Health Impacts from Nuclear Weapon Effects in Modern Urban Environments

AAHP Special Session: Nuclear Weapons – Present and Past Hazards
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Health Impacts from Nuclear Weapon Scenarios

- Historical perspectives:
  - Hiroshima and Nagasaki
  - Knowledge from other historical incidents
  - Knowledge from historical experiments/tests

How do modern urban environments change anticipate health impacts?

- Insight from modeling and modern experiments:
  - Improvised Nuclear Device (IND)
    - Non-radiological injuries
    - Radiation Injuries
    - Combined Injury and Demographics

Historical Perspectives: Hiroshima and Nagasaki

- The atomic bomb survivors provide us with significant knowledge regarding the health effects from nuclear weapons
  - Current human $LD_{50/60}$ = 4.1 Gy estimate[1] is based on a Nagasaki cohort.

- The larger survivor cohort is the foundation for our current long-term health effects risk estimates (BEIR VII)

1: Anno et al., *Health Physics,* 2003.

Overview of Radiation Injury

- Acute Radiation Syndrome
  - Hematopoietic
  - Gastrointestinal
  - Neurovascular
  - Cutaneous (ref. METREPOL)
- Other effects:
  - Oropharyngeal
  - Lung damage
  - Eye damage
  - Multi-organ dysfunction

Dose (Gy)	Prodrome	Manifestation of Illness	Prognosis (without Therapy)
0.5-1.0	Mild	Slight decrease in blood cell counts	Almost certain survival
1.0-2.0	Mild to moderate	Early signs of bone marrow (BM) damage	Highly probable survival (>90%)
2.0-3.5	Moderate	Moderate to severe bone marrow damage	Probable survival
3.5-5.5	Severe	Severe BM damage; slight GI damage	Death within 3.5-6 wk (50% of victims)
5.5-7.5	Severe	Pancytopenia and moderate GI damage	Death probable within 2-3 wk
7.5-10.0	Severe	Marked GI and BM damage, hypotension	Death probable within 1-2.5 wk
10.0-20.0	Severe	Severe GI damage, pneumonitis, altered mental status, cognitive dysfunction	Death certain within 5-12 d
20.0-30.0	Severe	Cerebrovascular collapse, fever, shock	Death certain within 2-5 d

Waselenko, et al. *Annals of Internal Medicine*, 2004.

Additional Health Effects

- Blast effects can result in traumatic injuries from:
  - Perpendicular impact
  - Blunt trauma
  - Decelerative tumbling
  - Penetrating injuries (debris/glass)

- Thermal fluence can result in:
  - Direct thermal burns
  - Burns from fires resulting from blast effects and/or ignition

- Combined injuries, including infection

Combined Injuries

- Historical analyses (Textbook of Military Medicine[1]):
  - Based on A-bomb observations and modeling from nuclear weapons testing

Type of Injury	Percent Distribution
Single Injuries (30%-40%)	
Irradiation*	15-20
Burns	15-20
Wounds	≤ 5
Combined Injuries (65%-70%)	
Burns + Irradiation	40
Burns + Wounds + Irradiation	20
Wounds + Irradiation	5
Wounds + Burns	5

*Including fallout

1: Walker & Cerveny (1989) *Medical Consequences of Nuclear Warfare,* Table 1-1.

Knowledge from other Historical Incidents

- Chernobyl:
  - Airbursts of Nagasaki and Hiroshima resulted in little localized fallout
  - Chernobyl and atmospheric nuclear weapon tests provide an example of what impact direct fallout might have on health outcomes

- Goiania:
  - Provides an example of the logistical challenges of mass casualty screening in a large urban environment
- Criticality Incidents:
  - Illustrates our limited understanding of neutron dosimetry
  - Health impacts of neutron doses are even more limited; as different biophysical mechanisms are involved

Lessons Learned from Chernobyl

- 134 cases of ARS with 28 early fatalities*
- Skin doses exceeded bone marrow doses by a factor of 10–30.
  - Infection from large area beta burns contributed to least 19 of the deaths
- Internal contamination was of relatively minor importance in treatment.
- Long term treatment was required for beta burn fibrosis, skin atrophy, and cataracts.

Relationship of ARS degree, % skin burns, and dose in Chernobyl patients *(Alexahakin et al. 2005)*

		Percentage of skin surface radiation burn			
Number of patients	**ARS severity grade**	**50-100%**	**10-50%**	**1-10%**	**Approx. absorbed skin dose (Gy)**
31	I	0	1	2	8-12
43	II	1	9	2	12-20
21	III	3	15	3	20-25
20	IV	9	10	1	>25

*Mettler, et al., *Health Physics*, 2007.

Lessons Learned from Chernobyl

- Cutaneous component of ARS significantly complicated clinical prognosis and contributed to mortality *(Shapiro, 2008)*.
  - Severe beta-burns of the skin were observed
  - Severity of the burns could have been avoided by removing contaminated clothing.
  - Radiation-induced fibrosis is a predominant clinical problem

- Non-bone marrow syndromes *(Barabanova, 2006)* with ARS (n=115):

− Skin burns:	n=56	48.6 %
− Oropharyngeal:	n=90	69.5 %
− Gastrointestinal:	n=17	14.7 %
− Radiation Pneumonitis:	n=7	6.1 %

Insight from Goiania Accident

- Stolen medical Cs-137 source, punctured, sold to a scrap yard
- Impact:
  - Over 130,000 people were screened for contamination
  - 250 persons identified
  - 20 persons ultimately required treatment

- Follow-up screening of 112,000 people
  - 249 identified with contamination
  - 129 identified with internal contamination

IAEA, *The Radiological Accident in Goiania*, 1988.

Uncertainty in Physical Dosimetry and Health Impacts of Neutrons

- Vinca Criticality accident, Yugoslavia, 1958
- Doses were reconstructed based on shielding, Na neutron activation, etc.
  - Jammet et al. 1959, Hurst et al. 1961. Pendic 1961, Auxier 1961, Mole 1984, Pesic 2012.

Patient	Jammet 1959	Hurst 1959	Auxier 1961	Pesic 2012
	rem	rad	rad	rad
V	840	640	436	363
M	856	580	426	352
G	920	600	414	351
D	1024	500	419	266
H	694	420	323	312
B	408	350	207	479

Knowledge from Historical Weapons Tests and Experiments

- Military tests such as Operation PlumbBob provide much of our knowledge on injury criterial models today
  - Ex. relationship between overpressure and thermal fluence to probability of effects and general dose response in different animal models
- Messerschmidt, 1976
  - Detailed review of experience from Hiroshima and Nagasaki, as well as animal experiments
- Baum, 1990
  - Detailed review of pathophysiology from studies of combined injury in animal models

General consensus:

Combined injuries result in ***higher mortality*** and ***earlier onset*** of clinical signs and symptoms.

How do modern urban environments change anticipate health impacts?

Modern Urban Environments

- Large urban environments have multistory buildings, sometimes very densely populated urban structures:
  - Buildings afford significant shielding from radiation
  - Buildings also create hazards from blast and thermal effects:
    - > Glass shattering
    - > Flying debris
    - > Building collapse

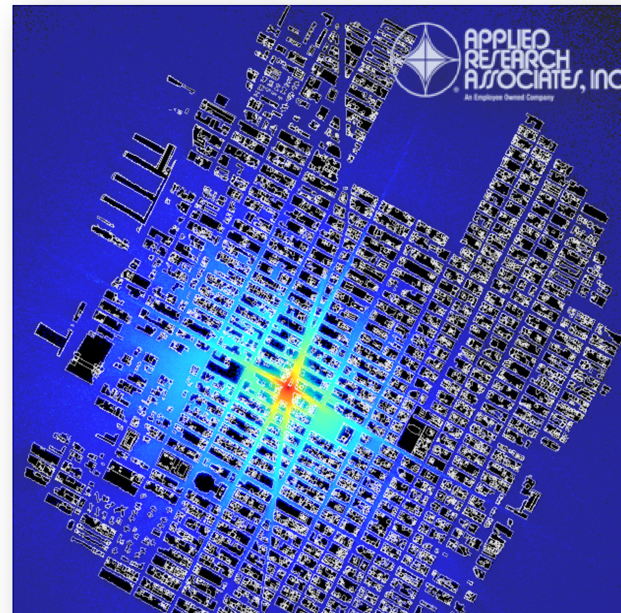
- Therefore, modern urban scenarios may have different proportionalities of injuries compared to historical data.
  - The proportion of combined injuries will likely be greater.

- As an example, in terrorist bombing case studies, patients have an average of **3 injuries/person.**

Insight Gleaned from Urban Improvised Nuclear Devise Modeling

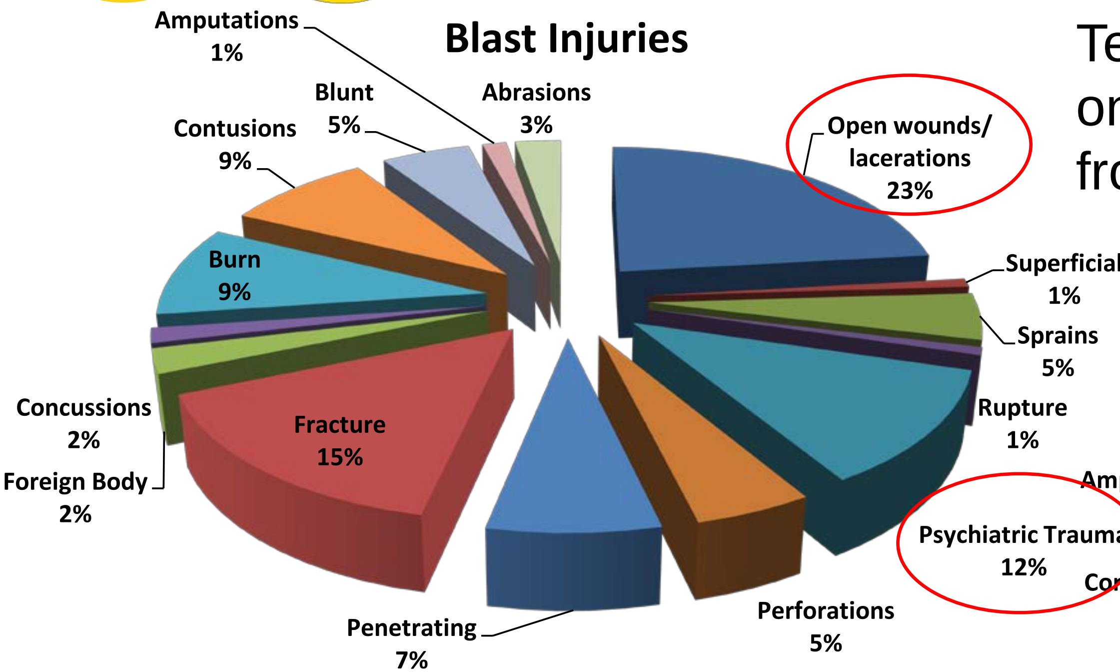
- Prompt radiation exposures
  - Gamma, some neutron
- Protracted radiation exposures
  - Neutron activation products
  - Radioactive fallout
- Blast-related Injuries
  - Flying debris
  - Glass shattering
  - Structural collapse
- Thermal-related Injuries
  - Flash burns
  - Secondary fires
- Inhalation Hazards
  - Smoke and heat from burning materials
  - Dense dust generated from building damage

Urban Radiation Shielding

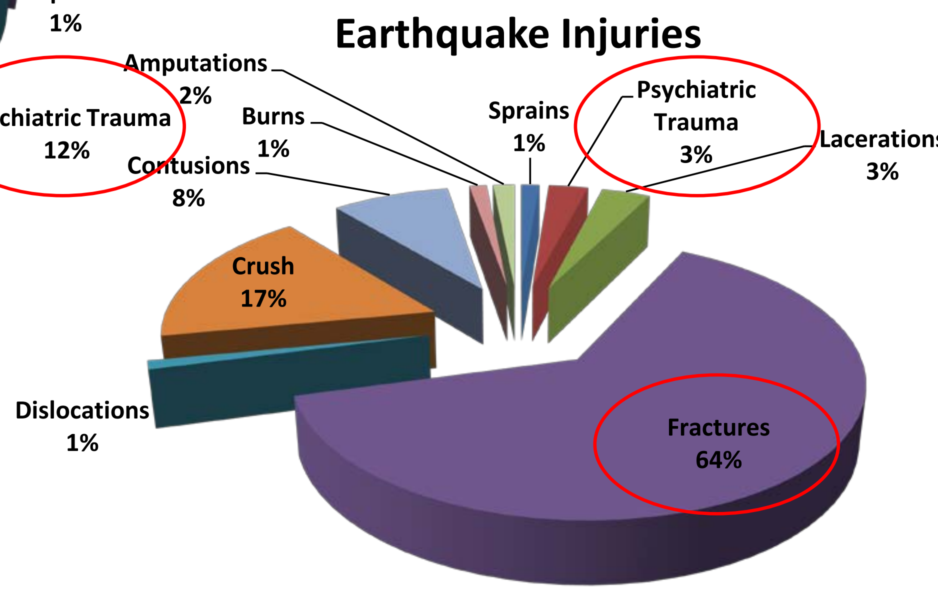


Many complex injuries with potentially survivable doses of radiation exposure

Spectrum of Potential Blast Injuries



Terrorist bombings provide insight on spectrum of injuries that result from blast wave interactions.

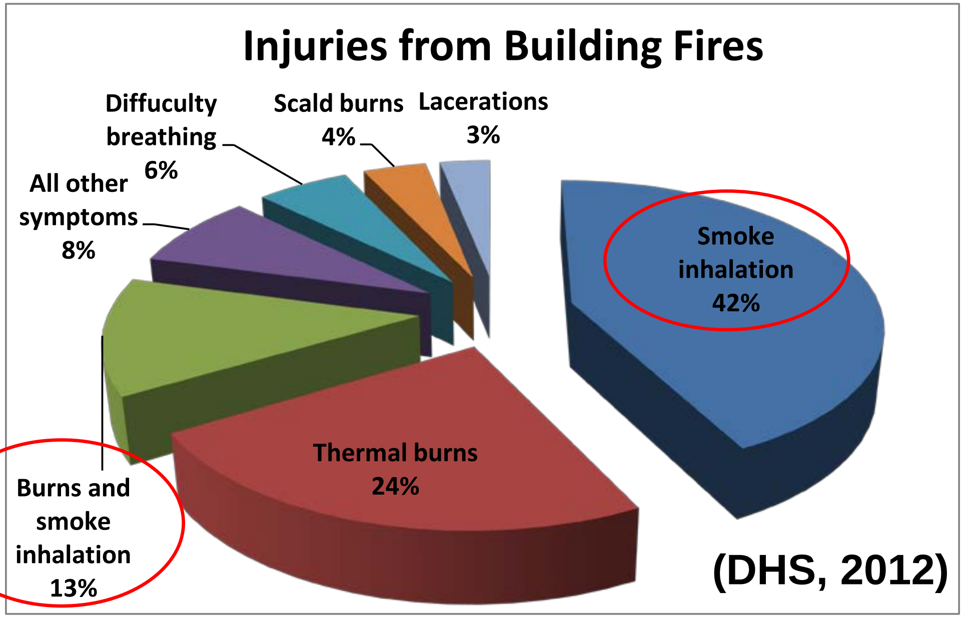


Earthquakes provide insight on spectrum of injuries that result from building collapse.

22 case studies on 486 bombings (n=16,588); 9 large earthquake studies (n=5,106)

Potential Injuries from Secondary Fires and Inhalation Hazards

- Urban modeling indicates few flash burns may be anticipated
  - Persons in direct line of sight to detonation
- Likelihood of secondary fires is city specific
  - Depends on building material and local hazards



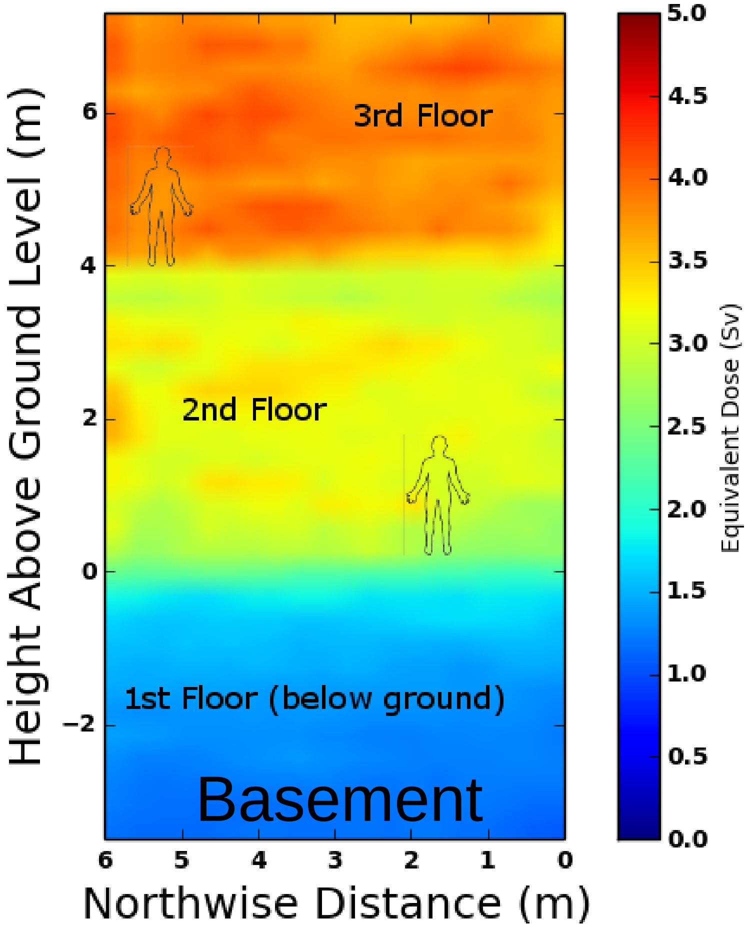
Radiation Exposures

- Prompt Exposures
  - Depends on device characteristics and height of burst (HOB)
  - Neutron/gamma ratio varies
  - *How do neutron exposures alter our interpretation of diagnostics, prognoses, and treatment?*
- Protracted Exposures
  - Impact of radiation is dose rate dependent and current general dose response is based on high dose rate exposures
  - *How does lethality for a **5 Gy** exposure change when delivered in **2 days** instead of **in seconds**?*
    - Dose rate of 0.10462 Gy/hr: marrow EPD 1.83 Gy, **8%** probability of lethality*
    - Dose rate of 300 Gy/hr: marrow EPD 3.5 Gy, **72%** probability of lethality*
  - Important in understanding diagnostic results, making prognosis of patients, and in triage of exposed.

Estimated using MarCell, Jones et al., 1992, and RIPD, EPD=equivalent prompt dose

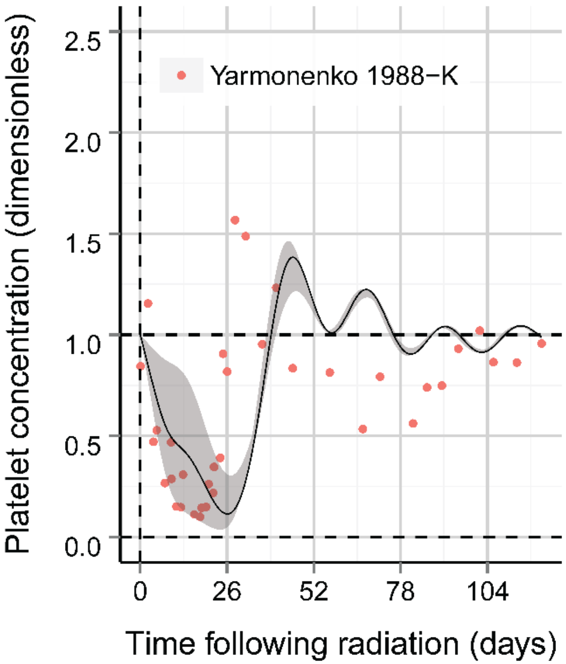
Shielding afforded by Urban Structures

- Urban structures afford variable levels of shielding
- Doses within the same building can range from ***"no acute effects"*** to ***"highly lethal"***
  - ***Highlights importance of radiation diagnostics***
- Partial body exposures?
  - **No complete shielding**
- Based on current analyses for prompt radiation:
  - Most exposures will be whole body but non-uniform.
  - Max shoulder to shoulder Δ 0.08 Sv
  - Max head to toe Δ 0.3 Sv
- ***How does whole body non-uniform exposure alter injury profile/treatment requirements?***



Non-Uniform Exposure Case Study

- Yarmonenko 1988
  - 2.8 Gy to left side
  - 10 Gy to right side
- Simulation comparison at 5.8 Gy[1]
  - Initially, more dramatic impact than whole body equivalent dose
  - Comparable recovery
  - Patient survival dictated by bone marrow sparring



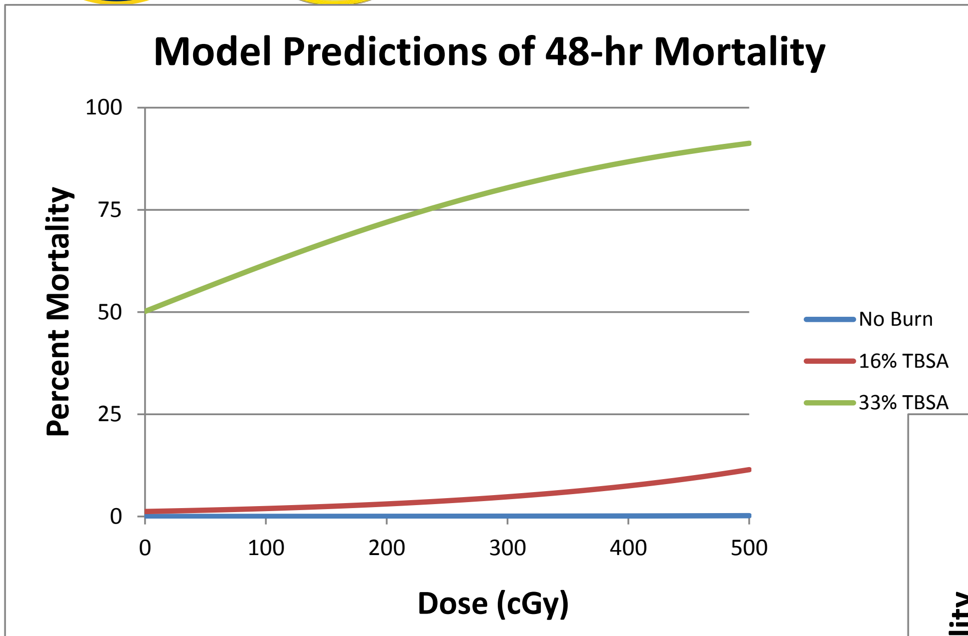
Simulation is run at 2.8 Gy (upper shaded), 10 Gy (lower shaded), and whole body eq. 5.8 Gy (black line)

1: DTRA-TR-14-031, *Mathematical Models of Human Hematopoiesis following Acute Rad Exposure*.

Impact of Combined Injuries

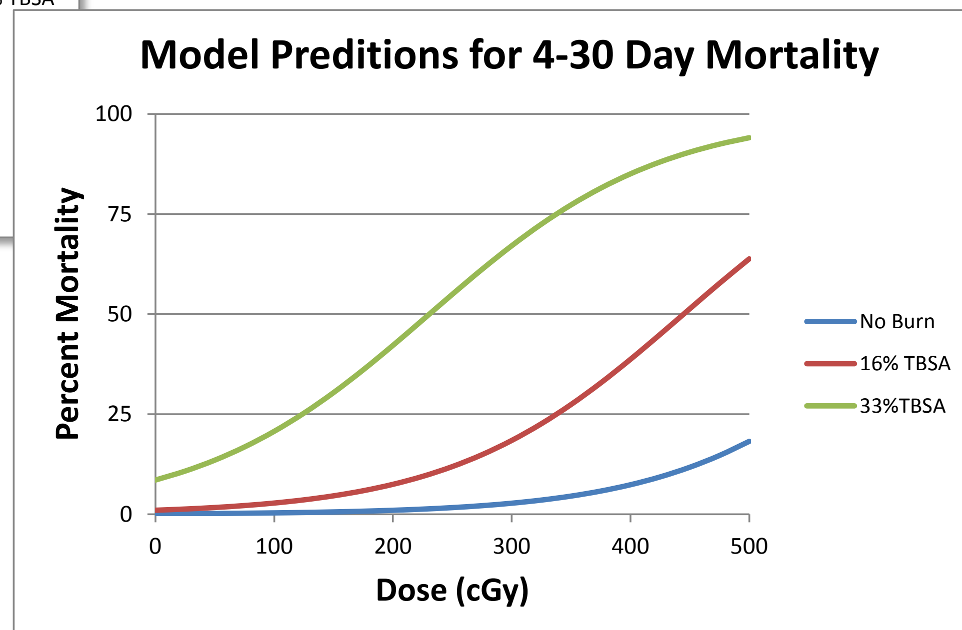
- How will combined injuries impact the course of radiation injury?
  - Faster onset of symptoms
  - Increased severity of symptoms
  - Delayed wound healing
- Many potential interactions:
  - Synergistic immuno-compromise → Sepsis
  - Radiation pulmonary effects + heat, particulates, and trauma → acute respiratory distress syndrome (ARDS)
  - Reactivation of latent viruses
    - Known complications and increased mortality in burn patients
- We are currently using mathematical modeling to understand the impact of combined injury on predicted outcomes.

Combined Injury Mortality Predictions



Indicates:
~40% increase in lethality from "shock" mechanisms at 33%TBSA* and 5 Gy

~10% increase in lethality from "shock" mechanisms at 16%TBSA* and 5 Gy

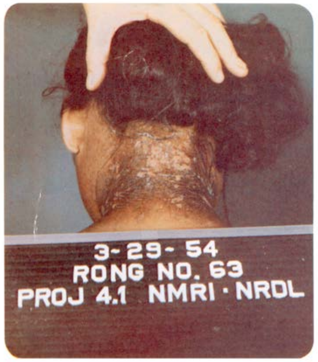


Indicates:
Of those surviving after 48hrs;
~40% increase in lethality from sepsis-related mechanisms at 16%TBSA* at 5 Gy

*% total body surface area burn, 2nd burn, in animal model (Alpen et al., 1954, Baum, 1991)

Cutaneous Radiation Doses

- Radioactive fallout on skin can deliver high localized dose.
- Dose and risk of injury depends on:
  - Time after detonation exposure occurs, concentration of nuclides, metrological conditions, etc.
  - Skin surface area exposed, location of deposition on skin
  - Duration of exposure on skin
- Example Model calculations:



Distance	Time	Skin Dose Rate
1 km	2 hrs	3.9 Gy/hr
1 km	12 hrs	0.3 Gy/hr
5 km	2 hrs	0.04 Gy/hr
5 km	12 hrs	0.003 Gy/hr

Grade	Dose (Gy)	Potential Effects
I	>2	Edema, mild atrophy, carcinogenic risk
II	>15	Atrophy, ulcerations
III	>40	Chronic ulceration
IV	>550	Chronic ulceration requiring skin graft(s)

Adapted from: http://www.bt.cdc.gov/radiation/criphysicianfactsheet.asp

Cutaneous Radiation Doses

- ~ 20% of Rongelap Marshallese exposed to radioactive fallout developed β-burns *(Cronkite 1954).*
  - Lesions comparable to 2nd degree thermal burns.
  - Lesions can result even if γ-radiation levels do not produce extreme illness or death.
  - Sweat resulted in concentrating and trapping nuclides in folds of the skin
- The β/γ dose ratios increase with time; decrease with distance
  - At 1cm: 0.5 and 24 hrs, β/γ=36.4 and 65.1
  - At 1m: 0.5 and 24 hrs, β/γ=10.4 and 12.2
- Clothing affords some protection.
  - 12-41% reduction in skin dose

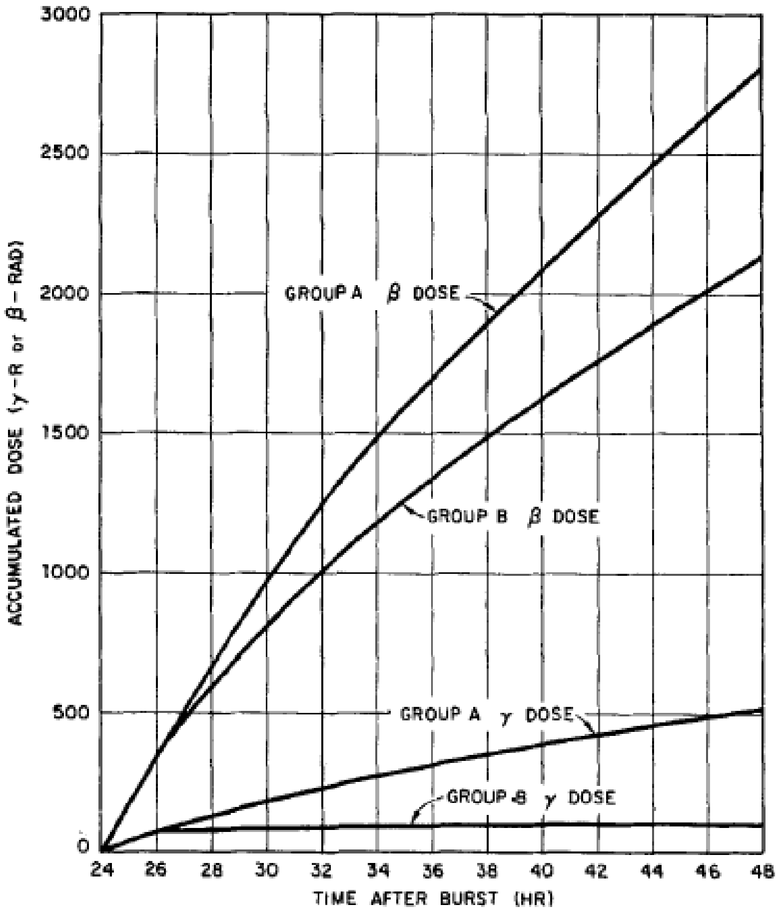


Fig. 8. Estimated radiation dosage accumulated by personnel who enter a fallout area and perform a crawling maneuver.

Black RH. *Health Physics*, 1962. and Barss NM and Weitz RL. *Health Physics*, 2006.

Demographic Variability

- The **fetus is highly vulnerable** to acute radiation.
- Males may be more susceptible to radiation illness and have higher risk of sepsis.
- **Infants and elderly** have poorer prognoses after acute injury.
- **Co-morbidities** significantly impact survival after acute injury.
- Carriers of **certain heritable mutations** and **dormant viruses** may have higher risk after acute radiation.

		Relative Change in Risk	
Demographic factors	Percent of US population*	Acute radiation	Acute injury
In utero	1.5	increase	NA
Age			
Children (≤14)	21.4	LD	variable
Elderly (≥75)	5.9	LD	increase
Gender			
Female	50.9	decrease	variable
Genetic suscept.	5	increase	NA
Co-morbidities	47	increase	increase
Diabetes	10	LD	increase
Renal disease	13	LD	increase
Heart disease	12	LD	increase
Cancer	1.5	LD	high increase
HIV	0.5	LD	high increase
Dormant Viruses	58-60	increase	increase
Pharmaceutical use	48	variable	variable

*Calculated from published data, 2005-2006 statistics, and 2000 census data.
LD, limited or no data available; NA, not assessed.

Stricklin, et al., *Health Physics*, 2012.

Summary and Conclusions

- A nuclear detonation scenario would result in a very complex set of combined injuries:
  - Many blast and thermal injuries with survivable radiation doses.
  - Much radiation injury will come from protracted fallout exposures.
  - Demographic factors, inhomogeneity, combined injury, and protraction will impact projected outcomes.
  - Mechanistic modeling is helping us to understand the impact of combined injuries.

- Gaps still exist in our understanding of:
  - Impact of cutaneous radiation doses on outcomes.
  - Reduction of mortality with inhomogeneous exposures.
  - Impact of neutron doses on injury and effectiveness of treatment.
  - Impact of injuries in a diverse demographic population.