Are X-Ray Backscatter Scanners Safe for Airport Passenger Screening? For Most Individuals, Probably Yes, but a Billion Scans per Year Raises Long-Term Public Health Concerns[1]

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See also the article by Schauer in this issue.

Improved scanning of individuals boarding airline flights for explosives is both desirable and necessary. Currently, there are several possible technology options in this regard (1), and in this article, I will focus on the radiation safety of the most commonly deployed advanced imaging technology (AIT), namely, whole-body x-ray backscatter scanning.

Are airport whole-body x-ray backscatter scanners safe? In brief, yes and no. I will argue here that, in terms of individual risk, the radiation doses associated with whole-body x-ray backscatter scans are sufficiently low that it is reasonable to characterize them as "safe" (ie, representing at most an extremely small cancer risk) for most individuals who travel only a few times each year. Potential risks will be higher for high-level frequent fliers and flight personnel, however. Perhaps more importantly, from a public health policy perspective, given that up to 1 billion such scans per year are now possible in the United States, we should have concerns about the long-term consequences of an extremely large number of people all being exposed to a likely extremely small radiation-induced cancer risk—in particular given that there are current practical alternatives that do not involve ionizing radiation.

Whole-body x-ray backscatter scanners (1,2) have been deployed at U.S. airports since 2007, though in fairly small numbers and to screen a limited number of passengers. Indeed, in 2003, the National Council on Radiation Protection and Measurements (NCRP) published a report on their use and safety (3), and there is an American National Standards Institute standard effective dose limit (0.25 μSv per screening [4]). In early 2010, however, in response to the December 25, 2009, "underwear bomber" incident (5), the Transportation Security Administration (TSA) shifted the goalposts dramatically with regard to the use of whole-body AIT scanners. The Government Accountability Office (6) reported: "In response to the December 2009 attempted terrorist attack, TSA has revised its procurement and deployment strategy for AIT, increasing the number of AITs it plans to procure and deploy. In contrast with its prior strategy, the agency now plans … to use them as a primary screening measure where feasible, rather than solely as a secondary screening measure."

In other words, instead of using whole-body AIT scanners for a small number of selected passengers, the goal now is to use them for all U.S. airline passengers. The Figure shows the number of commercial passenger emplanements per year (past, present, and projected) in U.S. airports (7). While the number of passengers passing through security will be slightly less than the number of passenger emplanements, it is clear that there is the potential for as many as 1 billion whole-body scans per year in U.S. airports.

In fact, there are two quite different whole-body AITs currently being deployed at airports. One uses x-ray backscatter technology (2,3,8), raster scanning the whole body (in both posteroanterior and anteroposterior directions) with a pencil beam of either, depending on the manufacturer, 50- or 120-kVp x-rays. The second technology illuminates the subject with low-power millimeter-wave radiation. The reflected signals are detected and then analyzed with a holographic

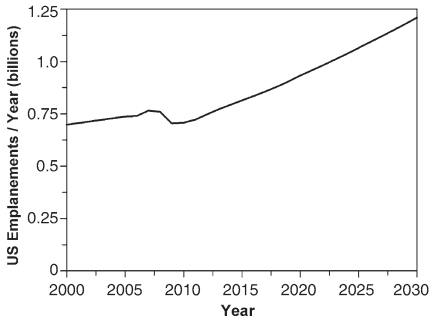
imaging algorithm (9). Millimeter-wave radiation is, of course, nonionizing. My primary focus in this article will be x-ray backscatter scanners, which represent the majority of deployed whole-body AIT scanners in U.S. airports. Since the TSA has purchased and is deploying both x-ray and millimeter-wave systems, it is reasonable to assume that they have comparable characteristics in terms of sensitivity, specificity, and logistics.

What Do We Mean by Safe?

This article addresses the issue of whether whole-body x-ray backscatter systems are safe, so it is important to be clear about what "safe" can mean in this context.

The most direct interpretation of "safe" refers to the exposed individual. One may ask what is the best estimate of the lifetime cancer risk incurred by an individual receiving one or more of these scans. But risks can also be viewed from the perspective of the entire exposed population (10). The estimated population risk (sometimes called the societal risk [11]) in this case relates to the number of cancers expected in the exposed population as a result of the proposed practice; this population outcome depends both on the individual risk and also, of course, on the number of people exposed to that risk.

To illustrate this distinction between individual and population risk, consider a hypothetical activity producing an extremely small individual cancer risk of, say, one in 10 million (ie, 10^{-7}). An individual cancer risk of 10^{-7} means that if 10 million people were exposed to this activity, on average, one cancer would be induced. So if, for example, only 100 people were exposed to this activity, it would be extremely unlikely that any of the 100 exposed individuals would actually develop cancer due to the activity in question. Now consider 1 billion (ie, 10^9) people are exposed to that same small cancer risk of one in 10 million (ie, 10^{-7}): In this case, it would be highly likely that some of the exposed population would develop cancer due to the activity in question—a population risk. This is both a common-sense conclusion and one that follows from Bernoulli's well-established Law of Large Numbers (12).



Graph shows total number of commercial passenger emplanements (total number of passengers boarding flights, including origination, stopovers, and connections) per year in U.S. airports, past, present, and projected by the Federal Aviation Administration (7). Number of passengers passing through airport security checkpoints will be slightly less than the number of emplanements because connecting passengers do not necessarily go through security again.

Both the International Commission on Radiological Protection (ICRP) (13,14) and the NCRP (15,16) have suggested that, as well as individual risk, population risk is an appropriate, if approximate, measure for assessing the acceptability of a large-scale activity that might be associated with small individual radiation risks. Thus, population risk is described by the ICRP (14) as "one input to … a broad judgment of what is reasonable" and by the NCRP (16) as "one of the means for assessing the acceptability of a facility or practice."

Population risks are also routinely used in other fields where policy choices involve large populations that are potentially exposed to small individual risks. For example, the World Health Organization has developed standard approaches to estimate current and future population risks from diverse factors such as air pollution and climate change (17,18). Other areas where population risks have been used as input to policy decisions include civil aviation (19), flood control (20), second-hand smoke (21), and vaccination policy (22). For example, both the individual risk of meningitis from pediatric measles vaccination (less than 10^{-6}) and the population risk of induced meningitis in the whole vaccinated population are taken into account in formulating measles vaccination policies (22).

Estimated Skin and Effective Doses per Scan for X-Ray Backscatter Scanners

Dose	50-kVp Scanner	120-kVp Scanner
Skin (μGy)	2.5	0.7
Effective (μSv)	0.9	0.8

Source.—Reference 8.

Note.—Minimum doses required to provide the relevant image resolution and quality.

Individual Risks Associated with X-Ray Backscatter Scanners

The Table shows the most recent estimates (8) of the dose each two-sided (posteroanterior and anteroposterior) whole-body x-ray scan requires to produce images of the appropriate resolution and quality; the effective doses are extremely low, of the order of 1 μSv. We do not know with any certainty the magnitude of the individual cancer risks associated with such low doses (23). The lowest doses for which we have definitive evidence for an increase in risk are in the range from 5 to 125 mSv (24), far larger than the doses of concern here. Epidemiologic studies at lower doses would be exceedingly difficult, if not impossible, because the signal-to-noise ratio is so small (25) (here the noise is approximately a 40% lifetime cancer risk or a 20% lifetime cancer mortality risk).

Following the guidance of the primary regulatory and advisory agencies (ie, ICRP, NCRP, United Nations Scientific Committee on the Effects of Atomic Radiation [UNSCEAR], Biological Effects of Ionizing Radiation [BEIR] committee [26–29]), one can make a best estimate of the individual risk by using a standard cancer mortality risk estimate of 5% per sievert. This would result in an estimated lifetime cancer mortality risk of about 10^{-7} (one in 10 million) for a trip involving two 1-μSv screening

scans (8). Of course, this risk estimate is highly uncertain, in large part because it is based on extrapolation of radiation risks estimated at much higher doses (30). Indeed, some have argued that the individual risk at extremely low doses is zero (31,32). By contrast, others have argued that recently studied phenomena (eg, tissue and organ microenvironment effects [33], bystander effects [34], and "sneaking through" immune surveillance [35]) suggest that low-dose radiation risks could be higher than those anticipated on the basis of extrapolating risks estimated at higher doses. Despite much research into this key topic, a definitive cancer risk estimate associated with these extremely low doses remains elusive. Therefore, the best estimate we can currently make regarding individual risks associated with x-ray backscatter scanners is, as recommended by the ICRP (26), NCRP (27), UNSCEAR (28), and BEIR committee (29), to apply the standard cancer risks per unit dose as estimated from higher-dose epidemiologic studies. This is what is done here, while recognizing the major uncertainties involved.

In terms of the significance of small individual risks, the NCRP has defined a negligible individual risk level (NIRL) as "the level of annual excess risk of fatal health effects attributable to radiation, below which efforts to reduce radiation exposure to the individual are unwarranted" (15). Not quite the same as "safe", but a reasonable practical proxy. The NCRP has suggested an NIRL of 10^{-7} per year (one in 10 million), which is of the same order as the estimated fatal cancer risk from two 1-μSv scans. It is not unreasonable, therefore, to describe x-ray backscatter scans as "safe" in terms of the individual risk associated with a small number of such scans.

One could perhaps debate whether this "safe" descriptor should apply to scanning children, for whom the cancer risks are probably 5–10 times higher than those for subjects in middle age (29,36); radiosensitive individuals, including the developing embryo and fetus; or flight personnel and high-level frequent fliers. For example, a domestic flight attendant or pilot in the United States passes through security in the range of 240–380 times per year (Laura Cox, written communication, October 2010), which would result in a potential effective dose from x-ray backscatter scanning of about 300 μSv per year. Likewise, a high-level frequent flier averages more than 200 flights per year (37) and, thus, could receive an annual effective dose of 200 μSv from x-ray backscatter scans. The corresponding best-estimate fatal cancer risks in these cases would be about 10^{-5} per year, which is larger than the NCRP NIRL of 10^{-7}.

Population Risks Associated with X-Ray Backscatter Scanners

The population risk relates to the expected number of cancers induced in the exposed population as a result of the activity in question. As discussed above, both the ICRP and the NCRP have suggested that population risk is an appropriate, if approximate, measure for assessing the acceptability of a large-scale activity that is associated with small individual radiation risks (13–16).

In the present context, if a billion (ie, 10^9) x-ray backscatter scans were performed each year and the average individual cancer risk per scan was 10^{-7} (see above), one might anticipate 100 cancers (ie, $10^9 \times 10^{-7}$) each year resulting from this activity. Of course, hidden behind this back-of-the-envelope calculation are a number of issues and uncertainties, some practical and some conceptual.

The first uncertainty in the population risk estimate relates to the uncertainty associated with the individual risk, as discussed above. It is perfectly possible that the individual risk could actually be substantially lower than the best estimate of 10^{-7} (eg, zero [31,32]), but it is also quite possible that the individual risk could actually be substantially higher than 10^{-7} (30,33–35). One can make plausible mechanistically based arguments either way here (30–35), but it is certainly reasonable to base the best-estimate population risk on the best-estimate individual risk.

There have also been suggestions that it is not reasonable to estimate population outcome by multiplying small individual risks by the number of people exposed to those risks. For example, Roger Clarke, the former chair of the ICRP, suggested that "if the risk of harm to the health of the most exposed individuals is trivial, then the total [population] risk is trivial—irrespective of how many people are exposed" (38). In general terms, it is hard to see the logic behind this suggestion, nor is there empirical evidence to support it, and indeed, it has been widely disputed (22,39,40). As discussed above, consideration of a population risk in situations where a large population is exposed to small individual risks is common in many areas of policy assessment apart from radiation (17–22). Of course, it is true that if the individual risk is actually zero, then the population risk is zero. It is also true that if the individual risk is highly uncertain, then the population risk will also be correspondingly uncertain. However, if the individual risk is actually small but nonzero, then the estimated population risk is just this small average individual risk multiplied by the number of people exposed. Bernoulli showed this 300 years ago (12), but it is no more than common sense.

The issue here relates to the numbers: Coming back to our example, if 100 people are exposed to a risk of one in 10 million (ie, 10^{-7}), we know that none will suffer any detriment (100×10^{-7} indeed represents a miniscule population risk). Even if we greatly increase the number of exposed people to, say, 1 million, it is still extremely unlikely that anyone will suffer any detriment ($10^6 \times 10^{-7}$ still represents a very small population risk). In most scenarios, therefore, it is true that, when the individual risks are extremely small, the population risks are negligible, even when the exposed population is quite large.

However, in the current context we are faced with the extraordinary scenario, one that was not anticipated, of a new activity involving up to 1 billion exposures each year. In this case, a risk of 10^{-7} multiplied by 10^9 exposures no longer represents a trivial population risk. In other words, when the number of exposures is extraordinarily large,

the argument (38) that "if the risk of harm to the health of the most exposed individuals is trivial, then the total [population] risk is trivial—irrespective of how many people are exposed" can no longer be valid.

As Low As Reasonably Achievable

The as low as reasonably achievable (ALARA) principle (41) requires making every reasonable effort to minimize ionizing radiation exposures as far below dose limits as is practical, consistent with practically achieving the desired goal. In the context of x-ray backscatter passenger screening, there are two relevant consequences of ALARA:

1. Comparisons with other risks are not necessarily relevant. The fact that flying involves other radiation exposures or other different risks is not relevant to the ALARA requirement to minimize the ionization radiation exposure associated with practical passenger screening. In another context, for example, one would not ignore the radiation exposures associated with computed tomographic scans simply because domestic radon exposure involves larger effective doses.

2. If there is a nonionizing radiation alternative that can reasonably achieve the same screening goal, then, in keeping with the ALARA principle, it should be used in preference to an x-ray–related technology. As far as is known, millimeter-wave whole-body scanning technology fulfills this requirement. In terms of specificity, sensitivity, cost, and speed, the millimeter-wave technology is generally comparable to the x-ray backscatter technology (3,6). Of course, one cannot rule out the possibility of adverse health effects associated with low-power millimeter-wave radiation, but in contrast to the situation for x-rays, there are no established mechanisms associated with millimeter-wave–induced carcinogenesis (42), and extensive studies have not revealed evidence of potential deleterious effects (43–49).

Machine Reliability

X-ray backscatter machines generate a raster-scanned pencil beam by using a collimated fan beam of x-rays and a rapidly spinning metal disk containing radial slits (2). This approach, sometimes called a flying spot, has been used in several clinically oriented imaging systems (50,51). Of issue here is the potential reliability of a rapidly rotating mechanical chopper-wheel system. For example, a system that was, say, 99.99% reliable and had a backup shutoff system that was also, say, 99.99% reliable would still be expected to have a finite number of failures when the number of scans reaches hundreds of millions. The safety concern would be for possible scenarios in which the raster-scanned pencil beam was stuck in the "on" position at a single location.

Conclusion: Are X-Ray Backscatter Scanners Safe for Passenger Screening?

In summary, individual cancer risks associated with the radiation exposure from a few whole-body x-ray backscatter scans are undoubtedly very small. There are indeed uncertainties regarding the doses (the most recent estimates [8] of the doses required to produce images of the relevant resolution and quality, though still extremely low, are an order of magnitude higher than earlier estimates [3,52]), and there are even more uncertainties regarding the cancer risks, if any, associated with these very low radiation doses. By using the most credible dose and risk estimates that we have, one can say that the individual radiation-induced cancer risk associated with a few whole-body x-ray backscatter scans is likely to be of the same order as the NCRP NIRL of 10^{-7} and can, therefore, be reasonably described as safe. Best-estimate lifetime cancer risks will be somewhat higher for children, for radiosensitive individuals, and, particularly, for aircrew and frequent fliers. Again it is important to emphasize the associated uncertainties in these individual risk estimates, which could result in the actual risks being either less than or greater than the best estimates discussed here.

As well as individual risk, however, from a public-health perspective, it is also important to take into account the population risk, which has been described by the NCRP (16) as "one of the means for assessing the acceptability of a facility or practice" and by the ICRP (14) as "one input to … a broad judgment of what is reasonable." In that x-ray backscatter scans have become a primary screening measure, very large numbers of people will likely be exposed to very small radiation-associated cancer risks from the associated radiation exposure. Given the large numbers of scans involved, potentially up to 1 billion each year in the United States, there is a substantial likelihood that, among the scanned population, there will be some cancers induced by the associated radiation exposure.

If there were no feasible alternatives to x-ray backscatter scanners, it could certainly be argued that such population risks would be more than balanced by the associated benefits of reducing the risk of a terrorist event. However, millimeter-wave scanning is a feasible and practical whole-body scanning technology that does not involve ionizing radiation and for which there is currently essentially no mechanistic or experimental evidence of biologic risks. Whatever the actual radiation risks associated with x-ray backscatter machines, the ALARA principle clearly implies that a comparable technology that does not involve x-rays is a preferable alternative.

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