*Information Content of Low-Dose Radiographs,
Part 2*

Roger A. Morris

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Abstract

The previous paper¹ described the concept of using the net number of information bits transmitted in a radiographic image as a measure of the contrast parameter of image quality. The concept is particularly useful when the image contrast is limited by the statistics of the photon fluence incident on the detector (low doses). The information content (IC) is calculated from

$$IC = H(y) - H(y|x),$$

where $H(y)$ is the total entropy of the image (y = image signal value) and $H(y|x)$ is the conditional entropy of the image given the object thickness x . The information content has units of bits if the entropy is calculated with logarithms to base 2. $H(y|x)$ is the entropy of the noise in the image.

The Wolfram Research Mathematica program (described in Ref. 1) that was used to simulate a noisy image of an object with two thicknesses and to calculate the resulting IC. The only noise source in the simulation was fluctuations in the photon fluence incident on the detector. The results from the simulation were compared to data obtained from actual radiographs of a copper step wedge radiographed with 10 and 50 pulses from a 150-pkV x-ray machine. Good agreement between the simulation and experiment was obtained when the photon fluence was considered a free, adjustable parameter.

This report extends the simulation described in Ref. 1 and shows how IC varies as the following radiographic parameters change:

- object thickness,
- object Z number,
- x-ray energy, and
- incident x-ray fluence.

In most cases, the IC is calculated when the object has two thicknesses which produces a maximum value of the IC of 1.0. However, the information capacity of a particular radiographic system can be calculated by increasing the number of steps in the object while keeping the total thickness constant until the IC reaches an asymptotic value. This value is the information capacity of the system. The term IC will be reserved for the information content of a particular image, not the capacity.

Simulations of Steel Penetrometer

The simulated steel object, or penetrometer, consists of a cube of steel 2.5 cm per side with a flat-bottomed hole drilled in the center of one side. The photon flux was perpendicular to this face. This produces an object with two thicknesses and, by changing the probability of a photon hitting the hole, the diameter of the hole is effectively changed. The hole diameter varied from 0.2 to 1.4 cm and the depth varied from 0.5 to 1.0 cm. The source for the calculations was a 300-kV monoenergetic isotope that simulates an Ir-192 source. Both high and low-dose images were simulated.

Two radiographic situations were considered; a high or normal dose to the detector and a low-dose radiograph. The results of the high-dose experiment produce a benchmark from which the effects of reducing the dose to minimum can be measured. Since one of the primary parameters is the linear attenuation coefficient and not the photon energy, the combination of the material type and attenuation coefficient determines the effective energy of the photon beam. The source can therefore be considered a virtual monoenergetic isotopic source where the energy is "dialed in" by defining the attenuation coefficient.

The source was assumed to be one Curie of an idealized isotope emitting a monoenergetic, 300-kV x-ray. The flux at one meter from such an isotope would be 2,944 photons/mm²/sec, or approximately, 150 mR/h at one meter. This flux converts to 91.2 photons/pixel/sec at one meter, assuming a pixel that is 0.176 mm on a side.

The simulations covered an unattenuated dose per pixel of 10,000 photons/pixel down to 10 photons/pixel. With an iron penetrometer, the total attenuation coefficient at 300 kV is 0.8/cm. The detector was assumed to be 100% efficient, absorbing every transmitted photon.

Results (High Dose)

Figures 1 and 2 are examples of the probability distributions of the image signal and the noise within the image for the steel penetrometer using an arbitrary set of radiographic parameters. The y axis is the probability of observing a pixel with a particular intensity value while the x axis is intensity in arbitrary units. The total range of observed intensity values is simply divided into 1,000 bins. The incident fluence is 10,000 photons per pixel (a high dose).

The first histogram is the actual probability of observing a particular intensity. Although noisy, two distinct peaks are visible, representing the two thickness regions.

The second histogram is the probability of observing a particular intensity given an object thickness; the conditional probability. Variations in object thickness are now removed from the distribution and we are left with the noise in the image.

Figure 1. Total probability density distribution of image intensity.

Figure 2. Conditional probability density distribution of image intensity.

Figure 3 shows the variation in IC as the hole depth (measured as the percentage of the total thickness) varies. The hole area was 50% of the total penetrometer area. Figure 4 shows the information content as the linear attenuation coefficient varies while Fig. 5 shows the same information but with the linear attenuation coefficient converted to photon energy when the object is 2.5 cm of iron.

Figure 3. Information content as a function of hole depth (percent of total thickness).

Figure 4. Information content as a function of attenuation coefficient.

Figure 5. Information content as a function of photon energy for an iron penetrometer.

Figure 6 shows information content as a function of the product of the thickness change and the square root of the area of one of the thickness regions. DeBen² has shown that the visibility of a penetrameter hole is proportional to this product. This implies that if the information content is a reliable measure of hole visibility, the IC should be proportional to this product. Since an explicit value of area is not one of the experimental parameters, the probability of a photon hitting one of the thicknesses, $px(1)$, is assumed proportional to the area of the region with thickness 1.

Figure 6. Information content as a function of DeBen's product.

Results (Low Dose)

Until now, all the results have been calculated with an incident fluence of 10,000 photons/pixel. If the incident fluence is reduced to 10 photons/pixel, the unattenuated dose at the film plane using a monoenergetic 300-kV isotopic source (iridium-192), is about 140 μ R. This can be considered a low-dose radiograph.

Figure 7 shows how the information content varies as the incident photon fluence varies from 5 to 100 photons/pixel when the thickness change is 40% (1.0-cm hole in a 2.5-cm penetrometer). The source approximates an iridium-192 source. A fluence of 10 photons/pixel approximates a total dose on the detector of 140 μ R using a pixel that is 176 micrometers on a side.

Figure 7. Information content as a function of absorbed photons/pixel.

Figure 8 shows the results of calculating IC for a steel step wedge with a total thickness of 1 cm as the number of steps is varied. The solid curve is the theoretical amount of information in the image while the dots represent the actual IC for a fluence of 1,000 photons/pixel. The actual IC seems to be approaching an asymptotic value slightly greater than 2.5 bits. This can be interpreted as the information capacity for this particular set of radiographic parameters.

Discussion

Figure 3 simply demonstrates that as the thickness change decreases, the visibility of the hole decreases. The utility of this fact lies in our ability to quantify information content to determine the limit of visibility. If this can be done, the potential of low-dose radiography to obtain an image of a particular feature can be determined with the model and the radiographic parameters specified before expensive equipment is purchased. One interesting point about Fig. 3 is that the IC is approximately equal to 0.3 when the thickness change is 2% and 0.1 for a thickness change of 1%. This implies that the IC at the limit of hole visibility lies between 0.1 and 0.2.

The implications of Figs. 4 and 5 are a bit more complex. There is a maximum in the IC as the linear attenuation coefficient varies. If the object is known this means that there is an x-ray energy that is optimum in the sense of producing the most information for a given thickness change. At lower energies, the object contrast increases but the increased noise in the image decreases the overall information content. As the energy increases, the information content decreases because the contrast decreases. However, the decrease is much slower because the statistical quality of the image increases. These results can also be derived analytically by simply calculating the signal-to-noise ratio of an image as the photon energy changes.

Note that these conclusions apply to a constant input photon fluence. With a real x-ray tube, the photon output (photon/sec) increases exponentially with tube voltage as the tube current is held constant. In fact, the exponent is about 2.8. If we were to conduct an experiment to measure the information content of a radiograph made with an x-ray tube operated at constant current but with varying voltage, the information content at high energies would be even higher than that shown in Fig. 4 because the tube output (photons/sec) increases with voltage, which increases the signal-to-noise ratio.

As seen in Fig. 5, the maximum occurs when the product of the linear attenuation coefficient and the total material thickness equals 2.0. In the object we are using, 2.5 cm of iron, this corresponds to an effective energy of about 300 kV.

Figure 6 shows that the information content varies linearly as the product of the hole depth and diameter up until the information reaches its maximum (of near 1.0 for large holes). This can be interpreted as being consistent with DeBen's results that showed that, at the limit of visibility, this product is a constant for a particular technique.

The discussion above assumes a fluence of 10,000 photons/pixel. At low doses (5 to 100 photons/pixel), the visibility of a thickness step becomes even more problematical. Figure 7 shows how the information content varies as the dose changes for a thickness change of 40%.

Simulated Images

The data used to calculate the ICs in the previous sections was used to generate simulated radiographic images of the penetrometers. The image was divided into 30 by 30 pixels and the round hole changed to a square simply for convenience in plotting the image. All of the images illustrate the visibility of a square hole that covers 50% of the penetrometer area. The gray levels are normalized to cover 256 levels for all the radiation doses. This simulates an actual image that is stretched to cover the same screen intensity range independent of the actual image intensity.

All of the images in Fig. 9 represent an unattenuated fluence of 10,000 photons/pixel (high dose), a 2.5-cm steel object, an attenuation coefficient of 0.8/cm (300-kV isotope) and a square hole in the penetrometer that covers 50% of the penetrometer area. The three images represent 1%, 2%, and 10% thickness changes.

Judging from the results of this paper and the experimental results in Ref. 1, a crude estimate of the value of IC at which a thickness step would just be visible could be placed somewhere between 0.1 and 0.2. This visibility level seems to be independent of the actual dose level as long as the image signal is stretched to an optimum viewing level.

The output signal used in these simulations is the transmitted photon fluence through the object. In a real radiograph, this signal would be the input signal to the detector and the actual output signal would depend upon the type of detector. The detector stage would introduce another source of noise and, in the case of film, a nonlinear amplification factor.

Figure 10 illustrates two simulated low-dose images for a 40% and 60% thickness change and an incident fluence of 10 photons/pixel.

Figure 9. Simulated images of high-dose radiographs of an ion penetrometer.

1% thickness change, information content = 0.156

2% thickness change, information content = 0.375

10% thickness change, information content = 0.815

Figure 10. Simulated images of low-dose radiographs of an ion penetrometer.

40% thickness change, information content = 0.203

60% thickness change, information content = 0.473

Conclusions

The importance of these simulations is not the absolute value of the fluence that produces a detectable change in thickness but in showing how image noise influences the detectability of a thickness change as other radiographic parameters change. To accurately evaluate the image quality as a function of source intensity and spectra, both source and detector would have to be modelled in much more detail. In particular, this would include knowing the QE and DQE of the detector as a function of photon energy.

References

1. R. A. Morris, "Information Content of Low-Dose Radiographs," Los Alamos National Laboratory report LA-13322-MS, June 1997.
2. Hillery S. DeBen, Photographic Science and Engineering, 6:5 (1962).