Radiation Dose to Patients and Clinicians During Fluoroscopically-Guided Biopsy of Peripheral Pulmonary Lesions

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BACKGROUND: Fluoroscopic guidance may be utilized in some bronchoscopic procedures, including ultrasound-guided bronchoscopy for investigation of peripheral pulmonary lesions. Some authors have suggested this procedure may be performed without fluoroscopy, to minimize risks due to radiation exposure. However, the radiation dose has never been quantified, so the risk remains unknown. OBJECTIVE: To determine the patient and clinician radiation exposure from fluoroscopy during bronchoscopy. METHODS: We recorded exposure parameters during 45 consecutive ultrasound bronchoscopies with fluoroscopic guidance with a mobile C-arm fluoroscopy system. We calculated the patient effective radiation dose with Monte Carlo computer simulations. Passive personal film dosimeters were placed on 4 sites on both the proceduralist and the primary nursing assistant. RESULTS: The mean fluoroscopy screening time was 96 ± 55 s. Patients received a median effective radiation dose of 0.49 ± 0.37 milli-Sieverts (mSv) (range 0.16–1.3 mSv). Only the film dosimeters worn outside the clinicians' protective aprons recorded measurable radiation doses. Based on typical attenuation properties of the protective garments across the diagnostic x-ray energy range, we estimate that the effective radiation dose per procedure to the proceduralist was 0.4 micro-Sieverts (μSv) and to the assistant was 0.2 μSv. CONCLUSIONS: Patients are exposed to relatively small amounts of radiation from fluoroscopy during bronchoscopy. Clinically indicated fluoroscopic guidance during bronchoscopy should not be precluded on the basis of radiation safety concerns. Adequate shielding of clinicians results in negligible radiation doses during ultrasound bronchoscopy. (Australian and New Zealand Clinical Trials Registry ACTRN12607000514404) *Key words: bronchoscopy; transbronchial lung biopsy; ultrasound; radiology toxicity; lung cancer; fluoroscopy*. [Respir Care 2010;55(11):1469–1474. © 2010 Daedalus Enterprises]

Introduction

Due to changes in the epidemiology of lung cancer,[1] a majority of lung cancers are now located in the lung periphery and therefore are not visible at routine bronchoscopy.[2] The diagnostic yield of transbronchial lung biopsy without guidance in the investigation of peripheral pulmonary lesions is less than 20%.[3,4] Diagnostic yield may be improved with fluoroscopic guidance to more accurately target the area of interest.[5,6] Recently, endobronchial ultrasound used in the investigation of peripheral pulmonary lesions has allowed accurate localization of such lesions, resulting in diagnostic accuracy of up to 85%.[7]

Initial reports describing the technique utilized fluoroscopic guidance in addition to ultrasound guidance,[8] though a more recent study suggested that the diagnostic yield of ultrasound bronchoscopy may be unaffected by removal of fluoroscopic guidance.[9] However, that report also noted a reduced yield in the right-lower lobe and attributed it to inadvertent relocation of the guide sheath during the procedure.[9] There is potential for movement of the bronchoscope probe after deployment in any lobe, due to deep respiration or vigorous coughing. Even movement to a bronchiole adjacent to a mass may compromise diagnostic yield.[10]

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As radial-probe ultrasound bronchoscopy is not a real-time procedure, we feel that once the lesion has been localized with endobronchial ultrasound, optimal performance of the biopsy is achieved with fluoroscopic guidance, as it allows confirmation that the guide sheath remains in its original position and that the biopsy forceps are passed the correct distance into the lung periphery. This ensures a high diagnostic yield and reduces the likelihood of advancing the biopsy forceps too far, which may result in pneumothorax. The benefit of using ionizing radiation in medical imaging should always outweigh the risks of the radiation exposure. The radiation exposure from fluoroscopic guidance during bronchoscopy has never been quantified.

In order to quantify the radiation exposure and, therefore, the risk associated with fluoroscopic guidance during ultrasound bronchoscopy, we measured the radiation exposure to the patient, bronchoscopist, and bronchoscopy assistant in consecutive ultrasound bronchoscopies with fluoroscopic guidance.

Methods

Our institutional ethics committee approved the study. We studied 45 ultrasound/fluoroscopy bronchoscopies conducted for the investigation of peripheral pulmonary lesions, from July 1, 2007, to January 31, 2008. All patients with pulmonary lesions not endobronchially visible were investigated with both radial-probe endobronchial ultrasound and fluoroscopic guidance. The procedures were performed as previously described,[8] by one physician (DPS).

Measurement of Patient Dose

Fluoroscopic guidance was performed with a C-arm mobile fluoroscopy system (GE/OEC 9600, General Electric Healthcare, New York, New York). In all the bronchoscopies the mobile image intensifier was positioned with the x-ray tube underneath the patient, which is a standard procedure to minimize radiation to the clinicians. To estimate the effective radiation received by the patient, we recorded the geometry, anatomical area screened, x-ray beam dimensions, peak kilovoltage (kVp), milli-Amperes (mA), and fluoroscopy screening time from the fluoroscopy x-ray equipment at the completion of the procedure. Machine parameters such as fluoroscopic radiation dose rate and kVp were measured with a radiation analyzer (9095 analyzer and 90X5-6 ion chamber, Radcal, Monrovia, California). The equipment's half-value layer was also estimated from these measurements. Using those measured parameters and the Monte Carlo software developed by Tapiovaara,[11] the effective dose received by each patient was estimated.

Measurement of Clinician Dose

Radiation to the clinicians was measured with passive personal film dosimeters (National Radiation Laboratory, Christchurch, New Zealand), which can record photon energies of 15–180 kilo-electronvolts (keV) and have a minimum reportable dose (threshold) of 50 micro-Sieverts (μSv). Four film dosimeters were placed identically on the bronchoscopist and the assistant in the following positions: one overlying the thyroid shield; one over the sternum outside the protective apron; one over the sternum beneath the protective apron; and one posteriorly at waist level, outside the protective apron. The film dosimeters (including control) were assessed at 3-month intervals.

Ultrasound Bronchoscopy Procedure

All procedures were performed with the patient under conscious sedation, as previously described,[12] with the patient in the supine position on a radio-transparent trolley. Fluoroscopic guidance was with a C-arm mobile fluoroscopy system, with a tube potential of 60–80 kVp, depending on the size of the patient. The fluoroscopy screening parameters (kVp, mA, and area screened) were optimized at the beginning of each bronchoscopy, and not altered during the procedure. Fluoroscopic screening was predominantly used to check that the guide sheath had not moved after the lesion had been localized with endobronchial ultrasound, and to visualize the forceps while specimens were obtained. Transbronchial lung biopsies and cytology brushings were performed in all cases.

The bronchoscopist was positioned at the head of the trolley and remained in that position throughout the procedure. The assistant usually stood next to the bronchoscopist, but moved away for brief periods to retrieve equipment or handle collected specimens, although this rarely occurred during fluoroscopy. All the clinicians in the procedure room wore lightweight "non-lead" composite aprons that cover both front and back. The apron's lead equivalence is 0.35 mm across the diagnostic x-ray energy range.

Results

Data were recorded during 45 consecutive bronchoscopies for suspected lung cancer. The mean lesion size was 3.1 ± 1.1 cm. The mean fluoroscopic exposure time was 96 ± 55 s.

The bronchoscopy was diagnostic in 36 patients (80%). Table 1 lists the diagnoses. Two patients demonstrated resolution of radiologic abnormality on subsequent imaging, confirming the benign nature of the pulmonary lesion. Of the remaining 4 patients, two had non-small-cell lung cancer demonstrated on subsequent procedures, and two are undergoing radiologic surveillance of pulmonary le-

Table 1. Diagnoses Based on Bronchoscopic Biopsy

Non-small-cell lung cancer	29
Small-cell lung cancer	3
Sarcoidosis	2
Bronchoalveolar cell carcinoma	1
Mycobacterium tuberculosis	1

sions. One patient experienced transient hypoxia following the procedure, which resolved with supportive care only. He was discharged home the same day. No other complications occurred.

Radiation Exposure to Patients

Sufficient data were recorded to allow calculation of effective radiation dose for 37 of the patients. The mean effective dose was 0.49 ± 0.37 milli-Sieverts (mSv) (range 0.02–1.3 mSv). There were substantial differences in the patients' calculated effective doses, as seen in Table 2, which shows quartile values for screening time and effective dose.

Table 3 shows radiation exposures from common sources of ionizing radiation, for comparison to our findings.[13-19]

Radiation Exposure to Clinicians

We assessed clinician radiation exposure during two 3-month intervals, with 21 and 24 procedures performed in the first and second periods, respectively. Table 4 shows the radiation doses recorded by the film dosimeters. The only film-dosimeter position that recorded a radiation dose above these dosimeter's minimum threshold was the sternum position outside the protective apron.

Discussion

To our knowledge, this is the first study to describe radiation exposure to patients and clinicians during fluoroscopy-guided bronchoscopy. Our study demonstrates that patients are not exposed to substantial radiation during fluoroscopy-guided bronchoscopy. The mean and median effective doses, which were < 0.5 mSv, are equivalent to approximately 10 chest radiographs,[13] and compare favorably to CT-guided lung biopsy, where the effective patient dose is 6 mSv,[17] and CT-fluoroscopy for transbronchial lung biopsy, with a mean thoracic-organ dose of 380 mSv.[20] It is much lower than the 5 mSv from low-dose chest CT, and substantially less than that in other fluoroscopy-guided medical procedures such as endoscopic retrograde cholangiopancreatography (6 mSv),[21,22] vertebroplasty (10 mSv),[22] and coronary angioplasty (11–17 mSv).[18]

Table 3. Effective Radiation Doses From Common Sources of Ionizing Radiation

	Effective Dose (mSv)
Chest radiograph[13]	0.05
8-h airline flight[14]	0.06
Bronchoscopy with fluoroscopy (present study)	0.49
Background cosmic radiation over 1 y[15]	2.4
Low-dose chest CT[16]	5
CT-guided lung biopsy[17]	6
Coronary angioplasty[18]	17
CT pulmonary angiogram[19]	19

CT = computed tomography

The variation in patient effective dose appears to be due to differences in patient size and in the complexity of the individual procedures. Wide variation in effective dose has been noted for both routine chest radiograph[13] and fluoroscopy-guided interventional cardiac procedures,[23] mainly due to differences in patient size. However, the additional variable of screening time, which is linearly related to effective dose, is most responsible for the wider variation in effective dose among our patients. Such variation has been noted in previous studies of fluoroscopy-guided procedures such as endoscopic retrograde cholangiopancreatography[21] and fluoroscopy-guided orthopedic procedures.[24]

Importantly, as well as minimizing patient radiation exposure, our results are consistent with previous reports that confirm ultrasound bronchoscopy to be a very safe procedure.[7,8] This is in contrast to percutaneous lung biopsy, which has a diagnostic yield comparable to that of ultrasound bronchoscopy[25,26] but is associated with a pneumothorax rate from 25%[25,26] to over 40%.[27]

Deterministic adverse effects of radiation exposure from fluoroscopy, such as radiation-induced dermatitis or burns,[28] have been reported but are of much less concern in bronchoscopic procedures that use mobile image inten-

Table 2. Patient Radiation Exposure From Fluoroscopy During Bronchoscopy

	Mean ± SD	First Quartile	Median	3rd Quartile	Maximum
Fluoroscopic screening time (s)	96 ± 55	44	98	131	250
Effective dose (mSv)	0.49 ± 0.37	0.18	0.37	0.74	1.3

Table 4. Effective Radiation Doses to Clinicians From Fluoroscopy During Bronchoscopy

Dosimeter Location	Dose (μSv)					
	Period 1 (n = 21)		Period 2 (n = 24)		Total	
	Bronchoscopist	Assistant	Bronchoscopist	Assistant	Bronchoscopist	Assistant
Thyroid, outside apron	< 50	< 50	< 50	< 50	< 100	< 100
Sternum, outside apron	90	50	110	50	200	100
Sternum, inside apron	< 50	< 50	< 50	< 50	< 100	< 100
Back	< 50	< 50	< 50	< 50	< 100	< 100

sifiers, because these have relatively low entrance skin dose rates and short screening times.[29] Stochastic effects, particularly malignancy, are a potential concern. Knowledge of cancer risk associated with exposure to ionizing radiation in excess of background radiation is largely based on studies of Japanese atomic bomb survivors, who were exposed to very high amounts of radiation and experienced higher rates of both solid-organ and hematological malignancies.[30,31] However, a dose-response relationship was seen, and no excess rate of solid-organ malignancy was observed among the population exposed to < 10 mSv.[30]

The patient effective dose during fluoroscopy-guided bronchoscopy is much lower than known radiation doses that are associated with no harm, and is equivalent to the dose received in an 8-hour airline flight (see Table 3).[32] It is also clear that the excess rate of radiation-induced cancer is very small in comparison to the spontaneous cancer incidence risk.[33]

Additionally, linear extrapolation of data from populations exposed to high doses, such as atomic bomb exposure, overestimates the cancer risk of low-dose exposures.[34] While biological effects may result from ionizing radiation doses in the diagnostic energy range,[35] the biologic effects of low-dose and high-dose ionizing radiation are not linearly distributed.[36] This allows further reduction in the estimated risk from fluoroscopy during bronchoscopy.

For the proceduralists and their assistants, who are exposed to radiation on repeated occasions, our study also provides reassuring results. We confirm that with adequate protective shielding they are not exposed to clinically important amounts of radiation during fluoroscopy-guided bronchoscopy. The film dosimeters positioned beneath the protective aprons recorded no radiation dose above the minimum 50 μSv threshold. The expected attenuation of ionizing radiation in the diagnostic energy range by shielding of 0.35 mm minimum lead equivalence is estimated at 93%.[37] Thus, on the basis of the externally recorded radiation dose of 200 μSv recorded over 45 procedures, we conclude that with a shield of 0.35 mm minimum lead equivalence the bronchoscopist is unlikely to be exposed to more than 0.4 μSv per fluoroscopic bronchoscopy, and the shielded thyroid exposure is less than 0.2 μSv per procedure.

Our recorded effective doses to clinicians compare favorably to other fluoroscopy-guided medical procedures. CT-guided biopsy results in a proceduralist effective dose of up to 28 μSv per procedure.[17] Effective doses of up to 38 μSv per procedure have been reported for diagnostic cardiac catheterization,[38] and up to 166 μSv per procedure for percutaneous coronary intervention.[39] Interventional cardiologists receive a maximum annual dose of 2.8 mSv, despite optimal shielding.[40] To achieve a similar (albeit safe) annual dose would require the performance of over 5,000 fluoroscopy-guided bronchoscopies, which is well beyond even the most prolific bronchoscopist.

Atomic bomb survivors do not provide useful comparison of risk in subjects exposed to much lower radiation doses over prolonged periods. Recovery from radiation-induced injury is much more effective following low-dose exposure[41] and with a low dose rate.[42] Cohorts exposed to occupational radiation are therefore more representative of the risks to bronchoscopists using fluoroscopy.

Airline cabin crews have radiation exposure above the background radiation level, due to ionizing cosmic radiation. Examination of 19,184 commercial airline pilots with mean annual doses of 2–5 mSv in excess of the background radiation level, and cumulative lifetime doses not exceeding 80 mSv, found no increase in all-cause or all-cancer mortality.[43] Nuclear industry workers have no increased incidence of malignancy, even following cumulative exposures of ≤ 200 mSv.[44] McGeoghegan et al recently reported on a cohort of 64,937 nuclear industry workers; subjects exposed to < 10 mSv had no adverse health effects at all.[45]

Fluoroscopic procedures are by far the largest source of occupational exposure in medicine,[46] but reports of deterministic injuries from such exposure are rare. Vano et al[47] reported a case series of ophthalmologically confirmed lens injuries in interventional radiologists who received estimated lens doses of 450–900 mSv per year, over several years, which is vastly in excess of the magnitude of radiation to which interventional bronchoscopists are exposed. The probability of stochastic risks is dependent on radiation dose. Lifetime risk of fatal cancer for bronchoscopists, based on the work of Goodenough,[48] is of the magnitude of 1×10^{-6} per procedure. The literature, there-

fore, clearly supports the assertion that fluoroscopic bronchoscopy should not be associated with any adverse outcomes.

Limitations

Effective patient and clinician doses differ considerably, according to fluoroscopy screening time, which is determined by the number of diagnostic specimens taken and the proficiency of the bronchoscopist.[49] Our results will not be identical to those for other bronchoscopists utilizing fluoroscopy, because the fluoroscopy parameters (most notably, screening time) will differ between proceduralists and institutions. In addition, the measurement of such low doses is subject to substantial uncertainty. However, the magnitude of radiation exposure is very likely to be reproducible, so, given the very small amount of radiation, we feel our findings of safe radiation exposure levels is generalizable to all bronchoscopists.

The use of ultrasound guidance, in addition to increasing the diagnostic accuracy of bronchoscopic biopsy, is likely to reduce radiation exposure by decreasing the time required to confidently locate the lesion. This is valuable in minimizing radiation exposure, and additional measures can further reduce patient dose, such as maximizing the distance between the x-ray tube and the patient, minimizing the distance between the patient and the image intensifier, coning the x-ray beam to the region of interest, minimizing the use of electronic magnification, lowering fluoroscopy frame rates, and more judicious use of screening.[50] The International Commission on Radiological Protection notes that the principal aim with regard to medical radiation exposure is to do more good than harm to the patient.[51] In the setting of almost certainly very low patient radiation exposure, we feel there is no rationale to preclude patients from undergoing a single bronchoscopy with fluoroscopy on the basis of safety concerns.

Conclusions

Adequate shielding of the proceduralist's front, back, and thyroid with protective garments with a minimum lead equivalence of 0.35 mm across the diagnostic energy range results in negligible radiation to the bronchoscopist from mobile C-arm fluoroscopic guidance.

The effective radiation doses we measured are much smaller than those previously associated with no adverse health outcomes. Concern regarding radiation exposure should not preclude the use of fluoroscopic guidance in the performance of diagnostic bronchoscopy if it is clinically indicated.

REFERENCES

1. Wingo PA, Ries LA, Giovino GA, Miller DS, Rosenberg HM, Shopland DR, et al. Annual report to the nation on the status of cancer, 1973-1996, with a special section on lung cancer and tobacco smoking. J Natl Cancer Inst 1999;91(8):675-690.
2. Brooks DR, Austin JH, Heelan RT, Ginsberg MS, Shin V, Olson SH, et al. Influence of type of cigarette on peripheral versus central lung cancer. Cancer Epidemiol Biomarkers Prev 2005;14(3):576-581.
3. Roth K, Hardie JA, Andreassen AH, Leh F, Eagan TM. Predictors of diagnostic yield in bronchoscopy: a retrospective cohort study comparing different combinations of sampling techniques. BMC Pulm Med 2008;8:2.
4. Wallace JM, Deutsch AL. Flexible fiberoptic bronchoscopy and percutaneous needle lung aspiration for evaluating the solitary pulmonary nodule. Chest 1982;81(6):665-671.
5. Milman N, Faurschou P, Munch EP, Grode G. Transbronchial lung biopsy through the fibre optic bronchoscope. Results and complications in 452 examinations. Respir Med 1994;88(10):749-753.
6. Rivera MP, Detterbeck F, Mehta AC. Diagnosis of lung cancer: the guidelines. Chest 2003;123(1 Suppl):129S-136S.
7. Paone G, Nicastri E, Lucantoni G, Dello Iacono R, Battistoni P, D'Angeli AL, Galluccio G. Endobronchial ultrasound-driven biopsy in the diagnosis of peripheral lung lesions. Chest 2005;128(5):3551-3557.
8. Kurimoto N, Miyazawa T, Okimasa S, Maeda A, Oiwa H, Miyazu Y, Murayama M. Endobronchial ultrasonography using a guide sheath increases the ability to diagnose peripheral pulmonary lesions endoscopically. Chest 2004;126(3):959-965.
9. Yoshikawa M, Sukoh N, Yamazaki K, Kanazawa K, Fukumoto S, Harada M, et al. Diagnostic value of endobronchial ultrasonography with a guide sheath for peripheral pulmonary lesions without X-ray fluoroscopy. Chest 2007;131(6):1788-1793.
10. Yamada N, Yamazaki K, Kurimoto N, Asahina H, Kikuchi E, Shinagawa N, et al. Factors related to diagnostic yield of transbronchial biopsy using endobronchial ultrasonography with a guide sheath in small peripheral pulmonary lesions. Chest 2007;132(2):603-608.
11. Tapiovaara MJ. Efficiency of low-contrast detail detectability in fluoroscopic imaging. Medical physics 1997;24(5):655-664.
12. Steinfort DP, Irving LB. Patient satisfaction during endobronchial ultrasound-guided transbronchial needle aspiration performed under conscious sedation. Respir Care 2010;55(6):702-706.
13. Wall BF, Hart D. Revised radiation doses for typical X-ray examinations. Report on a recent review of doses to patients from medical X-ray examinations in the UK by NRPB. National Radiological Protection Board. Br J Radiol 1997;70(833):437-439.
14. Regulla DF, Eder H. Patient exposure in medical X-ray imaging in Europe. Radiat Prot Dosimetry 2005;114(1-3):11-25.
15. Diederich S, Lenzen H. Radiation exposure associated with imaging of the chest: comparison of different radiographic and computed tomography techniques. Cancer 2000;89(11 Suppl):2457-2460.
16. Brenner DJ. Radiation risks potentially associated with low-dose CT screening of adult smokers for lung cancer. Radiology 2004;231(2):440-445.
17. Teeuwisse WM, Geleijns J, Broerse JJ, Obermann WR, van Persijn van Meerten EL. Patient and staff dose during CT guided biopsy, drainage and coagulation. Br J Radiol 2001;74(884):720-726.
18. Morrish OW, Goldstone KE. An investigation into patient and staff doses from X-ray angiography during coronary interventional procedures. Br J Radiol 2008;81(961):35-45.
19. Hurwitz LM, Reiman RE, Yoshizumi TT, Goodman PC, Toncheva G, Nguyen G, Lowry C. Radiation dose from contemporary cardiothoracic multidetector CT protocols with an anthropomorphic female phantom: implications for cancer induction. Radiology 2007:245(3):742-750.
20. Kickuth R, Kirchner J, Laufer U, Sanner B, Haske M, Liermann D. Better visualization of transbronchial biopsy using CT fluoroscopy. Cardiovasc Intervent Radiol 2000;23(5):347-350.

21. Buls N, Pages J, Mana F, Osteaux M. Patient and staff exposure during endoscopic retrograde cholangiopancreatography. Br J Radiol 2002;75(893):435-443.
22. Perisinakis K, Damilakis J, Theocharopoulos N, Papadokostakis G, Hadjipavlou A, Gourtsoyiannis N. Patient exposure and associated radiation risks from fluoroscopically guided vertebroplasty or kyphoplasty. Radiology 2004;232(3):701-707.
23. Ector J, Dragusin O, Adriaenssens B, Huybrechts W, Willems R, Ector H, Heidbuchel H. Obesity is a major determinant of radiation dose in patients undergoing pulmonary vein isolation for atrial fibrillation. J Am Coll Cardiol 2007;50(3):234-242.
24. Tsalafoutas IA, Tsapaki V, Kaliakmanis A, Pneumaticos S, Tsoronis F, Koulentianos ED, Papachristou G. Estimation of radiation doses to patients and surgeons from various fluoroscopically guided orthopaedic surgeries. Radiat Prot Dosimetry 2008;128(1):112-119.
25. Kurban LA, Gomersall L, Weir J, Wade P. Fluoroscopy-guided percutaneous lung biopsy: a valuable alternative to computed tomography. Acta Radiol 2008;49(8):876-882.
26. Ohno Y, Hatabu H, Takenaka D, Higashino T, Watanabe H, Ohbayashi C, Sugimura K. CT-guided transthoracic needle aspiration biopsy of small (≤ 20 mm) solitary pulmonary nodules. AJR Am J Roentgenol 2003;180(6):1665-1669.
27. Hirose T, Mori K, Machida S, Tominaga K, Yokoi K, Adachi M. Computed tomographic fluoroscopy-guided transthoracic needle biopsy for diagnosis of pulmonary nodules. Jpn J Clin Oncol 2000; 30(6):259-262.
28. Archer BR, Wagner LK. Protecting patients by training physicians in fluoroscopic radiation management. J Appl Clin Med Phys 2000; 1(1):32-37.
29. Advisory PH. Avoidance of serious x-ray-induced skin injuries to patients during fluoroscopically-guided procedures. Rockville, MD: Food and Drug Administration; 1994.
30. Thompson DE, Mabuchi K, Ron E, Soda M, Tokunaga M, Ochikubo S, et al. Cancer incidence in atomic bomb survivors. Part II: Solid tumors, 1958-1987. Radiat Res 1994;137(2 Suppl):S17-S67.
31. Preston DL, Kusumi S, Tomonaga M, Izumi S, Ron E, Kuramoto A, et al. Cancer incidence in atomic bomb survivors. Part III. Leukemia, lymphoma and multiple myeloma, 1950-1987. Radiat Res 1994;137(2 Suppl):S68-S97.
32. Barish RJ. In-flight radiation exposure during pregnancy. Obstet Gynecol 2004;103(6):1326-1330.
33. Shuryak I, Hahnfeldt P, Hlatky L, Sachs RK, Brenner DJ. A new view of radiation-induced cancer: integrating short- and long-term processes. Part II: second cancer risk estimation. Radiat Environ Biophys 2009;48(3):275-286.
34. Brooks AL. Developing a scientific basis for radiation risk estimates: goal of the DOE Low Dose Research Program. Health Phys 2003; 85(1):85-93.
35. Anoopkumar-Dukie S, McMahon A, Allshire A, Conere TJ. Further evidence for biological effects resulting from ionizing radiation doses in the diagnostic X-ray range. Br J Radiol 2005;78(928):335-337.
36. Sokolov M, Panyutin IG, Neumann R. Genome-wide gene expression changes in normal human fibroblasts in response to low-LET gamma-radiation and high-LET-like 125IUdR exposures. Radiat Prot Dosimetry 2006;122(1–4):195-201.
37. Christodoulou EG, Goodsitt MM, Larson SC, Darner KL, Satti J, Chan HP. Evaluation of the transmitted exposure through lead equivalent aprons used in a radiology department, including the contribution from backscatter. Med Phys 2003;30(6):1033-1038.
38. Kim KP, Miller DL, Balter S, Kleinerman RA, Linet MS, Kwon D, Simon SL. Occupational radiation doses to operators performing cardiac catheterization procedures. Health Phys 2008;94(3):211-227.
39. Lange HW, von Boetticher H. Randomized comparison of operator radiation exposure during coronary angiography and intervention by radial or femoral approach. Catheter Cardiovasc Interv 2006;67(1): 12-16.
40. Delichas M, Psarrakos K, Molyvda-Athanassopoulou E, Giannoglou G, Sioundas A, Hatziioannou K, Papanastassiou E. Radiation exposure to cardiologists performing interventional cardiology procedures. Eur J Radiol 2003;48(3):268-273.
41. Ohno T, Nishimura T, Nakano K, Kaneko I. Differential recovery from potentially lethal damage in normal human lung fibroblasts after irradiation with 60Co gamma-rays and accelerated N-ion beam. Int J Radiat Biol Relat Stud Phys Chem Med 1984;45(1):21-26.
42. Nagasawa H, Little JB, Tsang NM, Saunders E, Tesmer J, Strniste GF. Effect of dose rate on the survival of irradiated human skin fibroblasts. Radiat Res 1992;132(3):375-379.
43. Langner I, Blettner M, Gundestrup M, Storm H, Aspholm R, Auvinen A, et al. Cosmic radiation and cancer mortality among airline pilots: results from a European cohort study (ESCAPE). Radiat Environ Biophys 2004;42(4):247-256.
44. Cardis E, Gilbert ES, Carpenter L, Howe G, Kato I, Armstrong BK, et al. Effects of low doses and low dose rates of external ionizing radiation: cancer mortality among nuclear industry workers in three countries. Radiat Res 1995;142(2):117-132.
45. McGeoghegan D, Binks K, Gillies M, Jones S, Whaley S. The non-cancer mortality experience of male workers at British Nuclear Fuels plc, 1946-2005. Int J Epidemiol 2008;37(3):506-518.
46. United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. UNSCEAR 2000 report to the General Assembly, with scientific annexes. Annex E. Occupational radiation exposures. (Available at www.unscear.org). New York: United Nations, 2000.
47. Vano E, Gonzalez L, Beneytez F, Moreno F. Lens injuries induced by occupational exposure in non-optimized interventional radiology laboratories. British J Radiol 1998;71(847):728-733.
48. Goodenough DJ. Lessons learned in radiology. In: Radiological protection of patients in diagnostic and interventional radiology, nuclear medicine and radiotherapy: proceedings of an international conference held in Malaga, Spain, 26–30 March 2001. Vienna: International Atomic Energy Agency; 2001:145-155.
49. Uradomo LT, Lustberg ME, Darwin PE. Effect of physician training on fluoroscopy time during ERCP. Dig Dis Sci 2006;51(5):909-914.
50. Jain P, Fleming P, Mehta AC. Radiation safety for health care workers in the bronchoscopy suite. Clin Chest Med 1999;20(1):33-38, ix-x.
51. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103. Ann ICRP 2007; 37(2-4):1-332.