Bushberg Chapter 10: Image Quality

Contrast: Difference in the image gray scale between closely adjacent regions on the image.
-*Subject Contrast* (Cs): Difference in some aspect of the signal, prior to its being recorded.
- can be a consequence of a difference in intensity, energy fluence, x-ray energy, phase, radionuclide activity, relaxation characteristics, etc…
- can be defined as Cs = (A-B)/A, where A and B represent x-ray fluence through adjacent slabs of soft tissue (units in photons/cm^2). Or, Cs = e^{-uz}, where u is linear attenuation coefficient and z is difference between subject thickness of A and B.
-*Detector Contrast* (Cd): determined by how detector "maps" detected nrg into the output signal. Different detectors convert input nrg to output signal w/ different efficiency.
-*Radiographic Contrast*: only applicable for screen-film radiography and mammography, where the analog film is the ouput and the contrast that is seen is called the radiographic contrast. Radiographic contrast = OD_A- $OD_{B,}$ where A and B refer to adjacent regions on the radiographs.
-Digital Image Contrast (Contrast-to-Noise Ratio [CNR]): applicable for digital images. CNR = (A-B)/σ, where σ represents noise. Noise is simply the standard deviation of the mean number of photons per unit area (discussed below in the "Noise" section).

Spatial Resolution: Describes the ability of an image system to accurately depict objects in the two spatial dimensions of the image. Basically, the ability of an image system to distinctly depict two objects as they become smaller and closer together.
Ways to measure spatial resolution of an image system are:
Point Spread Function (PSF): Image produced from a single point stimulus to a detector. PSF describes the blurring properties of an imaging system. A point source is used for assessing nuclear imaging image system quality, a very thin metal wire is used in CT, a monofilament is used in US, and a small hole filled with water can be used in MRI.
Convolution: Describes mathematically what happens to the signal physically. It is assessed by breaking up an input image into its constituent point stimuli, individually blurring each point using the PSF of the imaging system, and then adding up the net result.

Other Spread Functions: Used in imaging systems in which it is difficult to experimentally measure a PSF (e.g. screen-film system). *Line Spread Function* (LSF) describes the response of an imaging system to a linear stimulus. To determine the LSF, a slit image is acquired and a 90-degree profile across the split is measured. Can be thought of as a linear collection of a large number of PSFs.
Edge Spread Function (ESF) uses a sharp edge rather than simply a line. ESF is measured when various influences to the imaging system are dependent on the area exposed, such as when the spatial properties of scattered x-ray radiation are measured, or for systems that have a large amount of optical light scattering, such as fluoroscopy.

Physical Mechanisms of Blurring: Common mechanisms include reduced spatial resolution of an image produced by an optical device by defocusing, thicker screens, motion, slice thickness (i.e. CT, MRI, US).

Image Magnification: Magnification of an object onto an imaging plane occurs in x-ray imaging. Magnification can interact w/ a finite-sized x-ray tube focal spot to degrade spatial resolution. Paradoxically, magnification can also improve spatial resolution if a very small focal spot is used (e.g. mammography). (See Bushberg Ch. 6 for more detail on image magnification).

Frequency Domain: Alternate way to express resolution properties of an imaging system. Just as sound waves are measured in temporal frequency (cycles/sec, or sec^{-1}), objects on an image can be measured by spatial frequency (cycles/mm). Shorter distances between objects correspond to higher spatial frequencies. Spatial frequency (F) = $1/(2\Delta)$, where Δ is the size of the object, measured in mm. Sine waves or square waves are used in measuring spatial frequency. With the square wave, each cycle becomes a line pair - the bright stripe and its neighboring dark stripe. Thus, the units of spatial frequency are sometimes expressed as line pairs/mm, instead of cycles/mm. Low spatial frequencies correspond to larger objects in the image, and higher spatial frequencies correspond to smaller objects.

Modulation Transfer Function (MTF [f]): The MTF is a plot of an imaging system's modulation versus spatial frequency.
Basically, suppose we have multiple sine waves of different frequencies. Now suppose each sine wave serves as an input to a hypothetical imaging system, and the amplitude of each input sine wave corresponds to 100 units (amplitude is really just the contrast between peaks and valleys of the sine wave). As the spatial frequency increases, the input sine waves are blurred more by the PSF of the imaging system, and thus causes a greater reduction in the output amplitude (i.e. contrast) of the imaging system. These output amplitudes are then plotted on an x-axis and the MTF (which is just a fancy way of saying output contrast) is plotted on the y-axis.
Thus, the MTF is simply just a plot that demonstrates the spatial resolution of an imaging system as a function of spatial frequency – the higher the frequency, the lower the resolution capabilities.

Noise: Noise simply adds or subtracts to a measurement value such that the recorded measurement differs from the actual value.
In imaging, one of the most important sources of noise is *quantum noise*. Quantum noise simply represents individual distinct, measureable quantities of noise. Examples of quanta are x-rays, electrons, ions, and light photons.
For a digital x-ray detector system with square pixels, if the average number of x-rays recorded in each pixel is N, then the noise (per pixel) will be $\sigma = \sqrt{N}$, where σ is simply the standard deviation (or NOISE!) of N. What's more important is the relative noise that the human observer perceives in an image. This is best interpreted using the signal-to-noise ratio (SNR). "Signal" here is identical to N. Thus, SNR = $N/\sigma = N/\sqrt{N} = \sqrt{N}$. So, as

signal (or N) is increased in an image, the SNR increases as $\sqrt{N}$. Thus, as N increases, SNR increases at a relatively slower rate, so to the observer, the relative noise goes down.

Other Sources of Image Noise: For an x-ray imaging system to be *x-ray quantum limited* (which is a desirable goal), the number of quanta used along the imaging chain cannot be less than the number of detected x-ray quanta. Thus, the better the light conversion efficiency, the less relative noise. A *quantum sink* occurs when the number of quanta in a portion of the imaging system is less than the number of detected x-ray photons. This implies a flaw in the imaging design since the system is no longer x-ray quantum limited.

Contrast Resolution: The ability to visualize low-contrast, subtle objects. To reliably identify and object, the SNR needs to be better than about 5 (this is known as *Rose's criterion*). If the contrast of an object on a homogeneous noisy background is increased, SNR will increase. If the area of the object is increased without a change in contrast, SNR will increase. Of note, normal tissue anatomy can act to mask subtle lesions and reduces contrast resolution, and this effect is called *structure noise*.

Noise Frequency, W(f): Noise on an image often has frequency components to it. Thus, it is not entirely random. A frequency analysis is performed by using the Fourier transform to calculate the noise power spectrum [NPS(f)]. Basically, as frequency increases (cycles/mm), noise power decreases.

Detective Quantum Efficiency (DQE): Used to describe overall SNR performance of an imaging system. Defined as the ratio of the SNR^2 output of the system to the SNR^2 of the signal input into the system. $DQE = SNR^2_{OUT}/SNR^2_{IN}$. As with NPS, as frequency increases, DQE decreases.

Contrast-Detail Curves: A *qualitative* way to combine the notions of spatial and contrast resolution. Typically, the x-axis of the image corresponds to the size of objects (*detail*), with smaller objects towards the left, and the y-axis corresponds to the contrast of the objects, with lower contrast toward the bottom of the image. As objects get smaller and lower in contrast, their SNR is reduced and they become harder to see on the image.

Receiver Operating Characteristic (ROC) Curves: Can be used to compare the diagnostic abilities of different radiologists, or it can be used to compare the diagnostic performance of two different imaging modalities. The purpose of the ROC curve is to analyze the SNR associated with a certain diagnostic task when comparing different imaging modalities or, in the case of human observers, to compare *internal noise*, which effects individual performance. An ROC curve is a plot of the true-positive fraction (TPF) on the y-axis versus the false-positive fraction (FPF) on the x-axis. TPF = TP/(TP + FN). FPF = FP/(FP + TN). Basically, a perfect ROC curve rides the left and top edges of the ROC plot. Pure guessing gives a diagonal line bisecting the plot. The area under the ROC curve is a concise description of the diagnostic performance of the systems being tested. A value of 1.0 is perfect performance. A value of 0.5 is worst performance (i.e. pure guessing).