An explanation for the extremely low, but variable radiation dosages measured in a linear slit scanning radiography system.

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ABSTRACT

Clinical trails performed for the FDA’s Section 510k compliance submission of the Statscan digital, full-body, linear slit scanning diagnostic radiography system revealed that comparable diagnostic results with a commercial full-field screen film device were obtained with the Statscan using much lower radiation doses. For certain imaging procedures the doses for Statscan were as much as twenty to thirty times lower. However the results varied by a large amount and in particular the results for chest radiographs were anomalous in that the Statscan dose was less reduced. Whilst it is well known that slit scanning radiography has considerably lower radiation exposure than full-field devices due to its much lower scatter to primary ratio and also that digital radiography has the potential for lower radiation dosages, it was thought that this alone did not fully account for the dose differences. This paper suggests that these dose differences, including the anomaly mentioned above, can be explained by considering the unique way that slit scanning is undertaken by Statscan i.e. by scanning the tube, detector, slit and collimators together along a linear path. The effect on measured skin entrance doses is explained and the dosage differences as affected by digital technology, higher DQE, slit scanning (low scatter to primary ratio) and linear slit scanning methods are quantified.

Keywords: Slit scanning, linear slit scanning, digital, x-ray, radiation exposure, skin entrance dose, Scatter to primary ratio.

1. INTRODUCTION

The measurement of X-ray radiation dose and the manner in which it is often quoted (or misquoted) in diagnostic imaging is contentious. This is further complicated by the difficulty in measuring the effective dose equivalent (in sievert), which is the most relevant for human risk. Instead the skin-entrance dose, measured in grays, is in many instances used as a surrogate for radiation control in diagnostic radiology. Even within one modality (e.g. conventional screen film) widely differing measurements are quoted for the same procedure. Suppliers of modern digital radiography devices often make claims such as “50% less dose” or “the lowest radiation dose in the industry” doses without publishing comparative dosage measurements. Statscan™ claims very low dose required to achieve diagnostic equivalence with other technologies. The work reported in this paper was therefore undertaken to investigate to what extent statements such as “Statscan uses ten times less radiation exposure than conventional screen film (other than for the chest)” could be quantified. It will be apparent that, due to the large differences in radiation dose that are analyzed (e.g. unit multiples like 4 times or 8 times), relatively small factors such as the effect of backscatter† on the difference between skin-entrance and free in air Kerma doses are ignored.

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2. BACKGROUND

In this paper, the technical principle by which Statscan operates is termed “Linear Slit Scanning Radiography” or LSSR) in short. In other commercially available slit/slot scanning systems the X-ray source remains spatially fixed, either by remaining stationary or by rotating to face at the detector which is scanned. This method is referred to as FSSR for fixed source slit/slot scanning radiograph.

The radiographic geometric principles of LSSR differ from those of conventional radiography in some important ways:

- The X-ray tube, X-ray fan beam, collimating slit and detector all move together in fixed relationships along a linear scanning path.
- The X-rays are highly collimated by a narrow slit into a fan-beam.
- The X-ray detector moves synchronously with the X-ray fan beam.
- The detector is sensitive only to X-rays exactly in the fan-beam so very few scattered X-rays are detected. This means that the LSSR is only slightly susceptible to the effects of scattered X-rays, resulting in a far better contrast and signal-to-noise ratio and better image quality with ultra low X-ray doses.

Figure 1 shows where the LSSR geometry fits into the field of presently available medical diagnostic radiographic technologies:

Figure 1 Major system technology categories in diagnostic medical imaging.
Following the installation of the production prototype Statscan at Groote Schuur Hospital in Cape Town, South Africa during 1999, clinical trials where performed for the FDA’s 510K application to confirm clinical image quality equivalence to a conventional X-ray system. During these trials the skin entrance x-ray doses for both modalities were recorded. It was found that the doses used for Statscan were considerably lower, sometimes by as much as thirty times.

Subsequent to this, image quality has been improved by minor modifications improving the signal to noise ratio, as well as optimization of the standard radiographic technique factors to cater for the average USA trauma patient being much heavier than those at Groote Schuur Hospital.

Also, when comparing Statscan’s dose performance with accepted industry norms in the USA, a commonly accepted standard has been used as a reference dose. Such an updated comparison is shown in Table 1 below:

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Reference Dose * µGy</th>
<th>Statscan™ Dose ** µGy</th>
<th>Statscan™ Dose Comparison for Diagnostic Equivalence % of conventional</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spine (LAT)</td>
<td>15000</td>
<td>1640</td>
<td>11%</td>
<td>9.1</td>
</tr>
<tr>
<td>Abdomen AP</td>
<td>5000</td>
<td>409</td>
<td>8%</td>
<td>12.2</td>
</tr>
<tr>
<td>Pelvis</td>
<td>5000</td>
<td>409</td>
<td>8%</td>
<td>12.2</td>
</tr>
<tr>
<td>Skull</td>
<td>2500</td>
<td>210</td>
<td>8%</td>
<td>11.9</td>
</tr>
<tr>
<td>Full Body AP</td>
<td>1500</td>
<td>150</td>
<td>10%</td>
<td>10.0</td>
</tr>
<tr>
<td>Extremity</td>
<td>450</td>
<td>60</td>
<td>13%</td>
<td>7.5</td>
</tr>
<tr>
<td>Chest AP</td>
<td>200</td>
<td>142</td>
<td>71%</td>
<td>1.4</td>
</tr>
</tbody>
</table>

*Typical Patient Radiation Doses in Diagnostic Radiology- 75th percentile, Dept of Radiology, Baylor College of Medicine, AAPM/RSNA Physics Tutorial 1998 (CR & High Speed Film)

** Statscan Skin Entrance Radiation Doses measured for “Large” Patient (120kg – 150kg)

Table 1 – Statscan skin entrance dose compared to standard guide levels

It can be seen that Statscan operates at approximately a tenth of conventional radiography skin entrance doses except in the case of chest X-rays. This paper attempts to quantify the radiation dosage differences between LSSR and conventional geometry full-field radiology and to extrapolate this to other diagnostic modalities. In particular the investigation shows the effect of LSSR’s method of performing linear slit scanning over large areas can account for some of the observed reduction in radiation dose.

3. METHOD

Four primary reasons for the Statscan dosage differences for diagnostic equivalence were proposed:

a. The fact that it utilizes digital technology
b. The fact that it has a high detective quantum efficiency, DQE
   c. The fact that use is made of slit scanning radiography which results in a very low scatter to primary ratio, thus obviating the need for a grid in many procedures.
   d. The technique of linear slit scanning.
These factors were surveyed and an attempt was made to quantify each. Factors a, b and c are well recognized in the literature, but no references were found for factor d. It was therefore decided to investigate this more fully and to accept the order of magnitude difference quoted in the literature for factors a) and b).

A quantification of the affect of factor c on radiation dose was performed as part of an associated investigation\(^2\). Source-to-object distance radiation measurements was performed on the Statscan, and the entrance radiation dose variation with distance between Statscan and relationships based on inverse distance and inverse distance squared were compared. This was modeled and compared to the doses at different SIDs and skin entrance positions expected from full-field radiology.

The results from factors a, b, c and d are quantified in Table 3 and dosage reduction factors are allocated to each according to different modalities.

### 3.1 Dose Saving Due to Digital Technology and Higher DQE (factors a and b).

It is well known that certain digital x-ray detectors yield equivalent diagnostic performance with lower total x-ray dose\(^8\). Mostly this can ascribed to the better detector DQE, and the wider dynamic range of digital systems. The latter leads to fewer repeat and duplicated exposures to read specific anatomical objects. In conventional radiography separate exposures are necessary for optimal visibility in the lungs and the mediastinum. In digital systems, the wide latitude and grayscale windowing ability obviate the need for two exposures. To quote a recent report from the USA’s NIST: “Recent studies indicates that digital radiography achieved comparable image quality with conventional film radiography with 50 to 70 percent radiation dose reduction.”\(^9\)

It was therefore decided to allocate an expected dose saving factor of 2 times, (range 1.5 and 3.33) due to digital imaging technology and a better DQE. (See “Digital & DQE” in Table 3 below.)

### 3.2 Dose Saving Due to the Use of Fixed Slit/Slot Scanning Radiology, Fan Beam Geometry (factor c).

Fixed slit scanning leads to vastly improved scatter-to-primary (SPR) ratio on a geometric basis. This has been quantified for slit (or slot) scanning configurations versus conventional geometry\(^7\). Conventional geometry systems require the use of a grid. Although a grid reduces the SPR at the detector, it also imposes a dose penalty equal to the grid attenuation of the primary beam. The grid attenuation is typically 50\%(\(^10,11,12\)).

Except in procedures with inherently very low scatter fractions, such as chest x-rays (with grid), the dose advantage is approximately two. To allow for reasonable variation in all the various systems, a range of between 1.5 and 3 was selected (see Table 3).

### 3.3 Dose Saving Due to the Use of Linear Slit Scanning Radiology, Fan Beam Geometry (factor d).

It is shown in Section 3.3.1 that a LSSR system does not obey the inverse square law of decrease in dose with distance from the source (r). It was therefore decided to investigate how this fact may affect the skin entrance dose (in grays) as commonly measured for radiation control purposes.

#### 3.3.1. Radiation Intensity versus Distance from the Source

Consider the two geometry configurations shown in Figure 2. In conventional geometry radiography (and most FSSR configurations), the measured dose D varies with the inverse square of the distance from the source (X-ray target). For LSSR, however, D varies inversely with this distance.

The 1/r dose dependency has been experimentally confirmed for Statscan, where the measured dose of the x-ray beam per unit area from the x-ray source diminishes inversely with the distance from the source rather than by the inverse squared distance (see Figure 3). The reason for this is that in the scan direction the x-ray flux is integrated and the field area swept by the beam is independent of distance from the source. The result is that that the field area and hence flux only diverges in the slit direction yielding a 1/r dose dependency.
Figure 2: Illustration of the effect that distance from the source has on measured dose in conventional and LSSR geometry systems.

\[ I_{\text{image}} = \frac{I_{\text{out}}}{r^2} \]  

\[ I_{\text{image}} = \frac{I_{\text{out}}}{r} \]

Figure 3: The change of dose with distance from the source shown calculated as a \(1/r\) or a \(1/r^2\) relationship. The measured dependency for a LSSR system is also shown. The good agreement shown confirms the fact the measured dose decreases according to a \(1/r\) law in LSSR systems.
3.3.2 Effect on Measured Skin Entrance Dose

It is postulated that the inverse linear rather then inverse square reduction has a significant effect on the radiation dose required in order to perform specific procedures.

Table 2 below shows the dose required at the input of an imaginary x-ray translucent object (equivalent skin entrance dose) at a specified distance from the detector for one unit of dose to reach the detector.

As an example, the dose for the Statscan configuration of LSSR is compared with the dose for conventional geometry as commonly practiced for an object whose skin entrance position is 0.4 meters from the detector. Comparing the dose of Statscan with a typical conventional geometry (full-field) system’s dose (SID of 1 meter), the Statscan dose benefit would be 1.44, compared to 2.78 (in bold), i.e. a factor of approximately 2. It can be seen that at greater skin entrance distances from the detector and for smaller SIDs, the dose difference will be larger.

<table>
<thead>
<tr>
<th>Equivalent skin entrance distance from the detector:</th>
<th>For Conventional Geometry (Full Field) at a source to image distance (SID) of:</th>
<th>For LSSR at SID of:</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2 1.3</td>
<td>1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00</td>
<td>1.00 1.08 1.11 1.13 1.18 1.23 1.25 1.30</td>
</tr>
<tr>
<td>0.1 1.23 1.19 1.16 1.14 1.12 1.11 1.10 1.08</td>
<td>1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00</td>
<td>1.00 1.08 1.11 1.13 1.18 1.23 1.25 1.30</td>
</tr>
<tr>
<td>0.2 1.49 1.44 1.36 1.31 1.28 1.27 1.23</td>
<td>1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00</td>
<td>1.00 1.08 1.11 1.13 1.18 1.23 1.25 1.30</td>
</tr>
<tr>
<td>0.3 1.62 1.56 1.47 1.41 1.38 1.30</td>
<td>1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00</td>
<td>1.00 1.08 1.11 1.13 1.18 1.23 1.25 1.30</td>
</tr>
<tr>
<td>0.4 2.04 1.89 1.78 1.69 1.62 1.56 1.51 1.47 1.44 1.41 1.38 1.30 1.30 1.30 1.30 1.30</td>
<td>1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00</td>
<td>1.00 1.08 1.11 1.13 1.18 1.23 1.25 1.30</td>
</tr>
<tr>
<td>0.5 3.06 2.84 2.64 2.42 2.25 2.12 2.01 1.92 1.84 1.78 1.63 2.04 2.04 2.04 2.04 2.04</td>
<td>1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00</td>
<td>1.00 1.08 1.11 1.13 1.18 1.23 1.25 1.30</td>
</tr>
<tr>
<td>0.6 4.00 3.36 2.94 2.64 2.42 2.25 2.12 2.01 1.92 1.84 1.78 2.04 2.04 2.04 2.04 2.04</td>
<td>1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00</td>
<td>1.00 1.08 1.11 1.13 1.18 1.23 1.25 1.30</td>
</tr>
<tr>
<td>0.7 5.00 4.30 3.94 3.64 3.42 3.25 3.12 3.01 2.92 2.84 2.78 2.70 2.64 2.56 2.49 2.42</td>
<td>1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00</td>
<td>1.00 1.08 1.11 1.13 1.18 1.23 1.25 1.30</td>
</tr>
</tbody>
</table>

Note: All distances in meters

Table 2 Differences in radiation exposure for conventional geometry and LSSR technology at various SID’s and distances from the detector

In the case of chest radiography it is apparent (see the gray shaded numbers at an equivalent skin entrance distance from the detector of 0.3 meters) that Statscan has a smaller dose advantage due this factor. The fact that chest X-rays are usually taken with large SID’s contributes to this.

3.3.3 Discussion

Although there may be controversy as to the extent to which the dose savings in Table 2 are translated into clinical practice, it is felt that this concept helps to explain the large measured dose differences between the LSSR and reference systems. Further work is required in order to clarify the hypothesis. The question is whether this “dose saving” would apply in the case of real 3-dimensional objects between the source and the detector. The assumption made is that in order to achieve a specific flux density of x-ray photons (necessary for detectability at the required SNR for image quality equivalence) at the detector through a real object a lower entrance dose as indicated in table 2 would be measured for LSSR than for conventional geometries, (possibly including FSSR systems).
Table 3 provides a summary of total skin entrance exposure (dose) savings for LSSR over other modalities. Note that in each case an expected dose saving is quoted as well as a range around this in order to account for realistically possible variations between various commercial offerings. For comparison purposes, the better performing technological embodiments in terms of dose efficiency were chosen. Whilst it was possible to find good references for comparing LSSR to screen film (SF) with conventional geometry (top line in Table 3), some the entries in the lower lines are more roughly estimated.

<table>
<thead>
<tr>
<th>Alternative Modality</th>
<th>Dose Reduction Factor of LSSR due to:</th>
<th>LSSR's Dose Advantage Multiple</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Digital &amp; DQE (Ref. section 2 a &amp; b)</td>
<td>Very High SPR (Ref. section 2 c)</td>
</tr>
<tr>
<td>Conventional Geometry Screen Film (SF) Radiology (Chest Only)</td>
<td>3.3 2.0 1.5</td>
<td>3.0 2.0 1.5</td>
</tr>
<tr>
<td></td>
<td>3.3 2.0 1.5</td>
<td>1.2 1.1 1.0</td>
</tr>
<tr>
<td>Conventional Geometry Digital Radiology (Chest Only)</td>
<td>1.1 1.0 0.9</td>
<td>3.0 2.0 1.5</td>
</tr>
<tr>
<td></td>
<td>1.1 1.0 0.9</td>
<td>1.2 1.1 1.0</td>
</tr>
<tr>
<td>Analog FSSR</td>
<td>3.0 2.0 1.5</td>
<td>1.0 1.0 1.0</td>
</tr>
<tr>
<td>Digital FSSR</td>
<td>1.1 1.0 0.9</td>
<td>1.0 1.0 1.0</td>
</tr>
</tbody>
</table>

Where: LSSR: Linear Slit Scanning (as in StatscanTM)  
FSSR: Fixed (X-ray source) Slit/Slot Scanning (as in other commercial configurations)  
SPR: Scatter to Primary Ratio

Table 3 – The quantification of LSSR’s expected radiation dose advantage over other modalities

The projected radiation dose advantage of LSSR over conventional SF is 8 times for non-chest images (see Table 3). This correlates well with the dose advantage ratios of 7.5 to 12.2 (excluding chest) shown in Table 1. Additionally, the predicted range of variation from 3.4 to 29.7 is very similar to that measured during the original FDA tests, considering the variability of the subjects X-rayed.

For chest X-rays, the expected dose advantage of LSSR over conventional SF is only 2.4 times (see Table 3). This does not correlate well with 1.4 in Table 1.

However, considering that the standardized doses shown in Table 1 were obtained from clinical radiography practice of chest exposures with a large SID of 1.8 meters, (compared to the Statscan SID of 1.3 meters) and that the Statscan images where exposed at doses suitable for both lung and the mediastinum, the smaller than expected dose saving could be accounted for.

5 CONCLUSIONS

The low dosage measurements arising from FDA clinical trials, and anomalies can be explained by considering four factors:

a. The fact that it utilizes digital technology
b. The fact that it has a high DQE
c. The fact that use is made of slit scanning radiography which results in a low scatter to primary ratio.

d. The technique of linear slit scanning.

The dosage characteristics of LSSR, including the anomaly in the case of chest exposure, can adequately be explained by taking into account the differences in SID and skin entrance positions commonly used.

ACKNOWLEDGEMENTS

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REFERENCES