The Dose from Compton Backscatter Screening

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Abstract

Systems based on the detection of Compton backscattered X-rays have been deployed for screening personnel for weapons and explosives. Similar principles are used for screening vehicles at border crossing points. Calculations based on well established scattering cross sections and absorption coefficients show that the dose from the personnel screening system is between 0.4 μSv and 9 μSv, depending on image quality. These calculated doses are greater than the proposed ANSI standard 43.17 of 0.25 μSv per screening. Vehicle scanning systems are probably in compliance.
Key words: American National Standards Institute (ANSI), Compton backscatter, dose assessment, X-ray screening

INTRODUCTION

Since the September 2001 terrorist attacks, there has been considerable interest in the development and deployment of personnel screening systems that will detect explosives and other contraband as well as metal objects. With over 650 million airline passengers per year in the US, screening technology must be fast and accurate (Bureau of Transportation Statistics 2008). Systems based on millimeter wave scattering and large angle Compton scattering are being used at airports and other facilities, such as prisons and detention centers, around the world. In X-ray scanning, a passenger is scanned by moving an X-ray beam rapidly over the body. The signal strength of detected backscattered X-ray allows a highly realistic surface image to be reconstructed. Screening is rapid and image resolution of the technology is high.

The deployment of X-ray screening units in major airports around the country has raised concerns about radiation doses to passengers. X-ray screening manufacturers claim that the radiation dose per scan is less than 0.1 μSv. This is substantially less than the average dose of 6.2 mSv that members of the US population get every year from all sources of radiation exposure, and is less than the increased cosmic radiation dose passengers receive during commercial airline travel (National Council on Radiation Protection and Measurements 2009). In 2002 the American National Standards Institute (ANSI) set a standard of 0.1 μSv per scan for an individual (American National Standards Institute 2002). The current ANSI standard is under revision. ANSI proposes to relax the dose limit from 0.1 to 0.25 μSv per "screening" and applies to "general use" systems. The reason for changing from a per-scan limit to a per-screening limit is to be fair to transmission systems that require only one scan vs. multiple scans.(Cerra 2009). The revised standard will be referred to throughout this paper instead of the current standard. Adoption of the revised standard is likely in 2009.

American Science and Engineering (AS&E), the manufacturer of the SmartCheck system (SmartCheck personnel inspection system, American Science and Engineering, Inc., 829 Middlesex Turnpike, Billerica, MA 01821) and Rapiscan Systems Ltd., the manufacturer of the Rapiscan Secure 1000 (Rapiscan Secure 1000 people screening system, Rapiscan Systems Ltd., Bonehurst Road, Salfords, Redhill, Surrey, England, UK RH1 5GG) both claim they are in compliance with this standard. AS&E also make a vehicle screening system, the Z Portal (Z Portal multiview vehicle and cargo screening system, American Science and Engineering, Inc., 829 Middlesex Turnpike, Billerica, MA 01821) based on the same principles.

Although vendor-determined doses are small and not associated with adverse health effects dose accuracy is in question because of inherent difficulties in measuring X-ray exposures from rapidly moving X-ray beams. In this paper we use the theory of image formation and well established scattering cross sections and absorption coefficients to estimate the dose. Calculations presented here suggest the dose per scan is higher than vendor estimates. However, the increased dose to individual passengers remains well below doses that are known to cause adverse health effects.

DOSE ESTIMATION

The outlines of a Compton backscatter screening system for personnel were given in the patent application of Smith (Smith 1998). The essential features of the system are shown as Fig. 1.

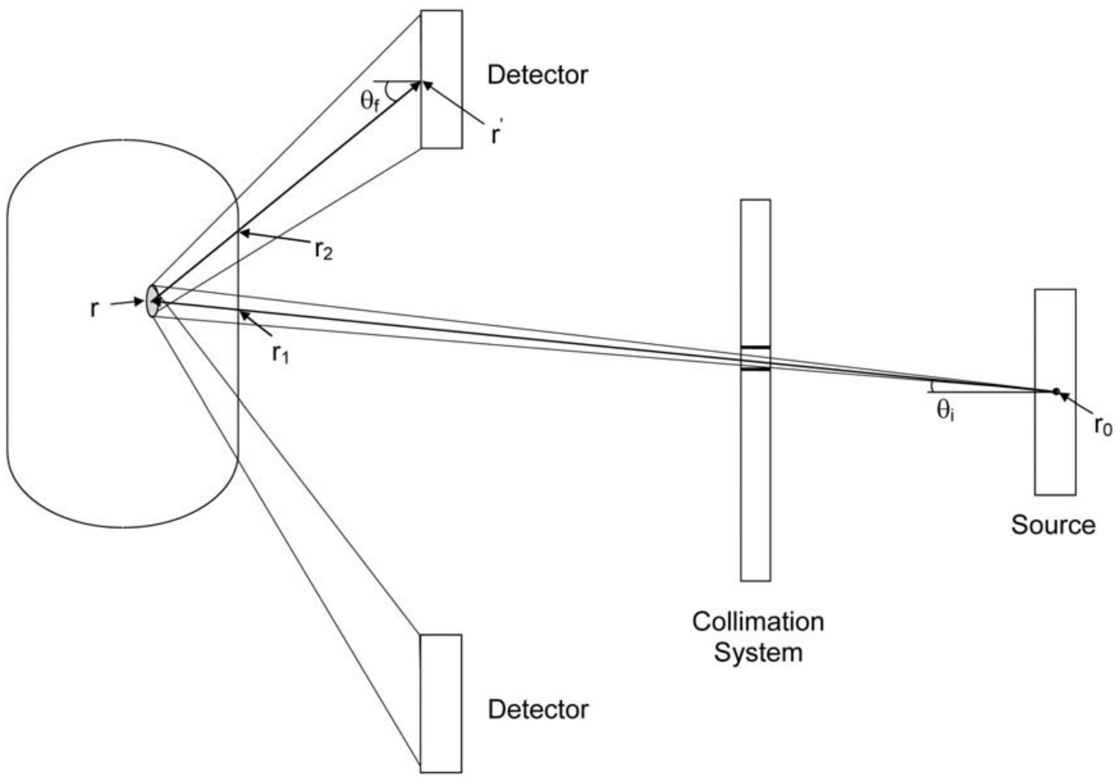

Fig.1. Schematic diagram of personnel screening system.

An X-ray tube with a collimator is used to generate a fan beam of X-rays, and a chopper wheel further restricts the X-rays to a pencil beam that scans in the vertical plane. Smith proposed using a 50 kV X-ray source, much lower in energy than the 100-120 kV X-ray source used in the AS&E personnel system or the source emitting 200 kV X-rays used in the vehicle scanning system. The detectors that he proposed are also probably smaller, and less efficient, than those used in the commercially available systems. The dose can be estimated from the image quality and the number of X-ray that would be generated from commercially available X-ray sources. The quality of the image sets limits on the number of X-rays detected for each pixel and the Compton scattering cross section can be used to estimate the number of incident X-rays per pixel. The dose can then be calculated from mass absorption coefficients. As Smith (Smith 1998) stated in his patent application the pixel size is critical. From features shown in published images in a report on the AS&E Bodycheck system (Baukus 2000), it would appear that the pixel size is 2mm (features on the gun and the zipper set these limits). The 2mm pixel size also is consistent with 1000 pixels in 2m, or 500 in 1m which would be appropriate for computer display of an individual. In one image it would appear that the pixel size is 1mm from features on a gun and the wire frame of glasses (Baukus 2000).

As a first stage the X-ray fluence required to give a peak image intensity (showing as white on a displayed image) will be estimated. The general expression for the Compton backscattered signal picked up at a point **r'** in the detector from a beam passing through points along the vector connecting $\mathbf{r_1}$ to $\mathbf{r}$ is

$$I = \iint \exp(-\mu_f \left|\mathbf{r_2}(\mathbf{r}-\mathbf{r'})-\mathbf{r}\right|) \frac{d\sigma}{d\Omega} I_0 N_e \exp(-\mu\left|\mathbf{r}-\mathbf{r_1}(\mathbf{r}-\mathbf{r_0})\right|) \frac{d^2 r'}{\left|\mathbf{r}-\mathbf{r'}\right|^2} d\mathbf{r} \qquad (1)$$

where $\mathbf{r_2}$ is the point on the surface of the person on the line connecting **r'** to **r** and $\mathbf{r_1}$ is the point on the surface of the person connecting $\mathbf{r_0}$ on the X-ray source to **r**, as shown in Figure 1. In equation 1 I_0 is the incident number of X-rays, N_e is the number of electrons per unit volume , μ_i is the absorption coefficient for the incident X-rays, μ_f the absorption coefficient for the Compton scattered X-rays and $\frac{d\sigma}{d\Omega}$ the Compton differential scattering cross section. To evaluate this would require a model for a human phantom, and detailed engineering diagrams showing the arrangement of the X-ray source and detectors.

Instead the maximum volume that could contribute to the signal will be estimated. Neglecting the curvature of the person being scanned, equation 1 becomes

$$I = \iint \exp\left(-\mu_f \frac{z}{\cos\theta_f}\right) \frac{d\sigma}{d\Omega} N_e I_0 \exp\left(-\mu_i \frac{z}{\cos\theta_i}\right) \frac{d^2 r'}{|\mathbf{r}-\mathbf{r}'|^2} d\mathbf{r} \qquad (2)$$

where z is a distance beneath the surface. To further simplify this expression the integration over the paths to the detector will be replaced by an effective solid angle, $\Delta\Omega$. Equation 2 now becomes

$$I = \int_0^\infty N_e \frac{d\sigma}{d\Omega} \Delta\Omega I_0 \exp\left(-\left(\frac{\mu_i}{\cos\theta_i} + \frac{\mu_f}{\cos\theta_f}\right) z\right) dz \qquad (3)$$

The absorption coefficients are about 0.15-0.2 cm^2/gm giving an effective absorption depth of 5-6 cm. which means that the integration through the body can be taken to infinity. As a last approximation the cosine factors will be set equal to 1 and the resulting integration gives

$$I = \frac{N_e \Delta\Omega I_0}{(\mu_i + \mu_f)} \frac{d\sigma}{d\Omega} \qquad (4)$$

Note that this approximation leads to a higher estimation for the detected signal and therefore a lower estimate for the incident fluence. This means that the dose estimates given below might be a factor of 2 -3 too low.

Rearranging eqn 4 to get I_0, we have

$$I_0 = \frac{I(\mu_i + \mu_f)}{N_e \Delta\Omega \frac{d\sigma}{d\Omega}} \qquad (5)$$

The Compton scattering cross sections can be calculated from the Klein Nishina formula (Heitler 1954, Johns and Cunningham 1983) and as shown in Fig. 2 the differential cross section becomes more forward peaked as the energy increases.

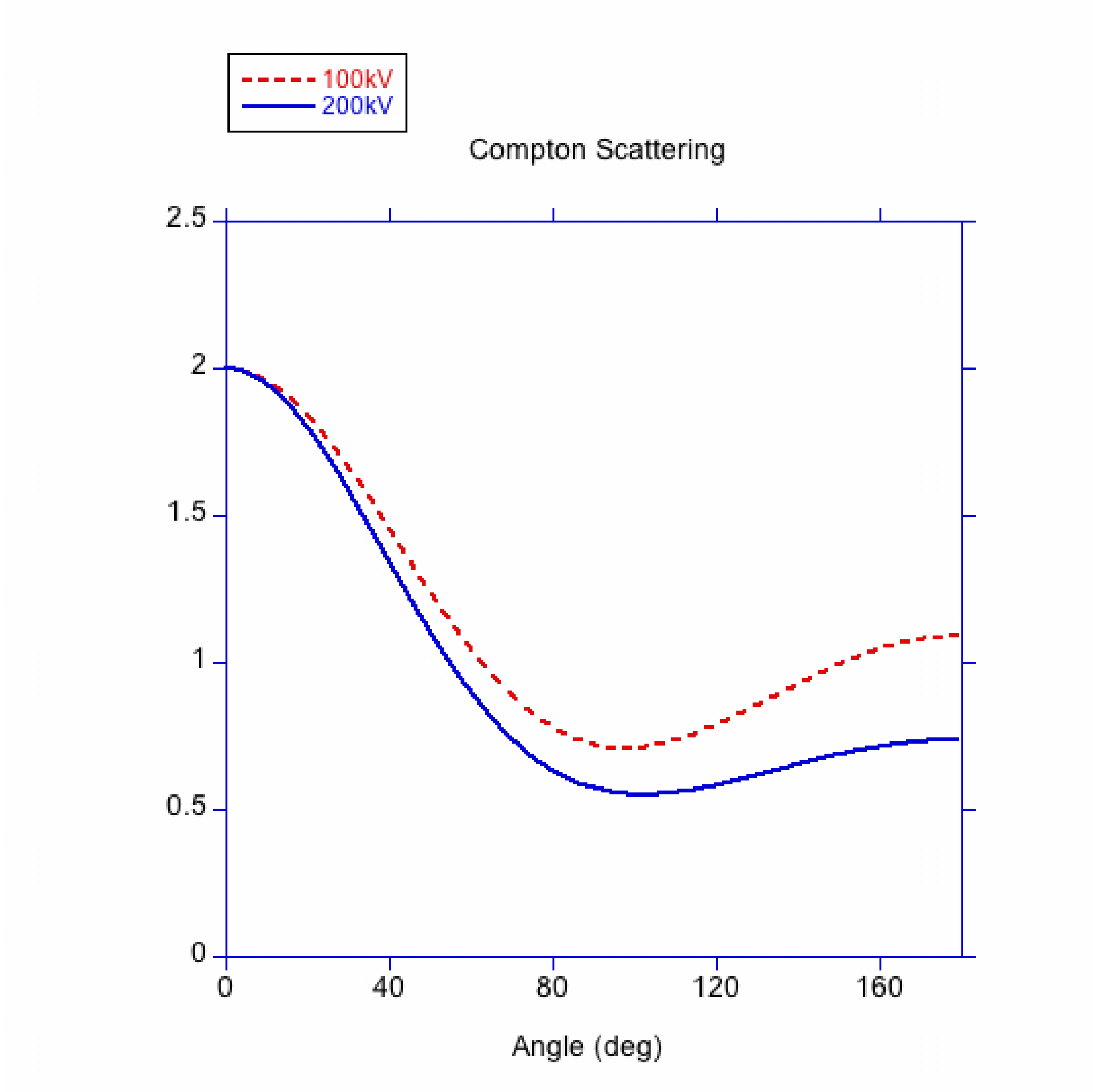

Figure 2. Variation of the differential scattering cross section for Compton scattered X-rays as a function of scattering angle. (in units of $\frac{r_0^2}{2}$ = 3.97 x10^{-26} cm^2 where r_0 is the classical electron radius)

The cross section for backscattering decreases as the energy is increased. From the footprint of both Rapiscan Secure 1000 and SmartCheck it would appear that the scattering angle is 135^o. This angle is not critical since the cross section varies slowly in this region. The SmartCheck system uses 100-120 kV x-ray generators with a tungsten target. (Callerame 2006, 2008). From a calculated X-ray spectrum the average X-ray energy is 80 kV and the differential cross section for Compton scattering is 3.85×10^{-26} cm^2. The Z-portal system uses a higher energy X-ray generator with a voltage greater than 200 kV. The average X-ray energy can be estimated from the image of the driver sitting in a truck with the window down. The image intensity of the arm is attenuated by a factor of 33% by transmission through the door and window. Using X-ray absorption coefficients from XCOM (Berger et al. 2005) and assuming the door is 1mm steel and the glass is 6mm thick the average energy for the incident X-rays is 200 kV. The differential cross section for Compton scattering relevant for the vehicle scanning system is 2.52×10^{-26} cm^2.

In the original patent filing of Smith (1998) it would appear that scintillators with an area of about 1 m^2 were placed above and below the person being scanned. The footprint of the Rapiscan Secure 1000 and the SmartCheck systems would suggest that the scintillators were of similar area at the side of the person. In either case a reasonable estimate for the solid angle would be 0.5 sr.

Since an 8 bit A/D converter was used and their signal processing algorithms require accurate intensity histograms, it is reasonable to assume that their images really do need 256 grey levels. To discriminate 256 levels requires 64000 counts ($\sqrt{N}$ uncertainty, 1 σ). This assumes single-photon counting with a detection quantum efficiency (DQE) of 1, which is possible for higher X-ray energies, using a scintillator

PM tube detector. Alternatively the number of counts could be estimated from the fluctuations in a constant area in the published images. In a region of high intensity the fluctuation in intensity is about 5 units on 200 units. This would imply 40 intensity levels, requiring 1600 counts for a perfect detection system. In reality the DQE would be closer to 0.5 (even this is optimistic) and about 3200 counts would be required.

The energy of the Compton scattered X-ray, E_f, is lower than the incident energy, E_i and is given by

$$E_f = E_i - m_0 c^2 (1 - \cos\theta) \tag{6}$$

The absorption coefficient is therefore higher. Absorption coefficients from XCOM (Berger et al. 2005) for 80 kV incident X-ray and 200 kV incident X-ray are given in Table 1 below.

Personnel Screening	Absorption Coefficient cm^2gm^{-1}	Vehicle Portal	Absorption Coefficient cm^2gm^{-1}
μ_i (80 kV)	0.1837	μ_i (200 kV)	0.1356
μ_f (63 kV)	0.2059	μ_f (120 kV)	0.1626

Table 1. X-ray absorption coefficients relevant for Compton backscattering screening systems

The numbers of incident X-ray can be calculated from equation 1 and are shown in Table 2.

Peak Detected X-rays / pixel	Personnel Screening (120kVp)	Vehicle Portal (>200kVp)
3200	1.94×10^5	2.27×10^5
64000	3.89×10^6	4.54×10^6

Table 2. Incident X-rays per pixel

These are high but reasonable numbers. AS&E claims that it completes a scan using the SmartCheck system in 8 sec. That means the dwell time per pixel is about 15 μsec per pixel which corresponds to 2×10^{11} photons per second. It is reasonable to assume that because of the collimation needed to get the pencil beam only 10^{-6} of electrons in the x-ray tube generate an X-ray photon. The tube electron current can then be estimated as about 30 mA, consistent with what the company claims.(Callerame 2006, 2008).

The dose is defined as the energy deposited per unit mass. The mass is given by the matter in the pixel

$$\Delta M = \rho \times \Delta x^2 \times t \qquad (7)$$

where ρ is the density and Δx is the pixel size

From Johns and Cunningham (Johns and Cunningham 1983) the dose can be calculated as

$$D = I_0 \left(\frac{\mu}{\rho} \right)_{abs} \Delta E_{abs} \frac{(\rho t)}{(\rho t \Delta x^2)} \qquad (8)$$

assuming the attenuation of the X-ray flux is small in mass thickness ρt.

The dose is critically dependent on the product of energy absorption coefficient $\left(\frac{\mu}{\rho} \right)_{abs}$ and energy absorbed ΔE_{abs}. Table 3 shows how they vary with x-ray energy for muscle.

Energy (keV)	$\left(\frac{\mu}{\rho} \right)_{abs}$ ($cm^2 gm^{-1}$)	ΔE_{abs} (keV)	ΔE_{abs} x $\left(\frac{\mu}{\rho} \right)_{abs}$ (keV $cm^2 gm^{-1}$)
10.000	4.7640	9.240	44.01936
15.000	1.3070	12.000	15.684
20.000	0.5206	13.400	6.97604
30.000	0.1474	12.100	1.78354
40.000	0.0664	10.100	0.67064
50.000	0.0409	9.130	0.373417
60.000	0.0312	9.200	0.28704
80.000	0.0257	11.300	0.29041
100.000	0.0253	14.900	0.37697
150.000	0.0275	27.600	0.759
200.000	0.0294	43.400	1.27596

Table 3. Energy Absorbed and Energy Absorption Coefficients from Table A 3c (from Johns and Cunningham 1983)

The minimum dose is expected where the product is a minimum at about 60 kV. Not surprisingly this is the window used for radiology; it also has significant contrast from photo-absorption. At higher energies the lower absorption is compensated by the higher energy absorbed; at lower energies the higher absorption means that the energy is deposited in a smaller mass.

Using equation 8 the dose can be calculated for the personnel screening and the vehicle portal and is summarized in Table 4. Since anterior and posterior views are taken for the personal screening systems the calculated dose per view has to be multiplied by 2 for a complete screening. For the vehicle scanning system, three views are taken so the dose is multiplied by 3 for a complete screening.

	Personnel Screening (120 kVp)	Vehicle Portal (>200 kVp)
3200 peak X-rays /pixel	0.4 μSv	0.03 μSv
64000 peak X-rays /pixel	9.0 μSv	0.6 μSv

Table 4. Dose for personnel screening and vehicle portal systems for different peak scattered X-rays

As can be seen from equations 5 and 8 the dose is very sensitive to the peak number of scattered photons needed for adequate contrast and the pixel size. Due to the large pixel size in the vehicle Z Portal system, a consequence of the large source-target distance, the vehicle Z Portal system gives doses below the revised ANSI standard of 0.25 μSv at 3200 peak X-rays per pixel but exceeds the revised standard at 64000 peak X-rays per pixel.. The personnel screening systems, even under optimistic assumptions for detection efficiency, will exceed the revised ANSI standard at either 3200 or 64000 peak X-rays per pixel. . This is due mainly to the high concentration of radiation in a small area. It should also be remembered that because of the simplifications leading to equation 4 these estimates are lower bounds for the doses. Uncertainties in these estimates mainly come from the detector solid angle, but this can not be more than about $\pm$ 30% since the detector is constrained by the lateral dimension of the system. The next largest source of uncertainty is the average scattering angle, but as can be seen from Fig 2, this can at most cause a variation of $\pm$ 10%. In comparison the Klein Nishina scattering cross section and the absorption coefficients have negligible uncertainty. It should also be remembered that these same absorption coefficients are used to convert ionization chamber measurements to dose and will therefore be present in experimental measurements.

NCRP Commentary No. 16 (2003) provides radiation protection advice (including radiation levels during screening) concerning ionizing radiation-producing devices that are being evaluated by federal agencies for uses in screening of humans for the purpose of security. The effective doses per scan reported by NCRP (0.05 µSv per scan for anterior plus posterior views) are substantially lower than the estimates provided in this report. NCRP used direct measurements of exposure from X-ray beams as described in the ANSI standard published document (ANSI 2002). However measurement of narrow x-ray beams that scan the subject at high speed (“flying spot”) is inherently difficult and unreliable due to partial volume irradiation and response times of any systems that do not use solid state detectors (Metzger 2009).

CONCLUSIONS

While the vehicle portal system is probably in compliance with the revised 0.25 μSv ANSI standard, it is very unlikely that the dose from any of the personnel screening systems is in compliance.

At 0.25 µSv per screening a total of 1000 scans would be necessary to reach the administrative dose limit of 0.25 mSv per year for a member of the general public (U.S.Nuclear Regulatory Commission 1991). Based on a calculated dose of 0.4 µSv for a low image quality scan and 9.0 µSv for a high quality image scan (Table 4), 625 scans and 28 scans respectively would be necessary to reach the administrative public doses limit of 0.25 mSv per year. It is quite plausible that employees and frequent visitors of prisons and detention centers using the Rapiscan 1000 or SmartCheck systems could reach the administrative dose limit.

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Figure Captions

Fig.1. Schematic diagram of a personnel screening system. The diagram shows a beam at an angle of incidence θ_i enetering a person being scanned at position $\mathbf{r_1}$, before being Compton scattered at position **r.** The scattered beam, at an angle θ_f, leaves the person at position $\mathbf{r_2}$ and strikes the detector at **r'**

Fig. 2. Variation of the differential scattering cross section for Compton scattered X-rays as a function of scattering angle. (in units of $\frac{r_0^2}{2}$ = 3.97 x10^{-26} cm^2 where r_0 is the classical electron radius)