Dollars and Sense:
An Analysis of Shielding Design in Diagnostic Imaging

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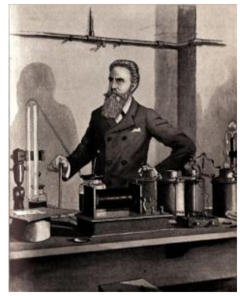
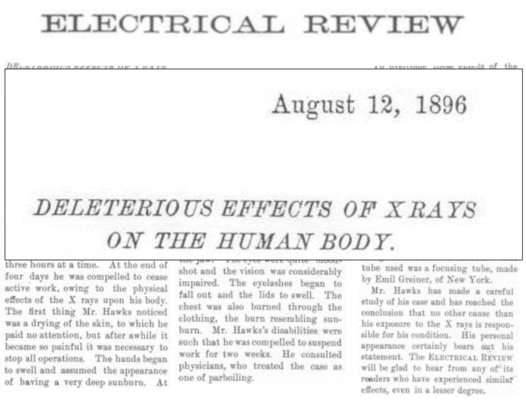
A Brief History…



1895

EINE NEUE ART
VON
STRAHLEN.
VON
DR. W. RÖNTGEN,

WÜRZBURG.



ELECTRICAL REVIEW

August 12, 1896

DELETERIOUS EFFECTS OF X RAYS ON THE HUMAN BODY.

three hours at a time. At the end of four days he was compelled to cease active work, owing to the physical effects of the X rays upon his body. The first thing Mr. Hawks noticed was a drying of the skin, to which he paid no attention, but after awhile it became so painful it was necessary to stop all operations. The hands began to swell and assumed the appearance of having a very deep sunburn. At … shot and the vision was considerably impaired. The eyelashes began to fall out and the lids to swell. The chest was also burned through the clothing, the burn resembling sunburn. Mr. Hawks's disabilities were such that he was compelled to suspend work for two weeks. He consulted physicians, who treated the case as one of parboiling.

… tube used was a focusing tube, made by Emil Greiner, of New York. Mr. Hawks has made a careful study of his case and has reached the conclusion that no other cause than his exposure to the X rays is responsible for his condition. His personal appearance certainly bears out his statement. The ELECTRICAL REVIEW will be glad to hear from any of its readers who have experienced similar effects, even in a lesser degree.

ELECTRICAL REVIEW

August 12, 1896

DELETERIOUS EFFECTS OF X RAYS ON THE HUMAN BODY.

"The first thing Mr. Hawks noticed was a drying of the skin" followed by swelling and a deep burn

ELECTRICAL REVIEW

August 12, 1896

DELETERIOUS EFFECTS OF X RAYS ON THE HUMAN BODY.

After two weeks: "skin all came off the hands," fingernails stopped growing, and the hair on the exposed parts of his hands, face, and head fell out.

ELECTRICAL REVIEW

August 12, 1896

DELETERIOUS EFFECTS OF X RAYS ON THE HUMAN BODY.

"Mr. Hawks first tried covering his hand with vaseline and then putting a glove on…affording no protection whatever."

ELECTRICAL REVIEW

August 12, 1896

DELETERIOUS EFFECTS OF X RAYS ON THE HUMAN BODY.

It seems that the wonderful effects of X rays have not all been learned. One of the newest of these takes the form of a physical effect upon the person who uses powerful X-ray apparatus for comparatively long periods at a time. Mr. H. D. Hawks, a graduate in the class of 1896, of Columbia College, has for the past few weeks been giving exhibitions in the vicinity of New York with an unusually powerful X-ray outfit. Mr. Hawks, during the afternoon and evening of each day for four days, was working around his apparatus for from two to [illegible]

[illegible] was a drying of the skin, to which he paid no attention, but after awhile it became so painful it was necessary to stop all operations. The hands began to swell and assumed the appearance of having a very deep sunburn. At the end of two weeks the skin all came off the hands. The knuckles were especially affected, they being the sorest part of the hand. Among other effects were the following: The growth of the finger nails was stopped and the hair on the skin that was exposed to the rays all dropped out, especially on the face and sides of the head. The hair at the temples has entirely disappeared, owing to the fact of Mr. Hawks having placed his head in close proximity to the tube to enable spectators to see the bones of [illegible]

[illegible] burn. Mr. Hawks's disabilities were such that he was compelled to suspend work for two weeks. He consulted physicians, who treated the case as one of parboiling.

To overcome these effects of the X rays, Mr. Hawks first tried covering his hand with vaseline and then putting a glove on, but the hand was at once burned again, the glove affording no protection whatever. The hand was finally protected by covering it with tin foil. Mr. Hawks coincides with Tesla's belief that X rays are practically minute material particles thrown off from the walls of the tube. The apparatus used was a 10-inch induction coil, manufactured by Ritchie & Son, of Brookline, Mass. The primary circuit was opened and closed by means of a rotary brake mounted on the shaft of a motor, there being 120 breaks a second. [illegible]

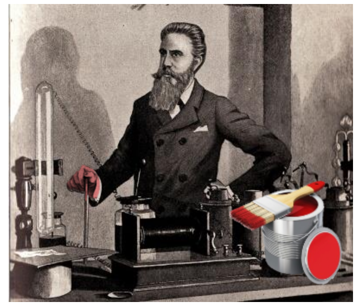
[illegible] his exposure to the X rays is responsible for his condition. His personal appearance certainly bears out his statement. The ELECTRICAL REVIEW will be glad to hear from any of its readers who have experienced similar effects, even in a lesser degree.

"His personal appearance certainly bears out his statement"

A CASE OF DERMATITIS FROM ROENTGEN RAYS.

[WITH CHROMOLITHOGRAPH.]

BY H. RADCLIFFE CROCKER, M.D., F.R.C.P.,



December 12, 1896

Effect of the Röntgen Rays on the Skin.

BY W. C. FUCHS.

1896

- Minimize exposure time
- Place the tube no less than 12" from the patient
- Rub vaseline into the skin
- Cover areas not to be exposed

The Frank Balling Case

1897

Lawsuit, seeking $25,000 for radiation damage from radiographs.

Wakarusa Public Library

1899

DENTAL COSMOS:

THE ROENTGEN ENERGY TO-DAY.

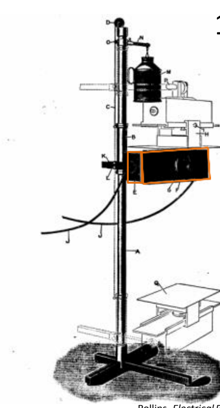
BY JOHN DENNIS, ROCHESTER, N. Y.

(Read before the Seventh District Dental Society of the State of New York, April 25, 1899.)

"…the time has now arrived when the abuse of this God-given energy should be controlled."

1900

Public Domain

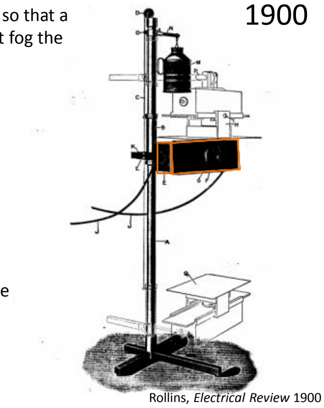


Rollins, *Electrical Review* 1900

1900

Enough lead should be used so that a 7-minute exposure does not fog the plate.

10 R/day tolerance dose



Rollins, *Electrical Review* 1900

1901

Correspondence.

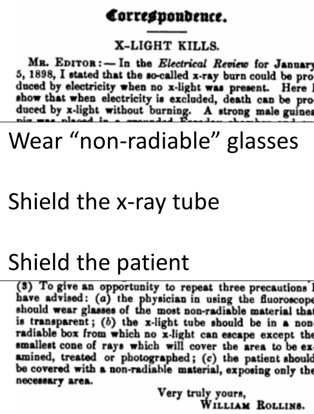
X-LIGHT KILLS.

MR. EDITOR: — In the *Electrical Review* for January 5, 1898, I stated that the so-called x-ray burn could be produced by electricity when no x-light was present. Here I show that when electricity is excluded, death can be produced by x-light without burning. A strong male guinea

(3) To give an opportunity to repeat three precautions I have advised: (*a*) the physician in using the fluoroscope should wear glasses of the most non-radiable material that is transparent; (*b*) the x-light tube should be in a non-radiable box from which no x-light can escape except the smallest cone of rays which will cover the area to be examined, treated or photographed; (*c*) the patient should be covered with a non-radiable material, exposing only the necessary area.

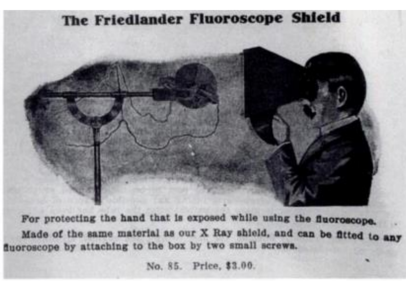
Very truly yours,
WILLIAM ROLLINS.

- Wear "non-radiable" glasses
- Shield the x-ray tube
- Shield the patient



1902

Rollins suggested the use of leaded glass goggles at least 1cm thick



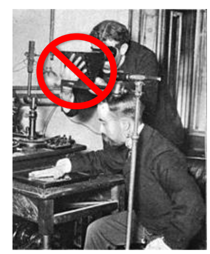
Brodsky & Kathren, "Historical Developments of Radiation Safety Practices in Radiology," RadioGraphics 9(6): 1989, pp.1267-75.

1903

Albers-Schonberg

X-rays induce sterility in rabbits…

…and in humans.



HE Schmidt:
"My efforts to obtain this information by a questionnaire have thus far yielded but very discouraging results."

1903

AMERICAN
ROENTGEN RAY SOCIETY
FOURTH ANNUAL MEETING.
DANGER OF THE X-RAY OPERATION.
BY JOHN T. PITKIN, M.D.

- Color changes in the skin
- Hair loss
- Partial loss of sensation
- Extreme itching, pustules
- Skin loss, extensive ulceration
- Pain and suffering

ARRS Fourth Annual Meeting, via Forgotten Books

1903

AMERICAN
ROENTGEN RAY SOCIETY
FOURTH ANNUAL MEETING.
DANGER OF THE X-RAY OPERATION.
BY JOHN T. PITKIN, M.D.

"For a description of the pain and suffering…no language, sacred or profane, is adequate. The sting of the honey bees or the passage of a renal calculus, is painful enough, but are comparative pleasures, because…they have a time limitation."

About 1/3 of prominent operators and instrument dealers have hands which have been more or less severely injured.

ARRS Fourth Annual Meeting, via Forgotten Books

1903

AMERICAN
ROENTGEN RAY SOCIETY
FOURTH ANNUAL MEETING.

DANGER OF THE X-RAY OPERATION.

BY JOHN T. PITKIN, M.D.

- Vision impairment
- Headache
- Indigestion
- Sore throat
- Infection
- "The sexual power will be temporarily lost."
- Flying fragments of glass
- Derangement?
- Cancer

ARRS Fourth Annual Meeting, via Forgotten Books

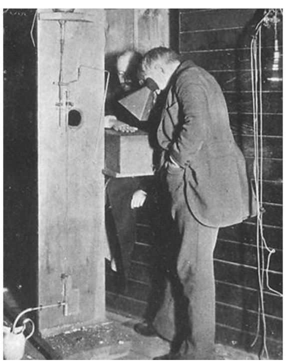
1903

AMERICAN
ROENTGEN RAY SOCIETY
FOURTH ANNUAL MEETING.
DANGER OF THE X-RAY OPERATION.
BY JOHN T. PITKIN, M.D.

Pitkin's precautions:

- Never allow the use of…my body for others to look through.
- Never adjust the tube while it is in operation
- Never use my hand as an X-radiometer
- Wear safety X-ray gloves
- Wear glasses
- Wear an office coat with extra long sleeves, lined with foil
- Stay out of the X-ray field

ARRS Fourth Annual Meeting, via Forgotten Books



Thomas Edison & Clarence Dally

1904

Clarence Dally dies
of metastatic skin cancer

<u>1911 – 1914</u>:
198 cases of radiation-induced malignancy and 54 deaths

<u>By 1934</u>:
Over 200 radiologists had died from radiation-induced malignancies

Mihran Krihor Kassabian, MD

Broadbent and Hubbard, "Science and Perception of Radiation Risk", RadioGraphics (12) 1992.

1915: British Roentgen Society adopts radiation protection guidelines

1) Enclose the x-ray tube in a protective box made of lead

2) The worker should remain behind a protective wall or cubicle during the exam

Brook War Hospital
Woolwich, London
c. 1916

http://antiquescientifica.com/catalog20.htm

1915: British Roentgen Society adopts radiation protection guidelines

1) Enclose the x-ray tube in a protective box made of lead

2) The worker should remain behind a protective wall or cubicle during the exam

1921: British X-ray and Radium Protection Committee Report No. 1

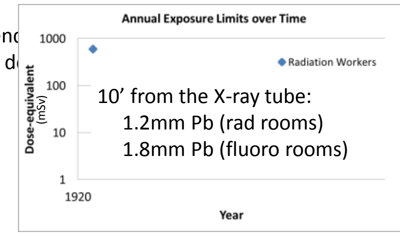
1922: American Roentgen Ray Society

1923: British X-ray and Radium Protection Committee Report No. 2

- Control booth screens should be at least 3'6" wide, 7' high and should extend to within 1" of the ground
- Work time:
  - < 7 hours a day
  - Sundays and 2 half-days off each week, "to be spent as much as possible out of doors"
  - Annual holiday of 1 month or 2 separate fortnights

1925: American physicist Arthur Mutscheller

- "In order to be able to calculate the thickness of the protective material…there must be known the dose which an operator can, for a prolonged period of time, tolerate without ultimately suffering injury."
- Recommend… ne erythema d…

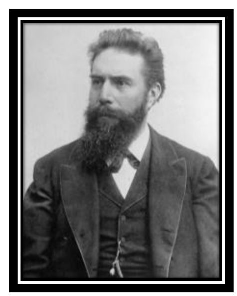


10' from the X-ray tube:
1.2mm Pb (rad rooms)
1.8mm Pb (fluoro rooms)

1927: British X-ray and Radium Protection Committee Report No. 3

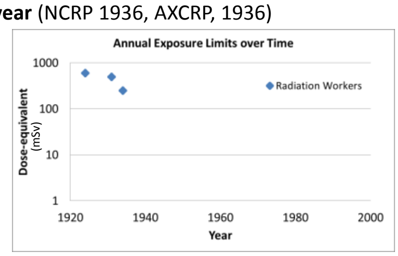
- Recognized implications of exposure to employees and the **public** in areas adjacent to the x-ray room

1928: International Congress on Radiation introduces the unit of Roentgen



1930s
Tolerance Dose – A level below which injury will not appear

- **500 mSv/year** (ACXRP & NCRP 1931, 1934)
- **250 mSv/year** (NCRP 1936, AXCRP, 1936)



1931: NCRP Report No. 1

- All x-ray rooms (except for dental radiography) or booths shall be lined with **at least 0.5mm sheet lead** or equivalent material…
- This may be omitted only on outside walls and sides adjacent to unoccupied rooms.

1931: NCRP Report No. 1 (continued)

- "Every assistant, technician, and operator should be given at least four weeks vacation a year with at least 2 weeks of this consecutively and during the summer months."

1941

Limits placed on ingested radium → Safety Factor of 10

https://en.wikipedia.org/wiki/Radium_Girls#/media/File:USRadiumGirls-Argonne1,ca1922-23-150dpi.jpg

1940s and 1950s:

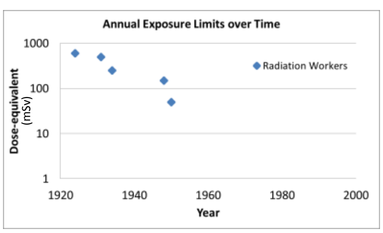
NCRP Reports from 1949-1960

- Introduced the concept of benefit vs risk (ALARA)

1948: 150 mSv/year

1957: 50 mSv/year (ICRP)

1958: 50 mSv/year (NCRP)



1950s – Radiation-induced genetic effects

- Data from atomic bomb survivors
- Early analysis indicated a change in the ratio of males to females born to survivors.
- (Later analyses showed the early assessment of bomb survivor data was incorrect)

Wikipedia Commons

1958

NCRP: lifetime: years as an adult x 50 mGy

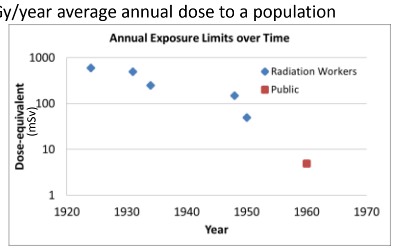
public: 5 mGy/year

1960

Federal Radiation Council

public: 5 mGy/year to an individual

1.7 mGy/year average annual dose to a population



1960s – Cancer risk

- Risk of genetic effects had been over-estimated
- Atomic bomb data showed increased cancer risk
  - Do low levels of radiation cause cancer??

<u>Philosophical shift</u>

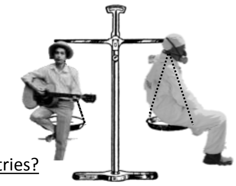
compliance with dose limits

→ emphasis on reducing overall cancer risks

1960s
ICRP:

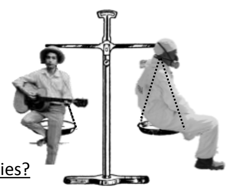
1. Justification
   - No new use of radiation unless there is a **net positive benefit**
2. Optimization
   - **ALARA**, taking into account economic and social factors

1977: ICRP Publication 26 - Risk-based Philosophy



- Incremental risk of death in safe industries?
  1 in 10,000 per year
- Atomic bomb survivor data:
  Risk of death from radiation-induced cancer: 1 in 10,000 per 10 mGy

1977: ICRP Publication 26 - Risk-based Philosophy



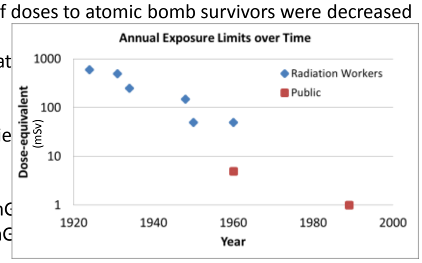
- Incremental risk of death in safe industries?
  1 in 10,000 per year
- Atomic bomb survivor data:
  Risk of death from radiation-induced cancer: 1 in 10,000 per 10 mGy
- ICRP:
  Maximum annual dose limit of 50 mGy/year
  (assuming that the average dose would be < 10 mGy/year)

1980s
Estimates of doses to atomic bomb survivors were decreased

Incidence rat
thought

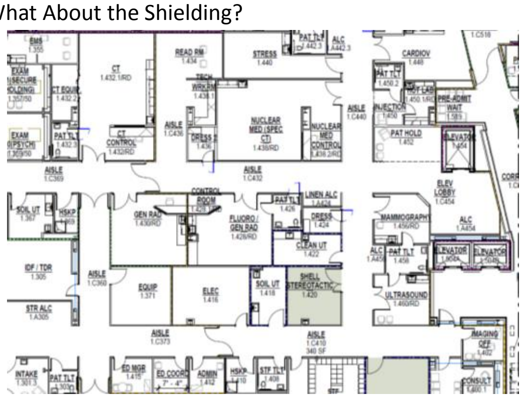
Risk coefficie

1990
ICRP: 100 mG
50 mG

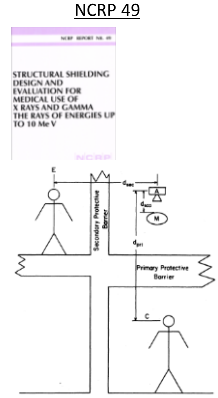


Public limit: 1 mGy/year (averaged over any 5-year period)

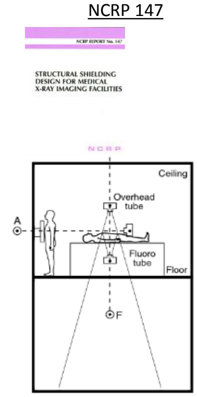
What About the Shielding?



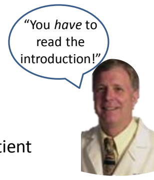
NCRP 49



NCRP 147

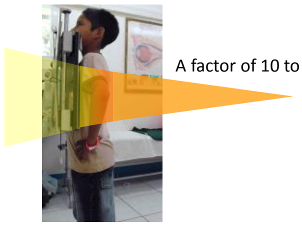


Assumptions Made in NCRP 147



1.4.3 *Shielding Design Assumptions*

Attenuation of the primary beam by the patient is neglected.



A factor of 10 to 100

Assumptions Made in NCRP 147

1.4.3 *Shielding Design Assumptions*

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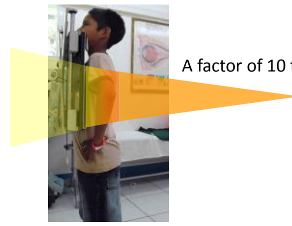
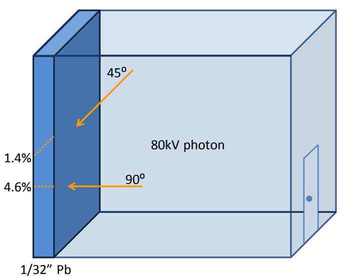
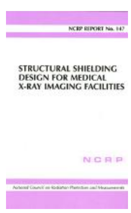


A factor of 10 to 100

Assumptions Made in NCRP 147

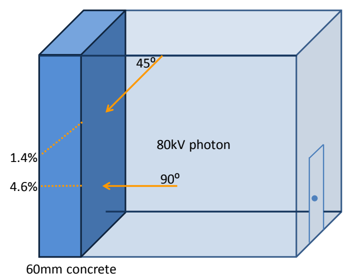
Always assumes perpendicular incidence of radiation





Assumptions Made in NCRP 147

Always assumes perpendicular incidence of radiation

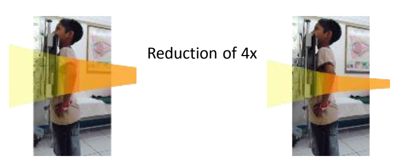


Assumptions Made in NCRP 147

Materials in the path of the beam are often ignored

Assumptions Made in NCRP 147

A conservative field size and phantom were used to calculate scattered radiation

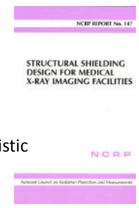


Reduction of 4x

Assumptions Made in NCRP 147

Occupancy factors are conservatively high

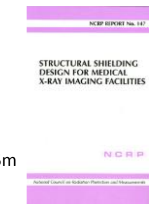
Public toilets, unattended vending areas, storage rooms, outdoor areas with seating, unattended waiting rooms, patient holding areas	1/20



"The qualified expert should make reasonable and realistic assumptions concerning occupancy factors, since each facility will have its own particular circumstances."

Assumptions Made in NCRP 147

Minimum distances assumed are conservative.



"For a wall this may be assumed to be not <0.3m"

"…for ceiling transmission the distance of at least 0.5m above the floor…is generally reasonable."

Q1: Patient attenuation of the primary beam is not considered in shielding design described by NCRP 147.

In actuality, what percent of the primary beam is transmitted through the patient?

20%	A. 0.1% to 1%
20%	B. 1% to 10%
20%	C. 10% to 30%
20%	D. 30% to 50%
20%	E. 50% to 70%

10

51

Answer 1

- B. 1% to 10%
- Ref: NCRP Report No. 147, "Structural Shielding Design for Medical X-ray Imaging Facilities," (NCRP, Bethesda, MD, 2004), p.5

52

Q2: What assumption does NCRP 147 make about the incidence of radiation on barriers?

20%	A. Radiation incidence is isotropic
20%	B. Radiation incidence is at an angle of 30°
20%	C. Radiation incidence is at an angle of 90°
20%	D. Radiation incidence between 30° and 150°
20%	

10

53

Answer 2

- C. Radiation incidence is at an angle of 90°
- Ref: NCRP Report No. 147, "Structural Shielding Design for Medical X-ray Imaging Facilities," (NCRP, Bethesda, MD, 2004), p.5

54

Q3: The occupancy factor for a staff restroom is 1/5. What does this mean?

20%	A. Each staff member spends an average of 8 hours a week in that restroom.
20%	B. The total amount of time the restroom is being used is 8 hours a week.
20%	C. No single employee is likely to spend more than 8 hours a week in that restroom.
20%	
20%	

10

55

Answer 3

- C. No single employee is likely to spend more than 8 hours a week in that restroom.
- Ref: NCRP Report No. 147, "Structural Shielding Design for Medical X-ray Imaging Facilities," (NCRP, Bethesda, MD, 2004), p.29

56

Q4: In NCRP 147, the calculated scattered radiation is based on a large field size and a highly-scattering phantom.

How much does this over-estimate the actual amount of scattered radiation that is likely in a clinical setting?

20%	A. A factor of 2
20%	B. A factor of 4
20%	C. A factor of 10
20%	D. A factor of 20
20%	

10

57

Answer 4

- B. A factor of 4
- Ref: NCRP Report No. 147, "Structural Shielding Design for Medical X-ray Imaging Facilities," (NCRP, Bethesda, MD, 2004), p.6

58

Q5: What thickness of concrete is needed to provide the same attenuation as 1/32" (0.8mm) of lead for secondary radiation?

20%	A. 1 mm
20%	B. 6 mm
20%	C. 60 mm
20%	D. 120 mm
20%	

10

59

Answer 5

- C. 60 mm
- Ref: NCRP Report No. 147, "Structural Shielding Design for Medical X-ray Imaging Facilities," (NCRP, Bethesda, MD, 2004), pp.141-142

60

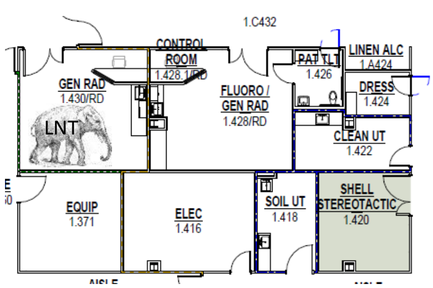
Factors in Shielding Calculations

- Shielding Design Goal
- Workload
- Occupancy Factors
- Equipment

Factors in Shielding Calculations

- Shielding Design Goal
- Workload
- Occupancy Factors
- Equipment

Factors in Shielding Calculations – Shielding Design Goal



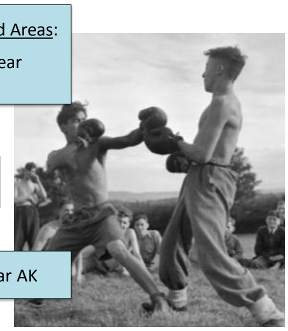
Factors in Shielding Calculations – Shielding Design Goal

Exposure Limits

Controlled Areas:	Uncontrolled Areas:
50 mSv/year (10 mSv x age)	5 mSv/year

Design Goal: One fraction of ½ of the limit

5 mGy/year AK	1 mGy/year AK



Factors in Shielding Calculations

- Shielding Design Goal
- Workload
- Occupancy Factors
- Equipment

Factors in Shielding Calculations - Workload

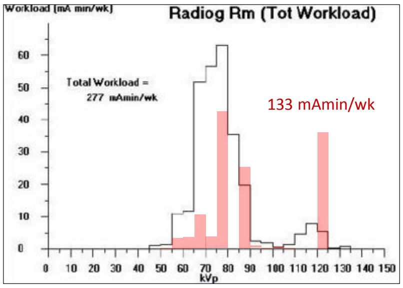
- Number of exams
- Type of exams
- Exam technique

→ mA*minute per week

	Workload (mA*min per week)	
	Simpkin (1996)	UCH (2016)
Rad room	277	133
Chest room	45	22
Cardiac angio room	3050	

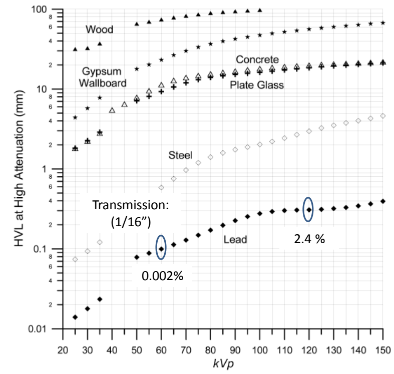
Factors in Shielding Calculations - Workload

- kV distribution of workloads was significantly below the single kVp operating value usually assumed



Factors in Shielding Calculations - Workload

- Transmission through shielding barriers increases by factors of hundreds going from 60kVp to 120kVp



Factors in Shielding Calculations

- Shielding Design Goal
- Workload
- Occupancy Factors
- Equipment

Factors in Shielding Calculations – Occupancy Factors

Occupancy Factor of 1/20 → 2 hours per week

- by any *single* person
- during a 40 hour work week

TABLE 4.1—*Suggested occupancy factors*[a] *(for use as a guide in planning shielding where other occupancy data are not available).*

Factors in Shielding Calculations

- Shielding Design Goal
- Workload
- Occupancy Factors
- Equipment

Factors in Shielding Calculations – Equipment

Attenuation through Bucky/detector/grid?

125 kVp:
ransmission (no grid)
ransmission (w/ grid)

Rad Room Sample Shielding	Primary (mGy/patient)	Secondary (mGy/patient)
$X_{barrier}$ (mm Pb)	0.76	0.31
Closest lead thickness	1/32"	1/64"

Factors in Shielding Calculations – Equipment

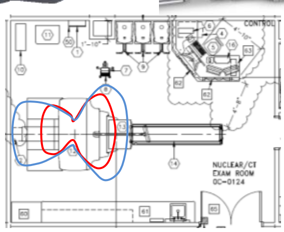
Beam Quality

	Minimum HVL (mm Al)	
measured kV	← June 2006 →	
60	1.2	1.3
70	1.3	1.5
80	1.5	1.8
100	2.7	3.6
120	3.2	4.3
140	3.8	5.0

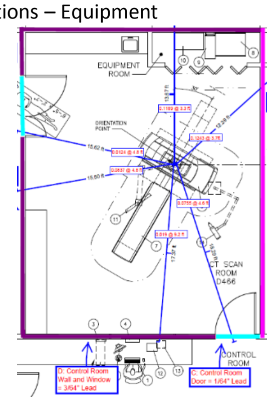
Factors in Shielding Calculations – Equipment

Factors in Shielding Calculations – Equipment

5.2 µGy/scan isodose line



Factors in Shielding Calculations – Equipment



NCRP 49

- Decreasing the shielding design goal from 50mGy/year to 5 mGy/year will only increase costs by about 25%
- "While specific recommendations are given, alternate methods may prove equally satisfactory in providing radiation protection. The final assessment of the adequacy of the design and construction of structural shielding **should be based on the radiation survey** of the completed installation."

Q6: NCRP recommends an annual exposure limit of 50 mSv/year for radiation workers.

How does this compare with the NCRP recommendation for shielding design goals for controlled areas?

20% A. The shielding design goal is of the annual exposure limit (5 mSv/year).

20% B. The shielding design goal is of the annual exposure limit (10 mSv/year).

20% C. The shielding design goal is of the annual exposure limit (25 mSv/year)All of the above

20% D. The shielding design goal is the same as the annual exposure limit (50 mSv/year).

20%

10

78

Answer 6

A. The shielding design goal is $^{1}/_{10}$ of the annual exposure limit (5 mSv/year).

- Ref: NCRP Report No. 147, "Structural Shielding Design for Medical X-ray Imaging Facilities," (NCRP, Bethesda, MD, 2004), p.4

79

Comparison of BIR and NCRP Shielding

Shielding Examples, mm of Pb		
	BIR	NCRP
Rad Room - Primary	1.14	1.45
Rad Room - Secondary	0.34	0.77
Cardiac Cath Lab	0.45	1.3
CT Room	0.6-1.5	

Based on a shielding design of 1 mGy/year

Diagnostic Radiology Physics, IAEA

Where Are We Now?

1925
1.2mm Pb (rad rooms) 1.8mm Pb (fluoro rooms)

2016
0.4mm – 1.6 mm Pb
(Rad, fluoro, & CT rooms)

Parting Thoughts…

Understand the origins of shielding design limits.

Recognize what assumptions you're making.

What, if any, data from NCRP 147 needs to be re-visited?

Consider the risk and cost.