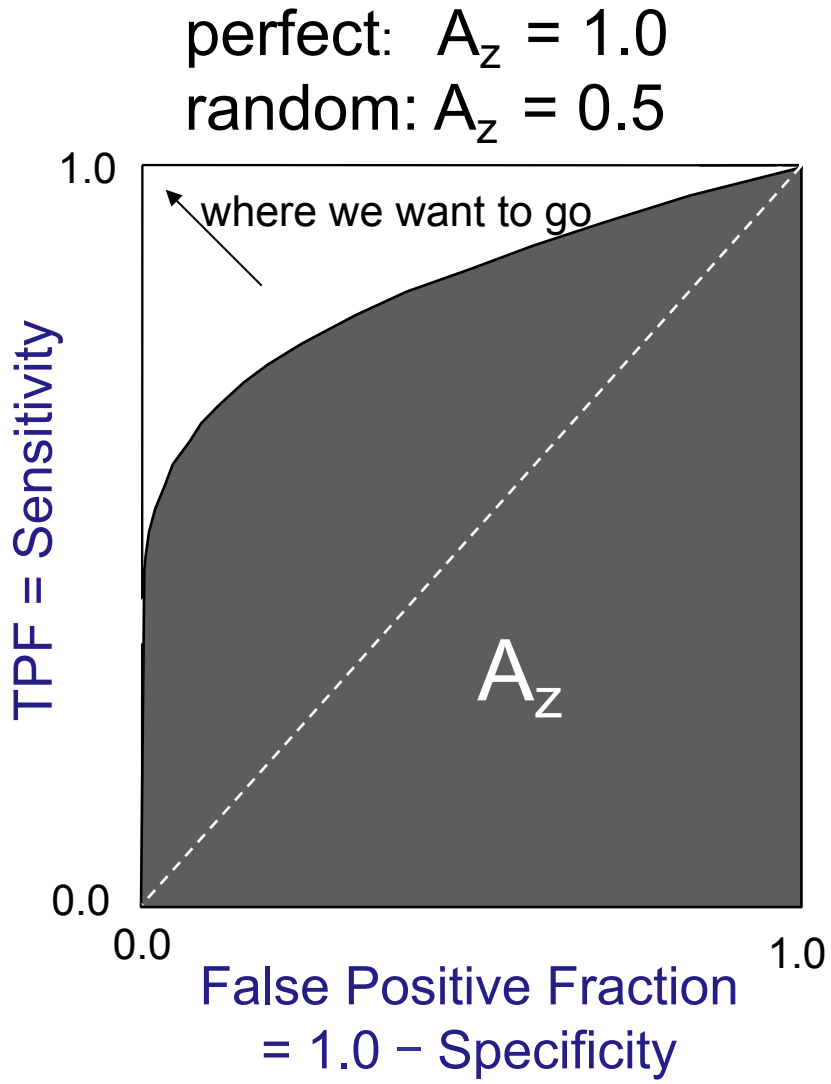


Conclusion:

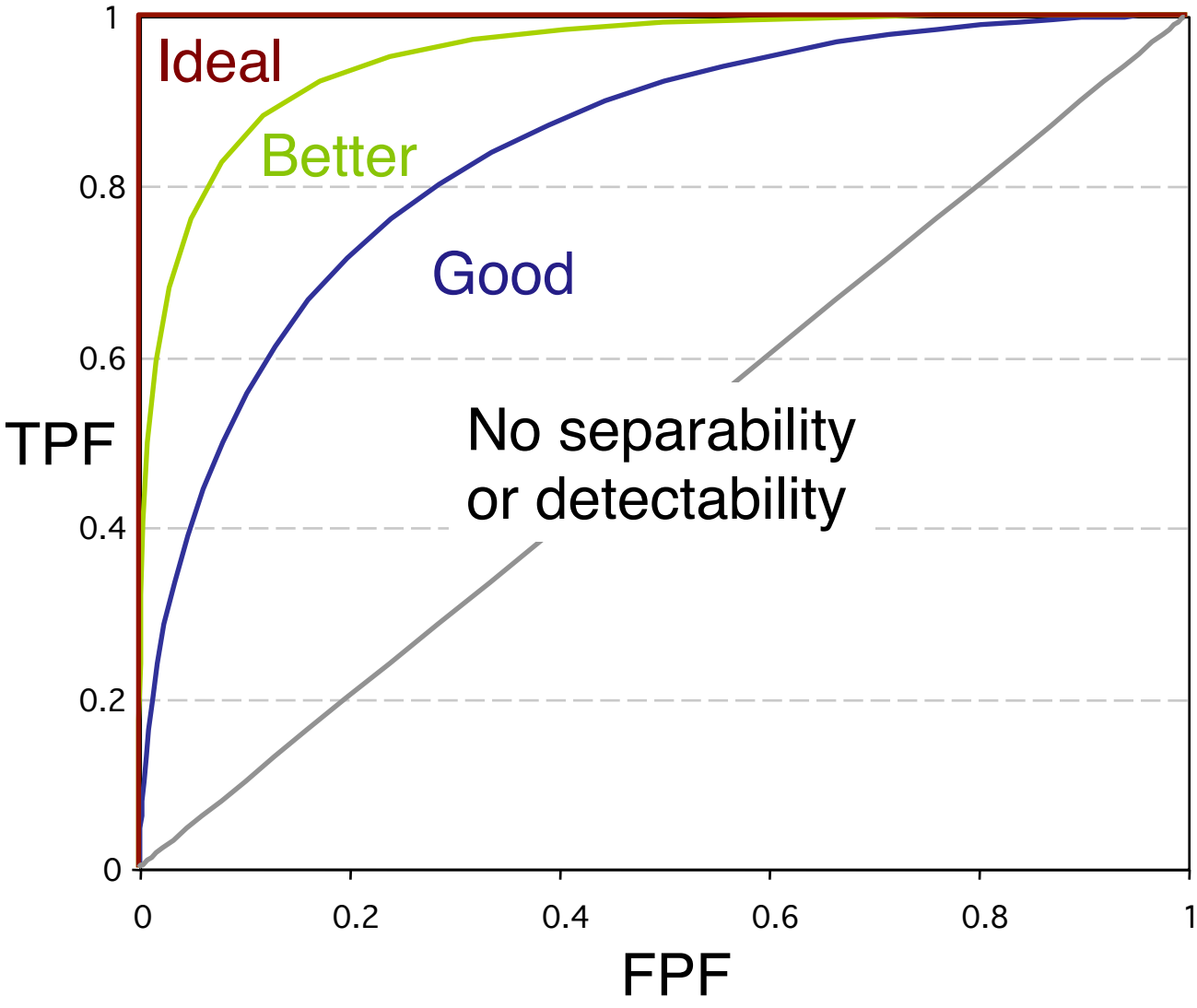
Modality B is better, because it can achieve:

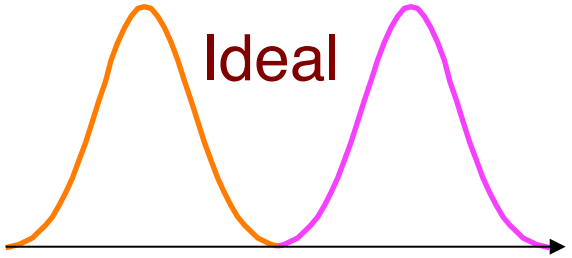
- higher TPF at same FPF, or
- lower FPF at same TPF

The ROC Area Index (A_z)

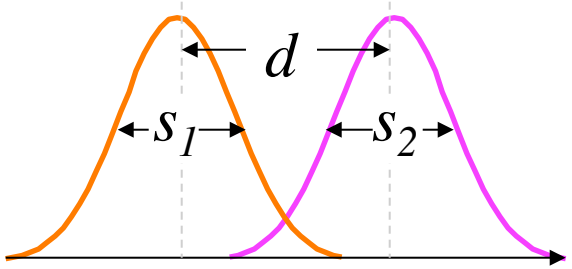


Comparing Imaging Systems



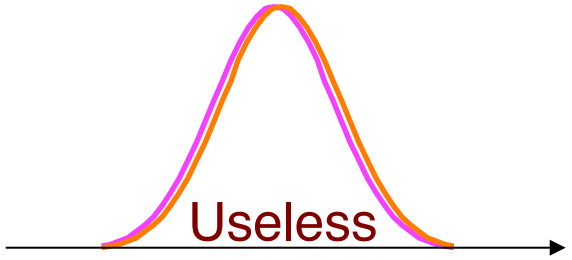


Typical



$$SNR = \frac{d}{\sqrt{\left(s_1^2 + s_2^2\right)/2}}$$

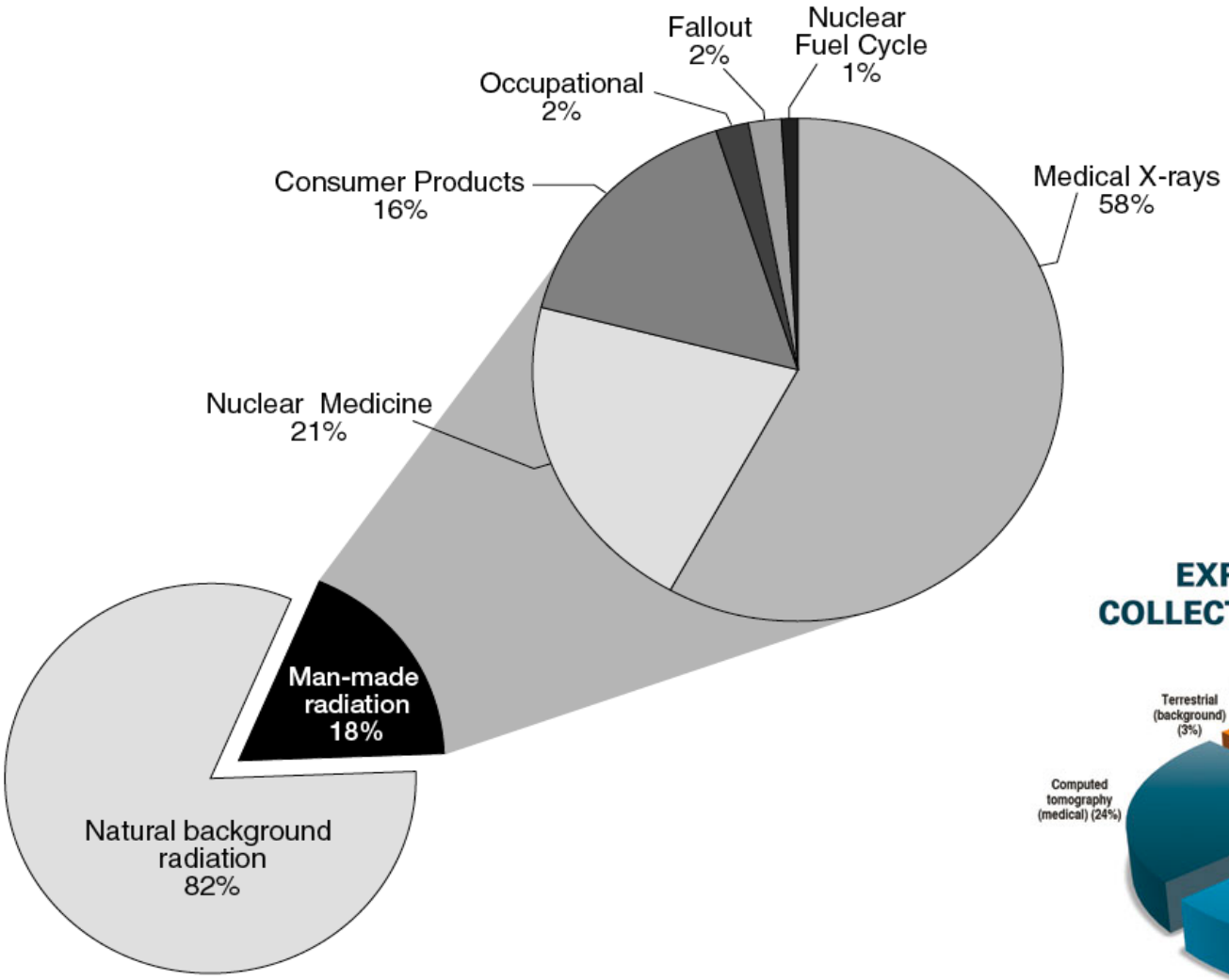
(SNR for detection task)

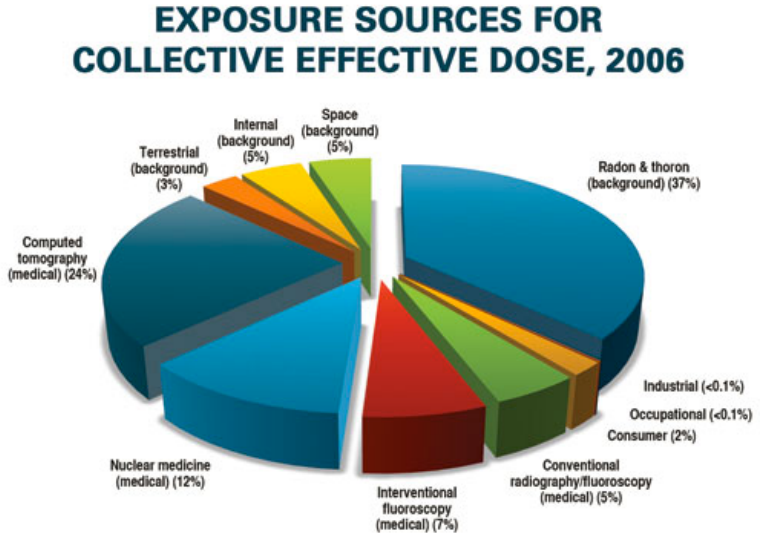


Radiation Dosimetry

a few beginning basics to a complex topic

Sources of Radiation Exposure in U.S.





This figure is based on data from "Ionizing Radiation Exposure of the Population of the United States", National Council on Radiation Protection and Measurements, No.93, 1987.

Dosimetry Descriptors - From Ionizing Radiation

Exposure:

Amount of ionization of air caused by radioactive source
Charge per mass of air, ***Coulomb/kg*** *=* ***3876 roentgens***
Can be measured directly
Does not account for biological effects

Absorbed Dose:

Energy per mass of tissue, Joules/kg = ***gray (Gy)*** *= 100 rads*
Usually calculated from exposure measurement
Does not account for biological effects

Equivalent Dose:

*(Absorbed Dose) * radiation weighting factor (w_R or Q factor)*
Also energy/mass, but units are ***sieverts (Sv)*** *= 100 rem*
Biological effects of absorbed dose depend on the type of radiation

Effective Dose:

*Sum Over All Tissues[(Equivalent Dose$_T$) * tissue weighting factor (w_T)]*
Also measured in ***Sv***

The risk of cancer from a dose equivalent depends on the organ receiving the dose. The quantity "effective dose" is used to compare the risks when different organs are irradiated.

Estimating Effective Dose

To go from absorbed dose (Gy) to equivalent dose (Sv), need:

Radiation weighting factors

Type	w_R
Photons	1
Electrons (β), muons	1
Neutrons (varies with energy)	5-20
Protons	5
alpha (α), heavy nuclei	20

For CT and PET, 1Gy = 1Sv

International Commission on Radiological Protection, ICRP, Publ. 60, 1990 (www.icrp.org, Annals of the ICRP)

To go from Equivalent Dose (Sv) to Effective Dose (Sv), need:

Tissue weighting factors

Tissue or organ	w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05
Total	**1.00**

$D_{WB}(P)$ = absorbed dose to the whole body that has probability P of causing cancer

$D_T(P)$ = absorbed dose in a single organ, T, that has probability P of causing cancer in that organ

$$w_T = \frac{D_{WB}(P)}{D_T(P)}$$

ALARA: As Low As Reasonable Achievable

TABLE 23-18. NUCLEAR REGULATORY COMMISSION (NRC) REGULATORY REQUIREMENTS: MAXIMUM PERMISSIBLE DOSE EQUIVALENT LIMITS[a]

Limits	Maximum permissible annual dose limits	
	mSv	rem
Occupational limits		
Total effective dose equivalent	50	5
Total dose equivalent to any individual organ (except lens of eye)	500	50
Dose equivalent to the lens of the eye	150	15
Dose equivalent to the skin or any extremity	500	50
Minor (<18 years old)	10% of adult limits	10% of adult limits
Dose to an embryo/fetus[b]	5 in 9 months	0.5 in 9 months
Nonoccupational (public limits)		
Individual members of the public	1.0/yr	0.1/yr
Unrestricted area	0.02 in any 1 hr[c]	0.002 in any 1 hr[c]

[a]These limits are exclusive of natural background and any dose the individual has received for medical purposes; inclusive of internal committed dose equivalent and external effective dose equivalent (i.e., total effective dose equivalent).
[b]Applies only to conceptus of a worker who declares her pregnancy. If the limit exceeds 4.5 mSv (450 mrem) at declaration, conceptus dose for remainder of gestation is not to exceed 0.5 mSv (50 mrem).
[c]This means the dose to an area (irrespective of occupancy) shall not exceed 0.02 mSv (2 mrem) in any 1 hour. This is not a restriction of instantaneous dose rate to 0.02 mSv/hr (2 mrem/hr).

Shielding

Distance

Exposure time

Average Dose Equivalent

TABLE 23-3. AVERAGE ANNUAL OCCUPATIONAL EFFECTIVE DOSE EQUIVALENT IN THE UNITED STATES

Occupational category	Average annual total effective dose equivalent	
	mSv	mrem
Uranium miners[a]	12.0	1,200
Nuclear power operations[b]	6.0	600
Airline crews	1.7	170
Diagnostic radiology and nuclear medicine techs	1.0	100
Radiologists	0.7	70

Adapted for measurably exposed personnel from National Council on Radiation Protection and Measurements. *Exposure of the U.S. population from occupational radiation.* NCRP report no. 101. Bethesda, MD: National Council on Radiation Protection and Measurements, 1989.
[a]Includes 10 mSv (1 rem) from high LET (α) radiation.
[b]Includes 0.5 mSv (50 mrem) from high LET (α) radiation.
LET, linear energy transfer.

Bushberg et al, The Essential Physics of Medical Imaging, Lippencott, Williams & Wilkins, Philadephia, 2002.

TABLE 9.1. *Characteristics of common radionuclides*

Nuclide	Photons (keV)	Production mode	Decay mode	Half-life ($T_{1/2}$)
^{67}Ga	93, 185, 296, 388	Cyclotron	EC	78 hr
^{99m}Tc	140	Generator	IT	6 hr
^{111}In	173, 247	Cyclotron	EC	68 hr
^{123}I	159	Cyclotron	EC	13 hr
^{125}I	27, 36	Reactor	EC	60 d
^{131}I	364	Fission product	β	8 d
^{133}Xe	80	Fission product	β	5.3 d
^{201}Tl	70, 167	Cyclotron	EC	73 hr

β, beta decay; EC, electron capture; IT, isomeric transition.

Some Reactor-produced Radionuclides Used in Nuclear Medicine and Radiotracer Kinetics

Radionuclide	Decay Mode	Production Reaction	Natural Abundance of Target Isotope (%)	σ_c (b)*
^{14}C	β^-	$^{14}N(n,p)^{14}C$	99.6	1.81
^{24}Na	(β^-,γ)	$^{23}Na(n,\gamma)^{24}Na$	100	0.53
^{32}P	β^-	$^{31}P(n,\gamma)^{32}P$	100	0.19
		$^{32}S(n,p)^{32}P$	95.0	—
^{35}S	β^-	$^{35}Cl(n,p)^{35}S$	75.5	—
^{42}K	(β^-,γ)	$^{41}K(n,\gamma)^{42}K$	6.8	1.2
^{51}Cr	(EC,γ)	$^{50}Cr(n,\gamma)^{51}Cr$	4.3	17
^{59}Fe	(β^-,γ)	$^{58}Fe(n,\gamma)^{59}Fe$	0.3	1.1
^{75}Se	(EC,γ)	$^{74}Se(n,\gamma)^{75}Se$	0.9	30
^{125}I	(EC,γ)	$^{124}Xe(n,\gamma)^{125}Xe \xrightarrow{EC} {}^{125}I$	0.1	110
^{131}I	(β^-,γ)	$^{130}Te(n,\gamma)^{131}Te \xrightarrow{\beta^-} {}^{131}I$	34.5	0.24

*Thermal neutron capture cross-section, in barns, for (n,γ) reactions (see Section D.1).

Properties of Gamma Rays and Beta Rays

Gamma Rays

massless photons travel potentially long distances in body

➔ *emitted with single energy (mono-energetic, allows energy discrimination)*

➔ *penetration is exponential:* $N=N_0 e^{-\mu(E,Z,r,interaction)*x}$

➔ *typical ~ cm-to-m penetration, no limits to penetration depth*

➔ *difficult to collimate – requires high Z &/or high density material (e.g Pb, W)*

Beta Rays (e- & e+)

charged particles with mass undergo many interactions in body

➔ *emitted with continuous energy distribution (energy discrimination not effective)*

➔ *no analytical rule for penetration depth (between exp.&linear)*

➔ *typical ~ mm penetration, maximum penetration depends on particle E*

➔ *easy to collimate*