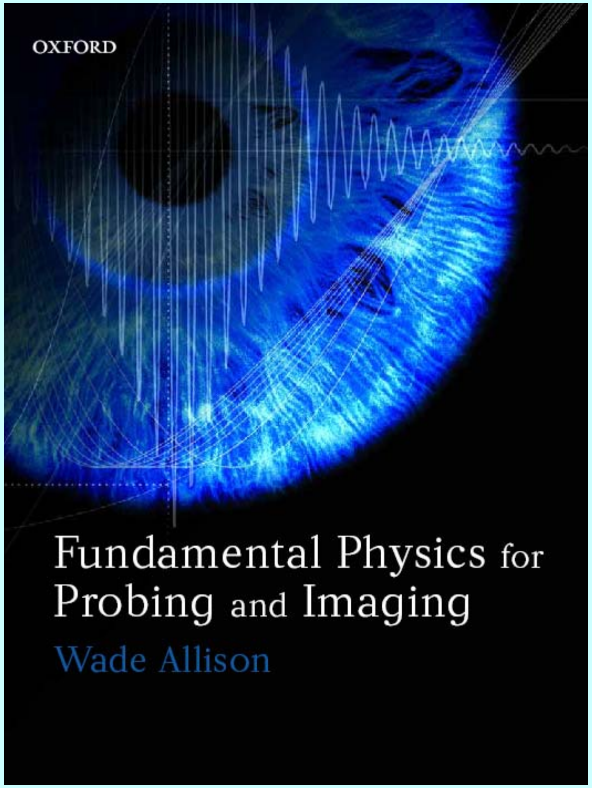
W W M1

# How dangerous is ionising radiation?

Wade Allison, Oxford Physics

Version dated 23 Nov 06

**W W M1** Allison, 09/10/2006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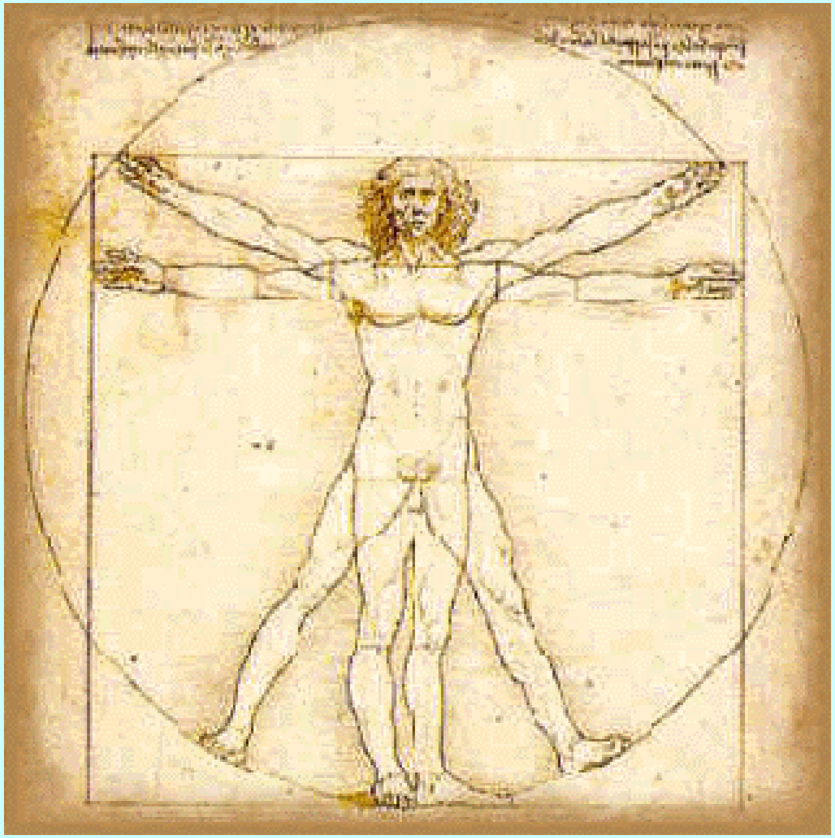
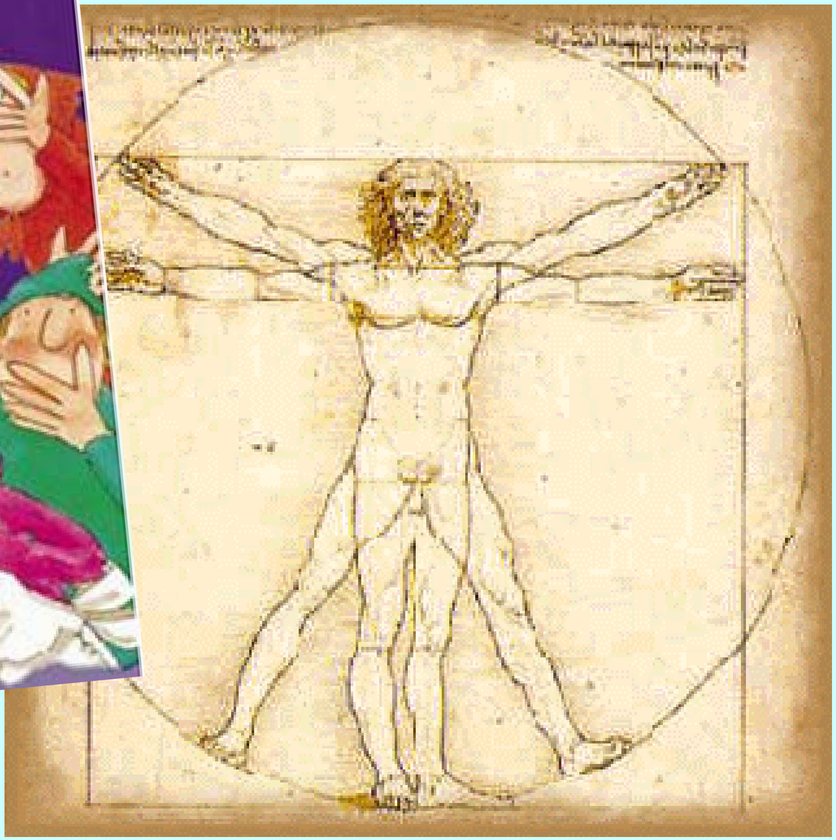
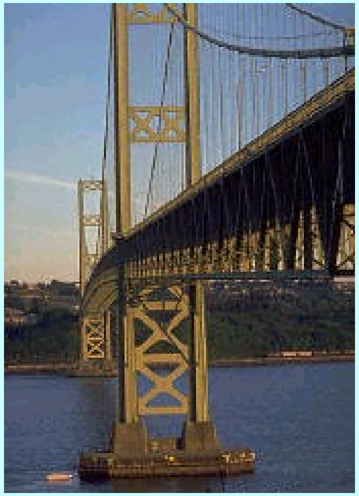



THE EMPEROR'S NEW CLOTHES
...and more
Hans Christian Andersen
fairy tales


# Safety, eg of a bridge

- Must be actually safe for its users -
  and users must feel that it is safe
- Actual safety described by a stress-damage curve
- If well designed, small stresses give no damage at all.
  Only for stresses beyond elastic limit is there damage.



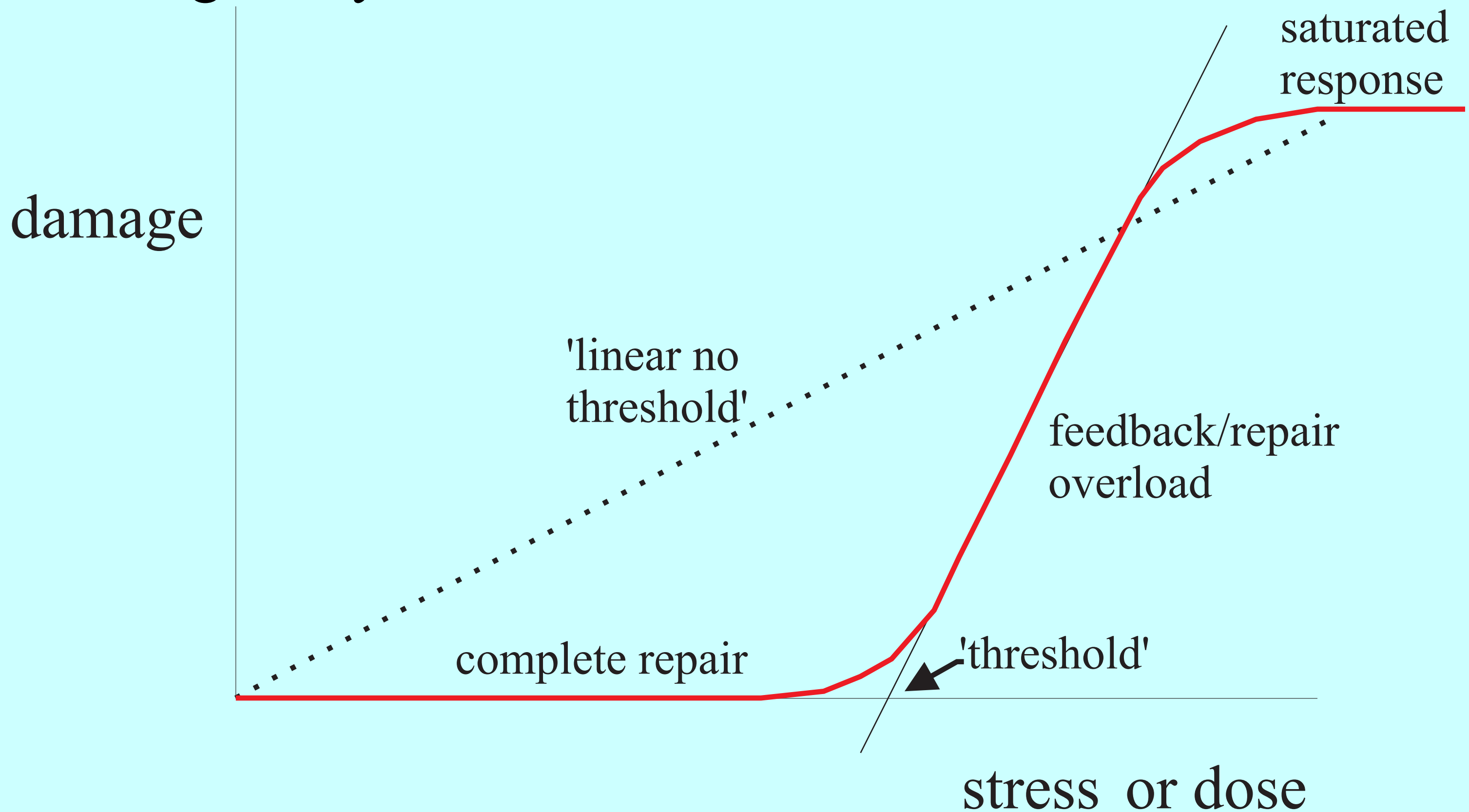

Tacoma narrows 1940

# Simple models of damage due to stress or dose

a) mathematically simple (LNT = linear no threshold)

b) non-linear with elasticity/feedback/repair – S-shaped response.

A well designed bridge, stabilised electronic amplifier, or
a simple biological system



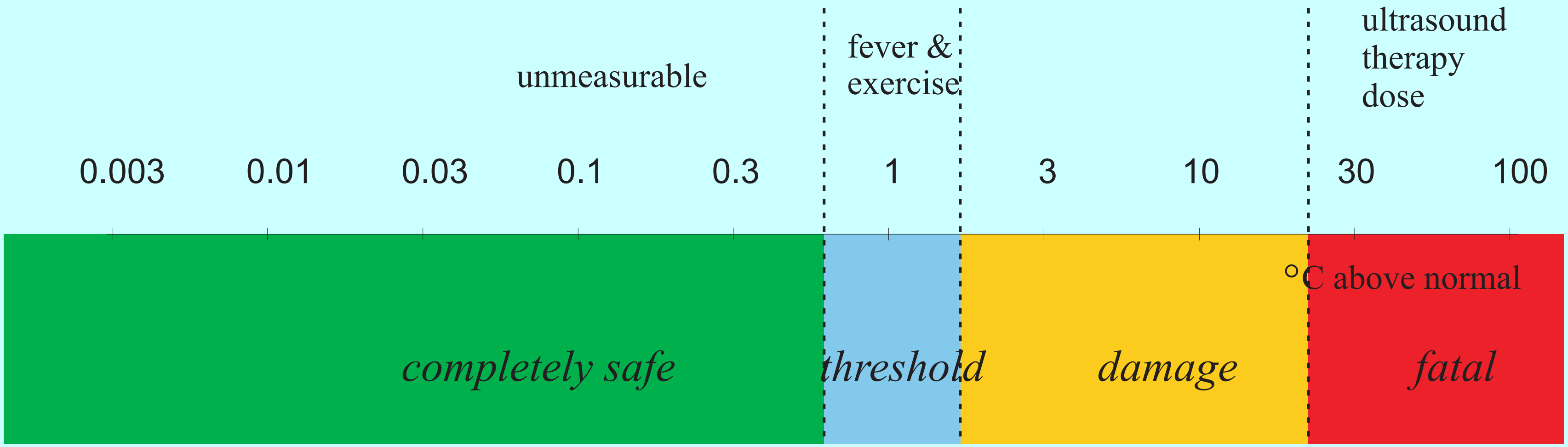
# correction feedback – for any hazard

- natural simplicity ≠ mathematical simplicity
- biological protection against regular hazards has evolved using feedback and repair
- feedback may require time, eg for repair
- until this is effective the dose integrates. If this exceeds a threshold, damage ensues
- need to know a) threshold, and b) repair time. Also c) appreciate mechanism.

# Examples

- **loss of blood**.
  Capacity of human body about 5 litres.
  Threshold? >½ litre.
  Repair time? < 56 days for complete recovery.
  Loss of 5 litres for 1 person = death
  Loss of 5 litres between 10 people = blood donation
  Loss of 5 litres for 1 person over 18 months = blood donation
- **laceration**.
  - modest laceration, 10 days, complete recovery
  - intermediate, leaves scar tissue but full function
  - severe, loss of function – incapacity – death
- **tissue overheating**...

a) tissue heated above normal temperature (35°C)




- body has an efficient cooling mechanism with large dynamic range - blood flow and evaporation
- body temp changes by 1-2 degs C.
  mild fever or exercise. no lasting damage
- at +20C (55/56C) living tissue melts, cooks, dies.
- as with blood, nature's design seems to keep about a factor ten between threshold and death

# Central question:
# Is ionising radiation like other hazards?

- Has evolution given correction feedback mechanisms that protect life with a non-linear ‘S’ response to radiation dose? Possibly with a factor ~10 for safety?
- If so, what are the threshold(s), timescale(s) and mechanism(s) that characterise this response?
- Is there any evidence for a residual linear behaviour?

# Conventional approach based on linear model (LNT)

"Whether there is a threshold dose below which no effect is produced is still open to doubt, but on present knowledge it seems unlikely that any such threshold exists. It must, therefore, be assumed that even very small doses produce some small risk of cancer and, if the individual is not beyond reproductive age, some risk of causing subsequent offspring to have a genetic defect."

From '**Epidemiological evidence of effects of small doses of ionising radiation with a note on the causation of clusters of childhood leukaemia'** R Doll 1993 *J. Radiol. Prot.* **13** 233-241

Is this reasonable? Data!

Attitude of extreme caution accepted from 1945 during the Cold War because:

- it was politically expedient that we were frightened – encouraging fear of nuclear radiation and nuclear weapons
- there were no good long-term data on health effects
- the cell biology was not well understood
- there was less urgency to press the question, climate change not on the agenda carbon-based energy was a reasonable choice

# But ionising radiation is like other hazards

We shall see that

1. biology structure of cells has evolved effective repair mechanisms, stimulated by the radiation environment
2. basic data support a non-linear dose-damage curve
3. we can determine thresholds from long term data, eg Hiroshima & Nagasaki survivors
4. we have data to limit lifetime risks to 1 person per 1000, a hundred times smaller than that due to smoking
5. there is public acceptance of very high levels of nuclear radiation in radiotherapy, the success of which actually depends on the non-linear response – the repair mechanism

# 1. The Radiation Environment

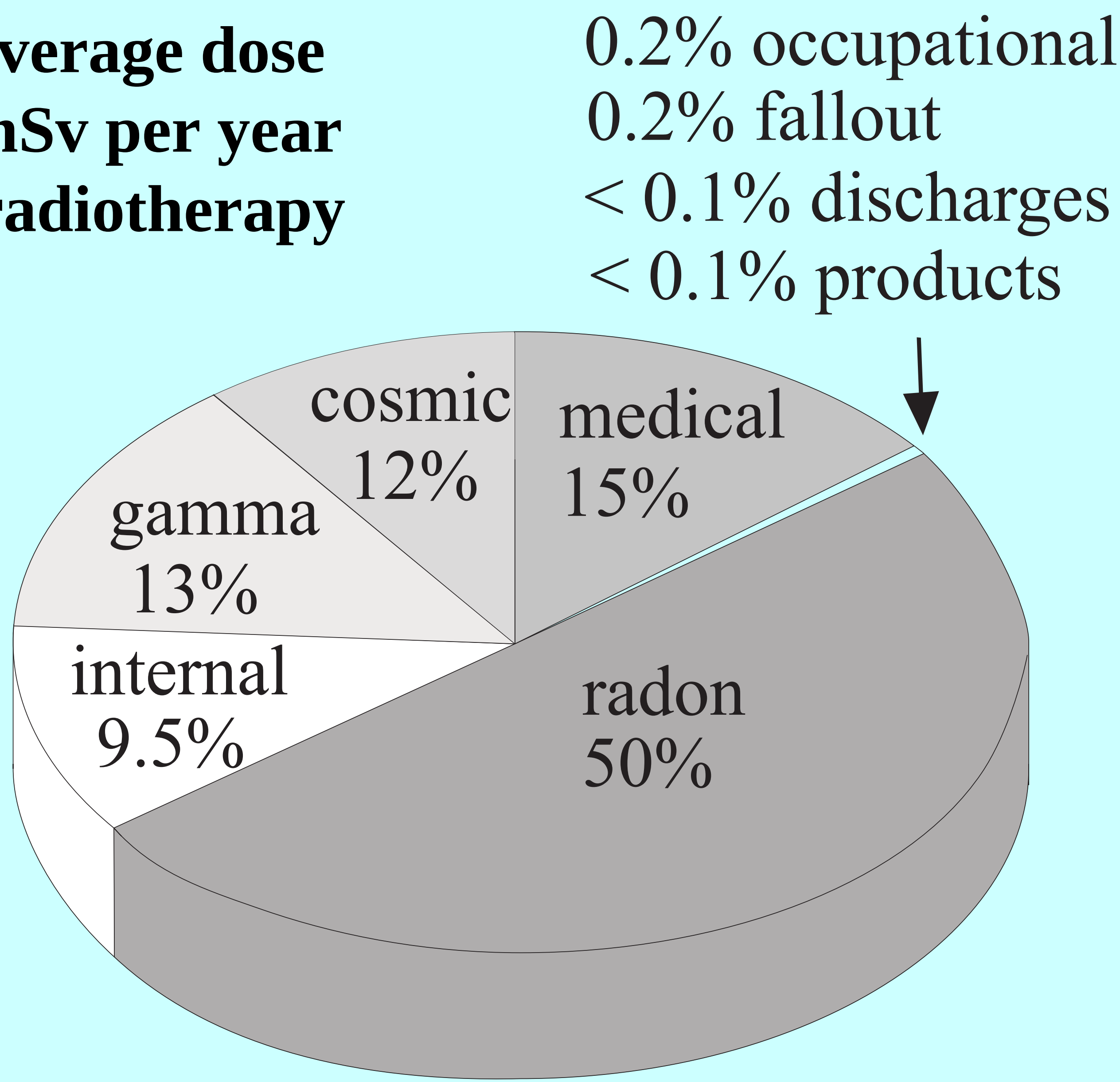
Easy to measure but invisible
(note, can be improved - but avoid clicking counters!)

- radioactive disintegrations per second (Bq)
- deposited energy per kg (Gy)
- biological damage Sv (1Sv = damage done by 1Gy of gammas or electrons)

Environment ~2.7mSv per year (average)

Radiotherapy, 2-3Gy (2-3Sv) per day to tumour, and half that to surrounding healthy tissue
(note factor 200,000 in the relative dose rate)

**UK average dose**
**2.7 mSv per year**
**excl radiotherapy**




Data from NRPB/HPA

“action level” is 200 Bq $m^{-3}$

Darkest areas > 30%

From HPA website

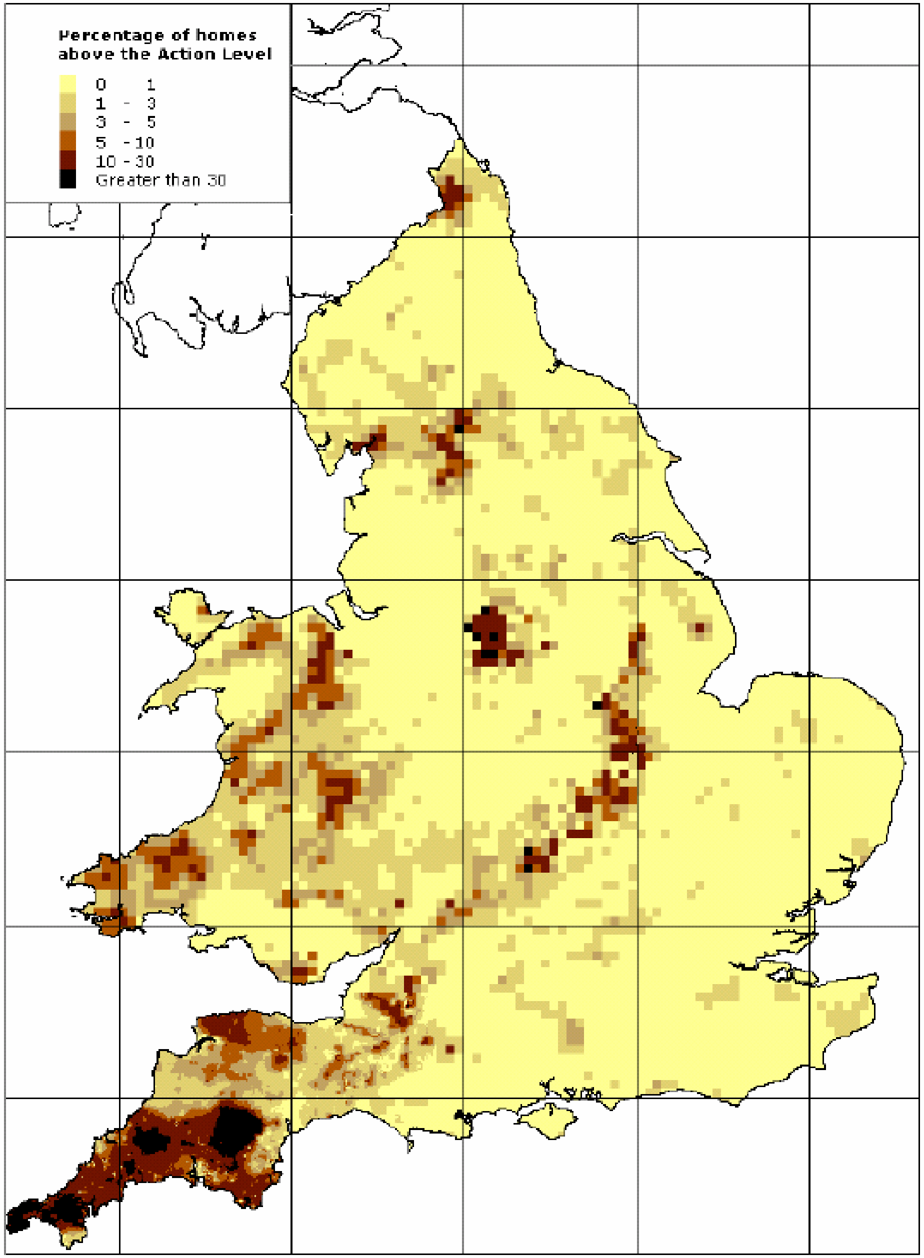
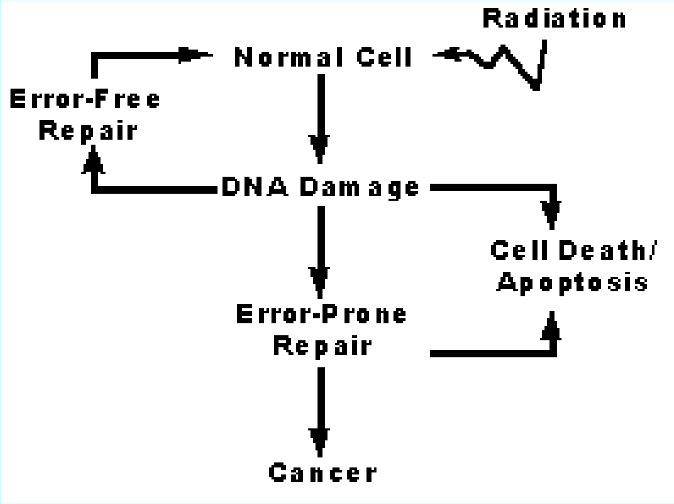



Figure 5 Overall map of radon Affected Area in England and Wales (axis numbers are the 100 km co-ordinates of the Ordnance Survey National Grid)




Knowledge of the repair mechanisms:

a) DNA redundancy, depends on cell cycle

b) DNA single strand breaks repaired (hours)

c) cell replacement (days/wks) removes most DNA multiple strand breaks.

Initial damage depends on oxygen, water.

The effect of these repair mechanisms is not linear

Failed repair of multiple breaks leaves "scar tissue" [damaged chromosomes].

These record radiation dose (not linearly).

So do unpaired electrons in teeth & bone - they can be measured by ESR

# 2. Data on non-linearity of dose-response

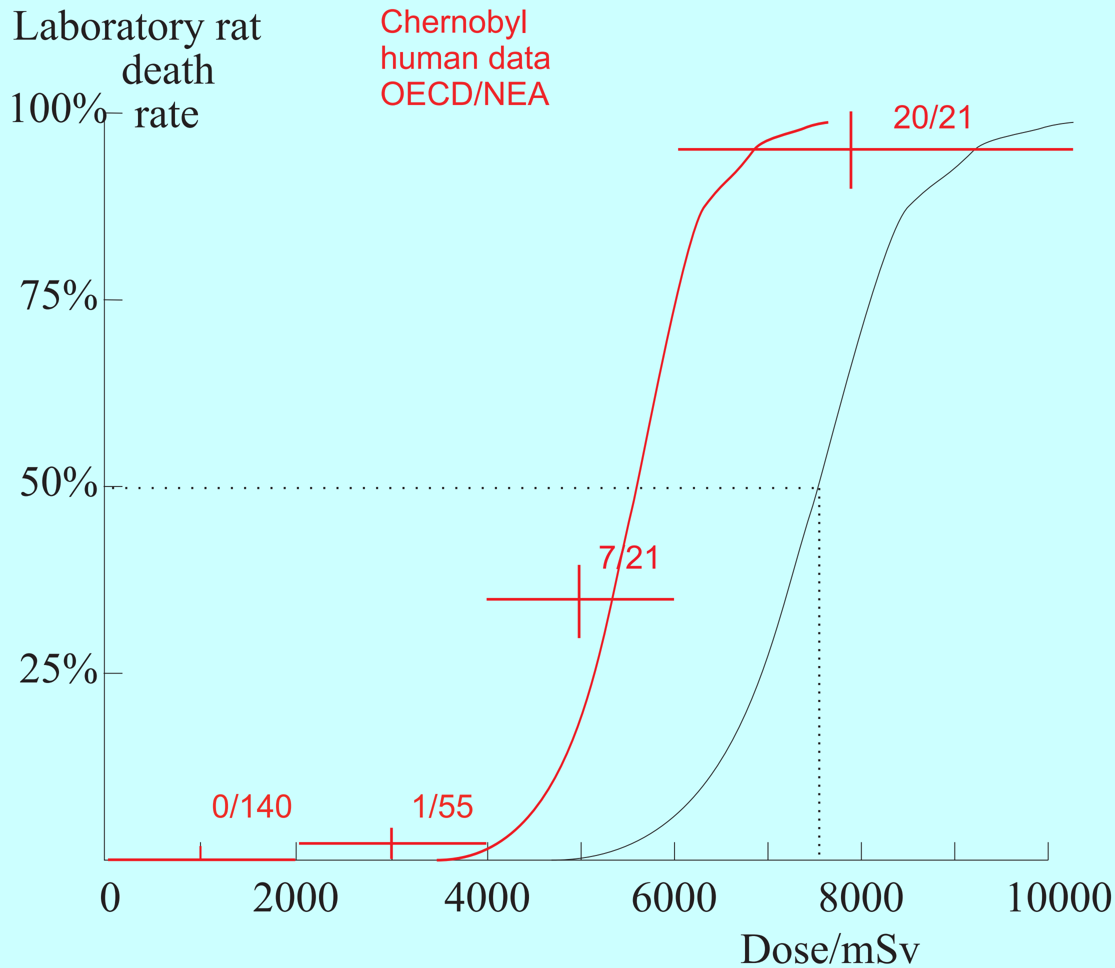
## S-shaped curve at high dose

**Chernobyl data**

**238 acute cases with 28 early deaths**

**By 1998 a further 11 had died of a variety of causes**

**Source OECD/NEA report 2003 (web)**



# evidence of non-linearity from spatial dispersion

Compare damage due to same energy deposited by a) many lightly ionising with b) few heavily ionising tracks.

a) Delocalised irradiation (e, mip,γ) single DNA hits, → optimised repair, less damage

b) Localised irradiation (non rel. protons, fission fragments, low energy n) multiple DNA hits, → poor repair, more damage.

Factor up to 20

**Table 6.4** Some values of the radiation weighting factor $w_R$ for different kinds of radiation.

| Radiation | Energy | $w_R$ |
|---|---|---|
| X-rays and $\gamma$-rays | any | 1 |
| Electrons | any | 1 |
| Muons and muons | any | 1 |
| Protons | >2MeV | 5 |
| Alpha/light ions | any | 20 |
| Fission fragments | any | 20 |
| Neutrons | <10 keV | 5 |
| Neutrons | 10–100 keV | 10 |
| Neutrons | 0.2–2 MeV | 20 |
| Neutrons | 2–20 MeV | 10 |
| Neutrons | >20 MeV | 5 |

$$Sv = w_R\, Gy$$

# Evidence of non-linearity from dispersion in time

Effectiveness of radiotherapy dose (especially with gammas) given in 20/30 ‘fractions’ eg a sequence of doses separated by recovery periods.

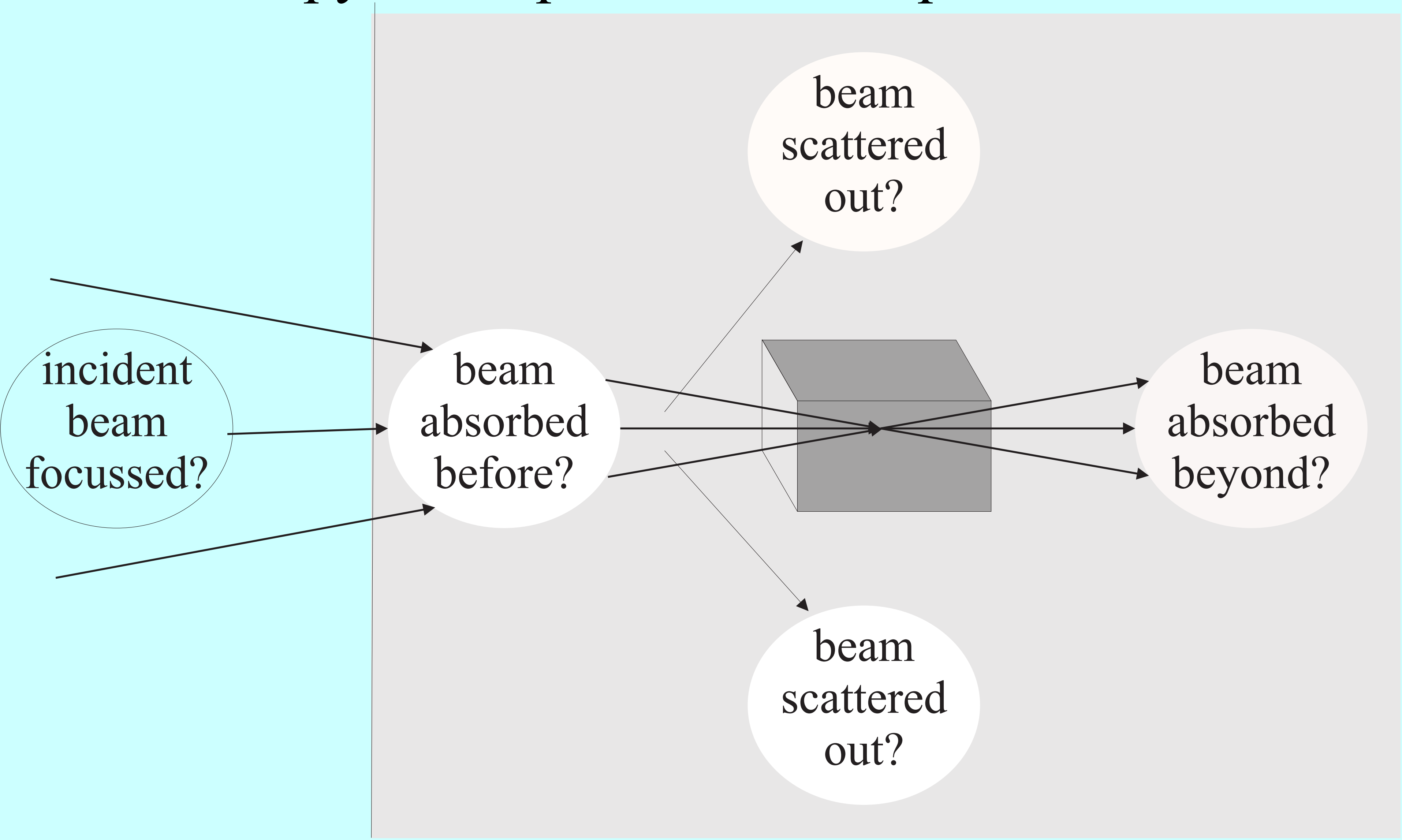
Iterative application of non-linear response curve.

Healthy tissue just recovers (many times).

Tumour tissue does not recover, hopefully.

[There is an additional effect due to the increased oxygen concentration in the tumour during this iterative treatment]

# radiotherapy of deep tumour – the problem

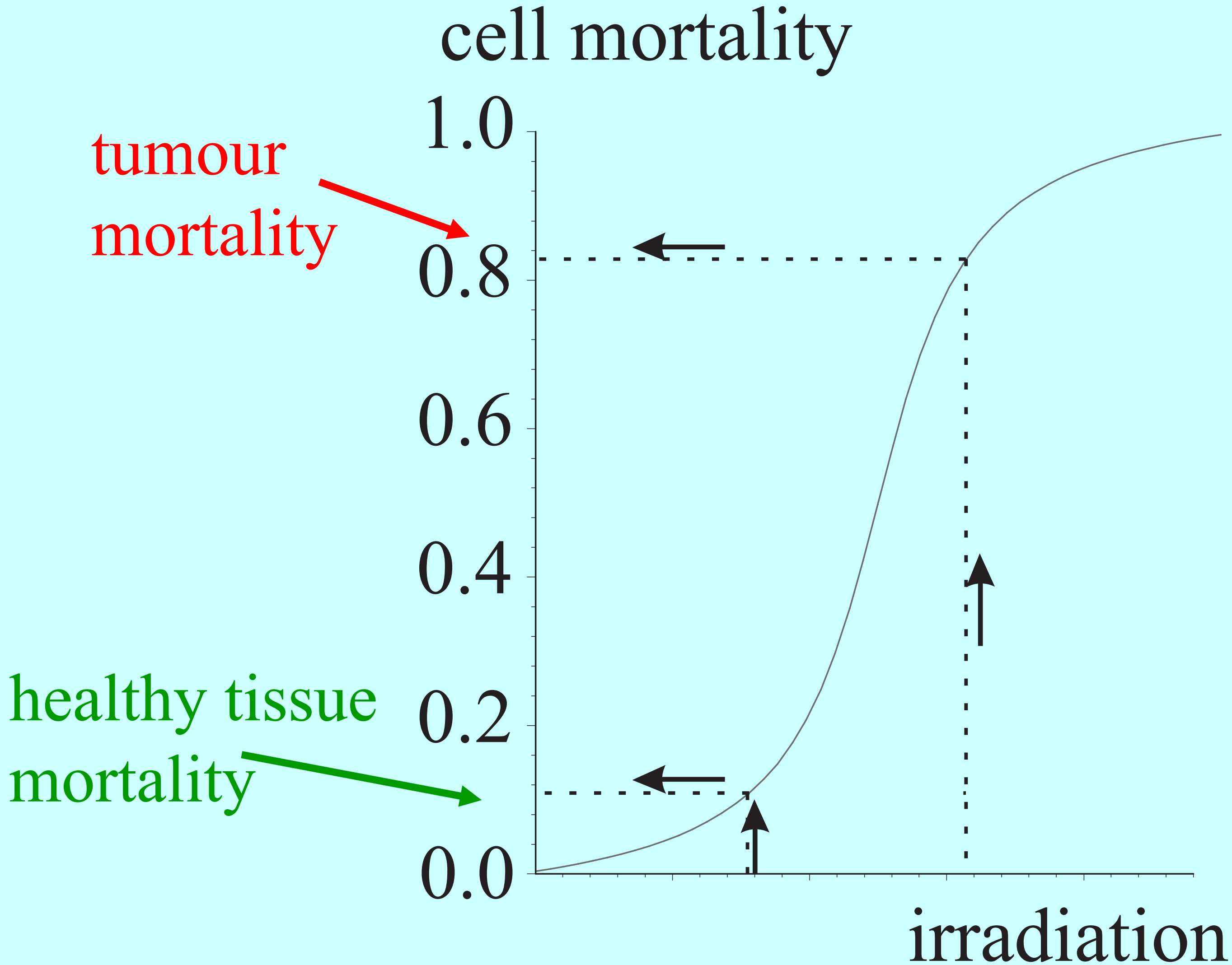


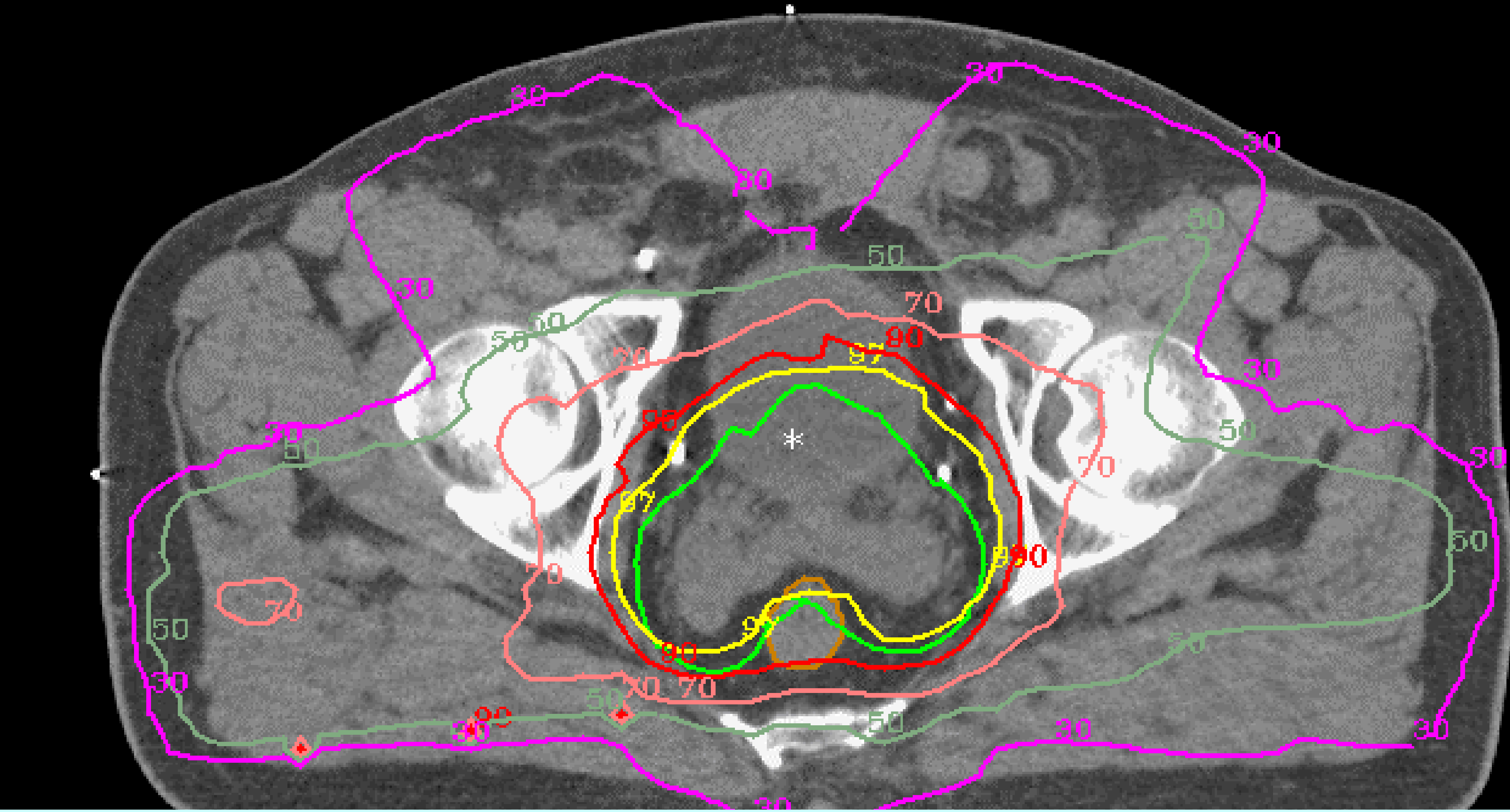
# with gamma ray radiotherapy

2-6 MeV gamma rays

- ✘ no focussing – pencil beams several cms across
- ✘ significant scattering
- ✘ tumour gets too little dose, healthy tissue too much
- ✘ success depends critically on non-linearity of dose-response curve
  - by irradiating at many angles (space)
  - by irradiating many times separated by recovery periods ~1 day, "fractions"
- ✘ (not widely discussed out of sensitivity to patients)

# Qualitative illustration. For a factor 2 in dose, we can get a factor 8 in survival - because of S-shaped curve






Example: Percentage contours of maximum dose to treatment of prostate(*)
100% = 3000 mSv per fraction, repeated about 20/30 times daily (example only)
so healthy tissue suffers perhaps 1500 mSv or more, also repeated 20/30 times.
Result: much scar tissue, modest prognosis, poor and protracted patient experience

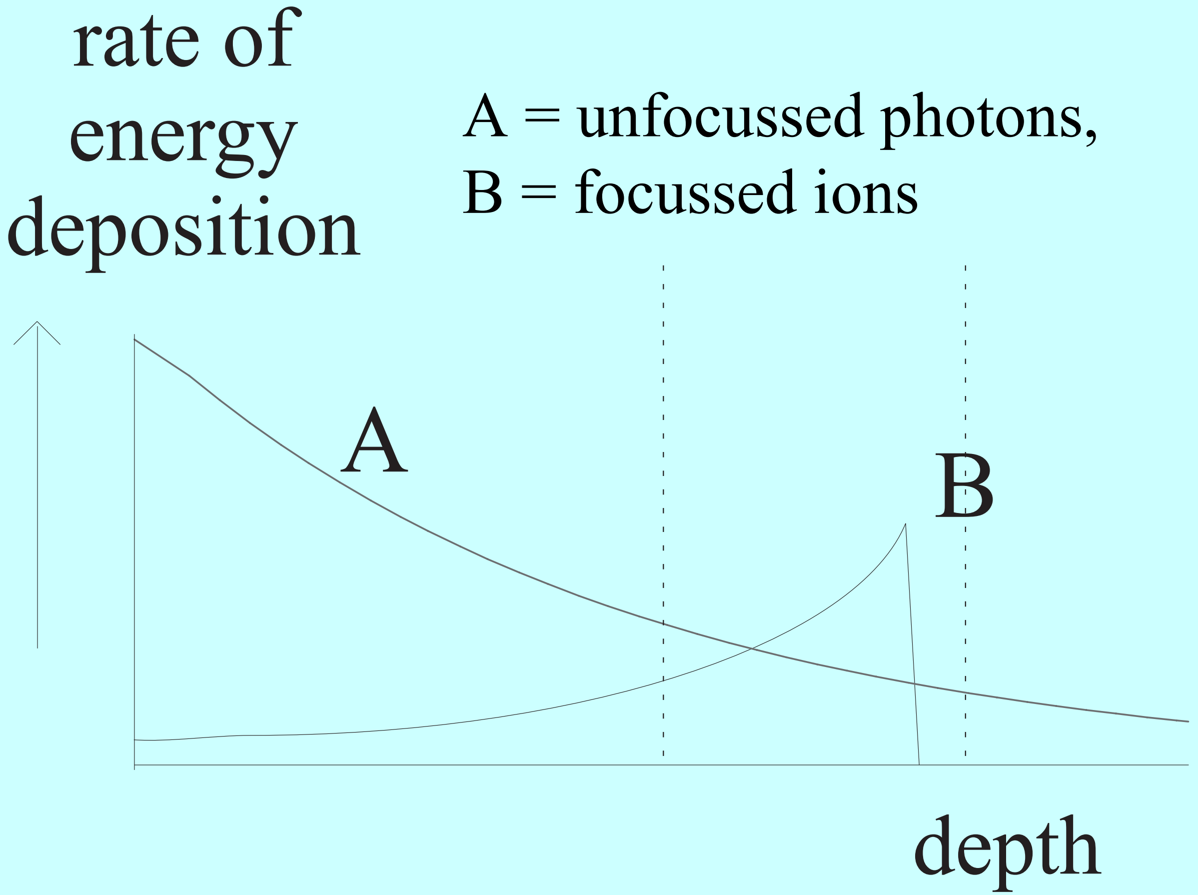
Improvements in the next decade –

✓Hi intensity focussed ultrasound (HIFU)

✓Ion beams, protons or carbon (BASROC)

eg ions:
transverse focus,
less scattering,
longitudinally ...

A = unfocussed photons,
B = focussed ions



# 3. Long term data

Hiroshima and Nagasaki survivor data

Radon data including the effect of smoking

Data on Chernobyl.

# Hiroshima and Nagasaki survivors

- largest experiment, many × Chernobyl
- longest experiment, data for 60 years
- 429,000 population, >103,000 died in 4 months
- since 1950 health records of 283,000 followed
- dose for 86,611 modelled (mean 160mSv), checked with ESR & chromosome counts
- control sample of 25,580 outside city
- leukaemia and solid cancers, pregnancies, etc recorded

**Table 6.7** An analysis of leukaemia and solid cancer deaths amongst the survivors of Hiroshima and Nagasaki between 1950 and 1990. The figures in brackets give the number predicted from the control sample. The excess gives the extra risk due to the radiation. This is shown per 10,000 people with estimated statistical errors. [Data from www.eh.doe.gov/radiation/workshop2005/presentations/neta.ppt]

| Dose range (mSv) | Number | Leukaemia deaths | Extra risk per $10^4$ | Number | Cancer deaths | Extra risk per $10^4$ |
|---|---|---|---|---|---|---|
| 0–5 | 35458 | 73(64) | $3 \pm 3$ | 38507 | 4270(4268) | $0 \pm 20$ |
| 5–100 | 32915 | 59(62) | $-1 \pm 3$ | 29960 | 3387(3343) | $15 \pm 20$ |
| 100–200 | 5613 | 11(11) | $0 \pm 10$ | 5949 | 732(691) | $70 \pm 45$ |
| 200–500 | 6342 | 27(12) | $24 \pm 10$ | 6380 | 815(716) | $155 \pm 45$ |
| 500–1000 | 3425 | 23(7) | $46 \pm 16$ | 3426 | 378(262) | $340 \pm 60$ |
| 1000–2000 | 1914 | 26(4) | $120 \pm 30$ | 1764 | 326(213) | $640 \pm 100$ |
| >2000 | 905 | 30(2) | $310 \pm 60$ | 625 | 114(58) | $900 \pm 170$ |

Background statistics limit errors to less than 0.1% (leukaemia) and about 0.2% (solid cancers).

# Hiroshima and Nagasaki conclusions

Assuming that an increase in the risk of disease over 40 years of less than 1 or 2 in 1000 is tolerable, then

- in the case of leukaemia a radiation dose of 200 mSv is harmless
- in the case of solid cancers a dose of 100 mSv is harmless
- adding up all the much smaller doses and dividing by 100,000 to get low-dose deaths (LNT) is wrong.

# Radon data, including effect of smoking

- Radiation at Hiroshima & Nagasaki was mostly neutrons, β and γ radioactivity, much in a single dose
- What about
  - a) lifetime exposure, or
  - b) α radioactivity with its high $w_R$?
- Good test: inhaled radon gas in home/workplace causing lung cancer
- radon in homes eg Cornwall.. and other such places (Czechoslovakia, Massif Central, China, India,..) ~3 times natural radiation levels, 7.5mSv per year

Question: Do people in Cornwall have an extra risk of lung cancer?

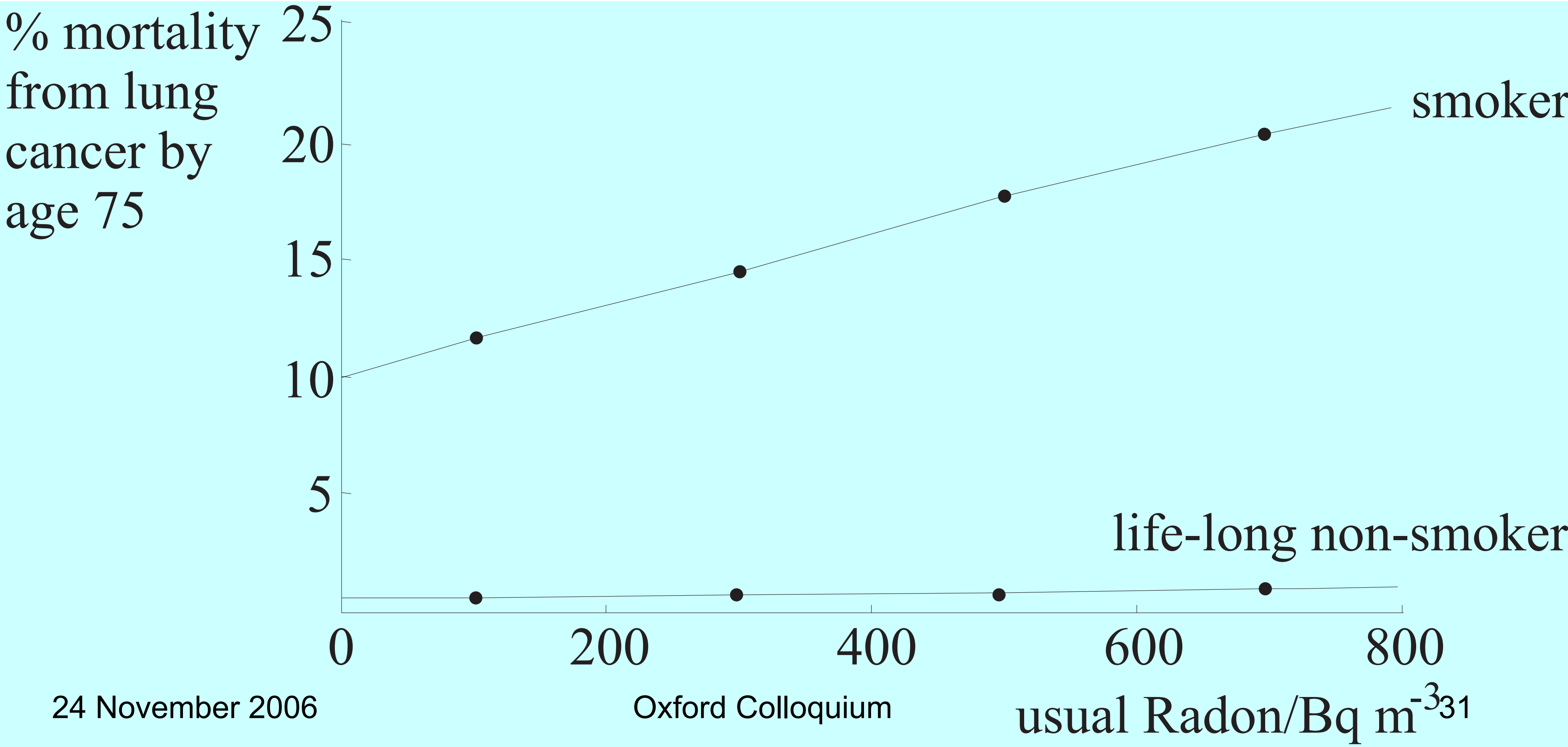
*No,*
*the result not statistically significant,*
*once account has been taken of smoking*

What if we look at data from all European studies together? Such a study...

Cite this article as: BMJ, doi:10.1136/bmj.38308.477650.63 (published 21 December 2004)

# Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies

S Darby, D Hill, A Auvinen, J M Barros-Dios, H Baysson, F Bochicchio, H Deo, R Falk, F Forastiere, M Hakama, I Heid, L Kreienbrock, M Kreuzer, F Lagarde, I Mäkeläinen, C Muirhead, W Oberaigner, G Pershagen, A Ruano-Ravina, E Ruosteenoja, A Schaffrath Rosario, M Tirmarche, L Tomášek, E Whitley, H E Wichmann, R Doll



# some simple remarks

- statistics were 7148 cases of lung cancer and 14208 controls, so statistical errors not much smaller than 1%
- with two causes the most general linear relationship ***prob. of cancer by 75*** $= A + B \times$ ***radon*** $+ C \times$ ***smoking*** where *smoking* = 1 for smokers and 0 for non-smokers
- $A$ = 0.4% chance of lung cancer, without radon or smoking
- chance of cancer due to smoking (no radon) is $C$ = 10%
- in any linear model the two lines <u>must</u> have the same slope ($B$)

The conclusions of Darby et al:

1. “In the absence of other causes of death, the absolute risks of lung cancer by age 75 years at usual radon concentrations of 0, 100, and 400 Bq/m3 would be about 0.4%, 0.5%, and 0.7%, respectively, for lifelong non-smokers, and about 25 times greater (10%, 12%, and 16%) for cigarette smokers.”

2. **“The dose-response relation seemed to be linear, with no evidence of a threshold dose.”**

3. **“Absolute hazard of radon for smokers and non-smokers.** If the proportionate increases in risk per unit exposure are approximately independent of smoking history then, as lung cancer is much commoner in cigarette smokers than in lifelong non-smokers, radon poses a much greater absolute hazard to cigarette smokers, and to recent ex-smokers, than to lifelong non-smokers.”

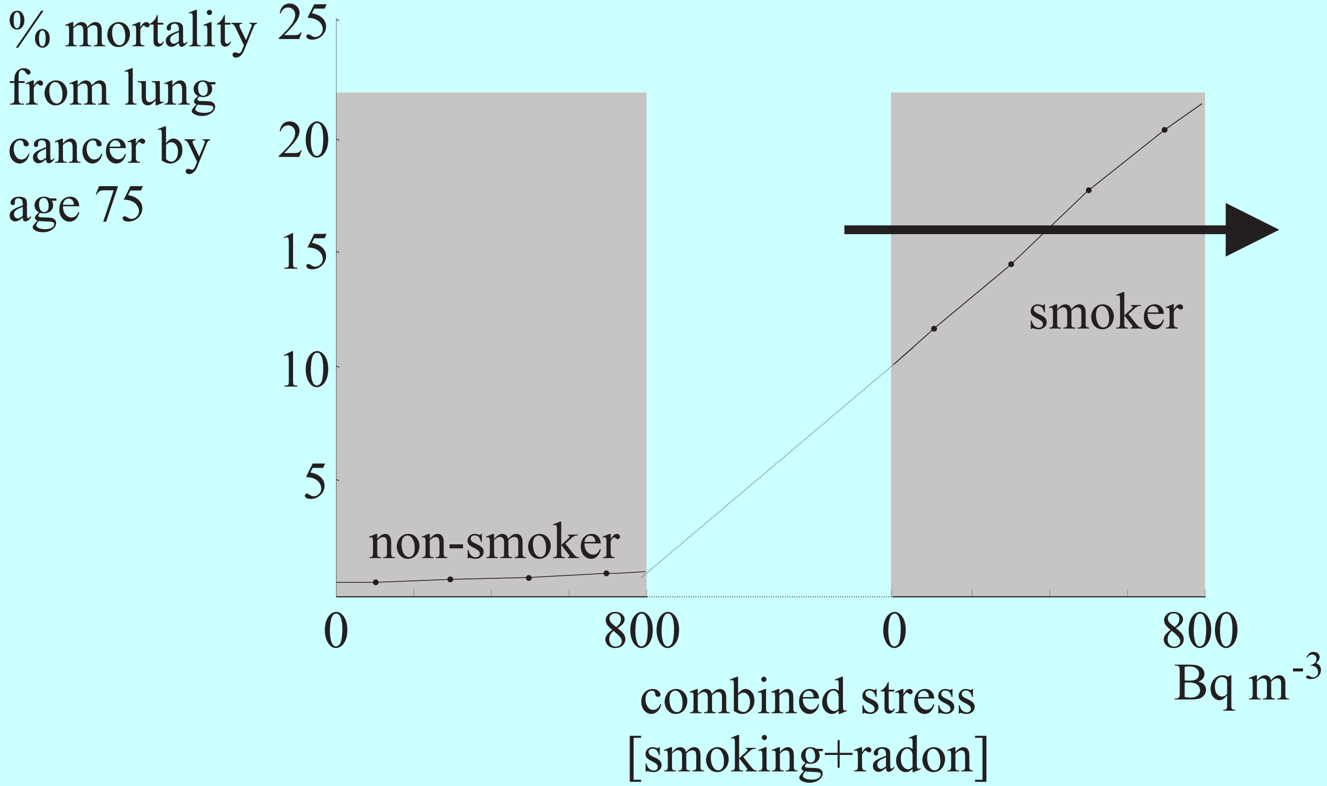
## Suggested simpler conclusions

A. The non-smoker data are consistent with flat.
Radon does not cause lung cancer in non-smoker homes.
[ie less than 2 or 3 per 1000. Even this combination of 13 studies fails to show any significant effect.]

B. The different slopes.
Either there is an actual interaction between smoking and radon
Not linear. No mechanism suggested by Darby et al.
Or there is a corrective feedback response to the stress which is a superposition $radon + \alpha \times smoking$

$$prob = f(radon + \alpha \times smoking)$$

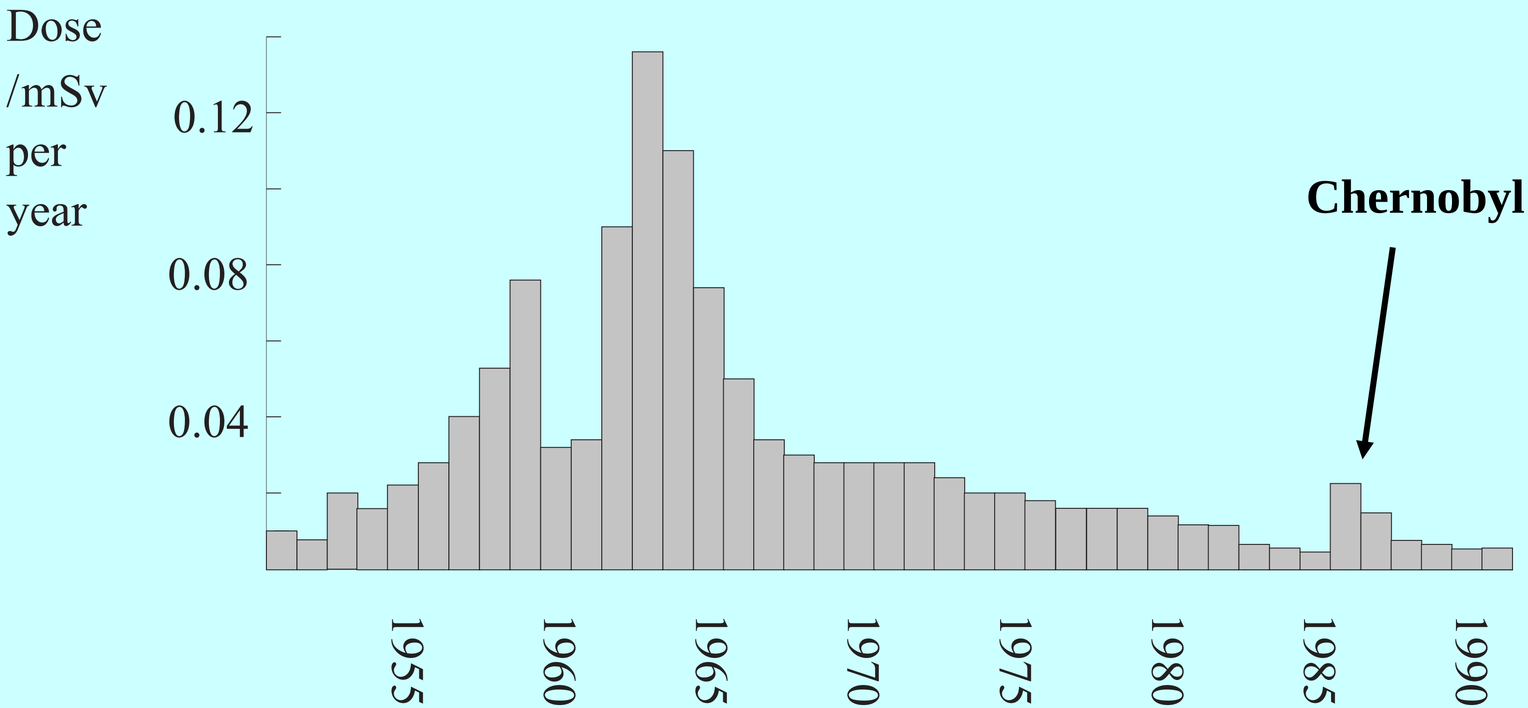
with $f$ an S-shaped non-linear function, as an evolutionary mechanism would lead us to expect. Thus (qualitatively) .....




1. Smoking/radon/lung cancer data are entirely consistent with a non-linear evolutionary response.
2. For non smokers The effect of radon is consistent with zero and less than 3 per 1000.
3. The public should not fear radon, but they should fear smoking.

# Chernobyl

Fallout in UK from atmospheric weapon testing & Chernobyl (NRPB)




The radioactive fallout (Cs/Sr) from weapon testing was 30/75 times the Chernobyl release.

Compare with 1000-2000 mSv per day to healthy tissue for typical course of radiotherapy. Insignificant in UK

# Child thyroid cancer and Chernobyl

**Table 6.11** Data on cases of child thyroid cancers by year, then aged up to 15, showing the steep rise from 1986 as a result of the Chernobyl accident. The upper rows show the number of cases. The lower rows show the numbers normalised per 100,000 of the whole population. At the time the table was compiled 3 of these 1036 children had died. [Source: table 13 *www.nea.fr/html/rp/reports/2003/nea3508-chernobyl.pdf*.]

| Year | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Belarus | 3 | 4 | 6 | 5 | 31 | 62 | 62 | 87 | 77 | 82 | 67 | 73 | 48 |
| Ukraine | 8 | 7 | 8 | 11 | 26 | 22 | 49 | 44 | 44 | 47 | 56 | 36 | 44 |
| Russia | 0 | 1 | 0 | 0 | 1 | 1 | 3 | 1 | 6 | 7 | 2 | 5 | 0 |
| Total | 11 | 12 | 14 | 16 | 58 | 85 | 114 | 132 | 127 | 136 | 125 | 114 | 92 |
| Belarus | 0.2 | 0.3 | 0.4 | 0.3 | 1.9 | 3.9 | 3.9 | 5.5 | 5.1 | 5.6 | 4.8 | 5.6 | 3.9 |
| Ukraine | 0.2 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.5 | 0.4 | 0.4 | 0.5 | 0.6 | 0.4 | 0.5 |
| Russia | | 0.3 | | | 0.3 | 0.3 | 0.9 | 0.3 | 2.8 | 3.5 | 0.6 | 2.2 | |

3 deaths, 1036 patients.

Iodine tablets should have protected the population.

# Solid cancers and leukaemia and Chernobyl

**Table 6.12** Distribution of estimated total effective doses received by the populations of contaminated areas (1986–1995) excluding dose to thyroid [Source: table 10 *www.nea.fr/html/rp/reports/2003/nea3508-chernobyl.pdf*.]

| Dose mGy | Number Belarus | Russia | Ukraine |
|---|---|---|---|
| <1 | 133053 | 155301 | |
| <5 | 1163490 | 1253130 | 330900 |
| <20 | 439620 | 474176 | 807900 |
| <50 | 113789 | 82876 | 148700 |
| <100 | 25065 | 14580 | 7700 |
| <200 | 5105 | 2979 | 400 |
| >200 | 790 | 333 | |

Using extra risk of death in 40 years using data per $10^4$ from H & N survivors

Number of extra deaths in contaminated areas:

| | cancers | | leukaemia | |
|---|---|---|---|---|
| <1 | - | 0 | - | 0 |
| <5 | - | 0 | - | 0 |
| <20 | - | 0 | - | 0 |
| <50 | - | 0 | - | 0 |
| <100 | - | 0 | - | 0 |
| <200 | $*70*10^{-4}$ | = 60 | - | 0 |
| >200 | $*155*10^{-4}$ | = 18 | $*24*10^{-4}$ | = 3 |

approx calculated total deaths 78 3

# leukaemia and Chernobyl

Solid cancers have a high background rate (smoking) 12%
leukaemia has a lower background rate 0.2% [from H & N]
child leukaemia not affected by smoking

From OECD/NEA report of 2002:

"Childhood leukaemia incidence has not changed in the decade since the accident. There is no significant change in the level of leukaemia and related diseases.... in the three states (WH95). Other attempts through epidemiological studies have failed to establish a link between radiation exposure from the Chernobyl accident and the incidence of leukaemia and other abnormalities.

However, if the last OECD/NEA report (1996) recommended to be prudent, to withhold final judgement, 6 years later, no increased risk of leukaemia related to ionising radiation has as yet been found among <u>recovery operation workers</u>. ... the next five years will be conclusive."

**NO effect, confirming expectation based on H & N data.**

# Chernobyl – causes & local victims

- cause 1: poor reactor design and management
- cause 2: effects of ionising radiation
- cause 3: failure of communication, health provision and social structure

- acute victims 28 deaths
- thyroid cancer from $^{131}$I (8 day), especially in children.
  3 deaths but many non-fatal cases of cancer (1036).
  Avoidable, iodine tablets should have been provided
- Cancer/leukaemia in population & recovery operation workers.
  Data confused by bad record keeping, smoking, social disintegration
- ‘On the basis of many studies, UNSCEAR in its last report (UN00) concludes that “no increase in birth defects, congenital malformations, stillbirths, or premature births could be linked to radiation exposures caused by the accident”.’ OECD/NEA 2002

# IAEA Safety Standards 115

http://www-pub.iaea.org/MTCD/publications/PDF/SS-115-Web/Pub996_web-1a.pdf *preamble p. 6*

*"Basic Principles*

*The total impact of the radiation exposure due to a given practice or source depends on the number of individuals exposed and on the doses they receive. The collective dose, defined as the summation of the products of the mean dose in the various groups of exposed people and the number of individuals in each group, may therefore be used to characterize the radiation impact of a practice or source. The unit of collective dose is the man-sievert (man-Sv)."*

Beware the collective dose.

If such a quantity is defined, people start to use it

- although nothing depends on it.

Blood loss? Collective dose? eg 5 man-litres?

- to 1 man, a fatality
- to 10 men, just 10 regular blood donations

# Summary of contested arguments

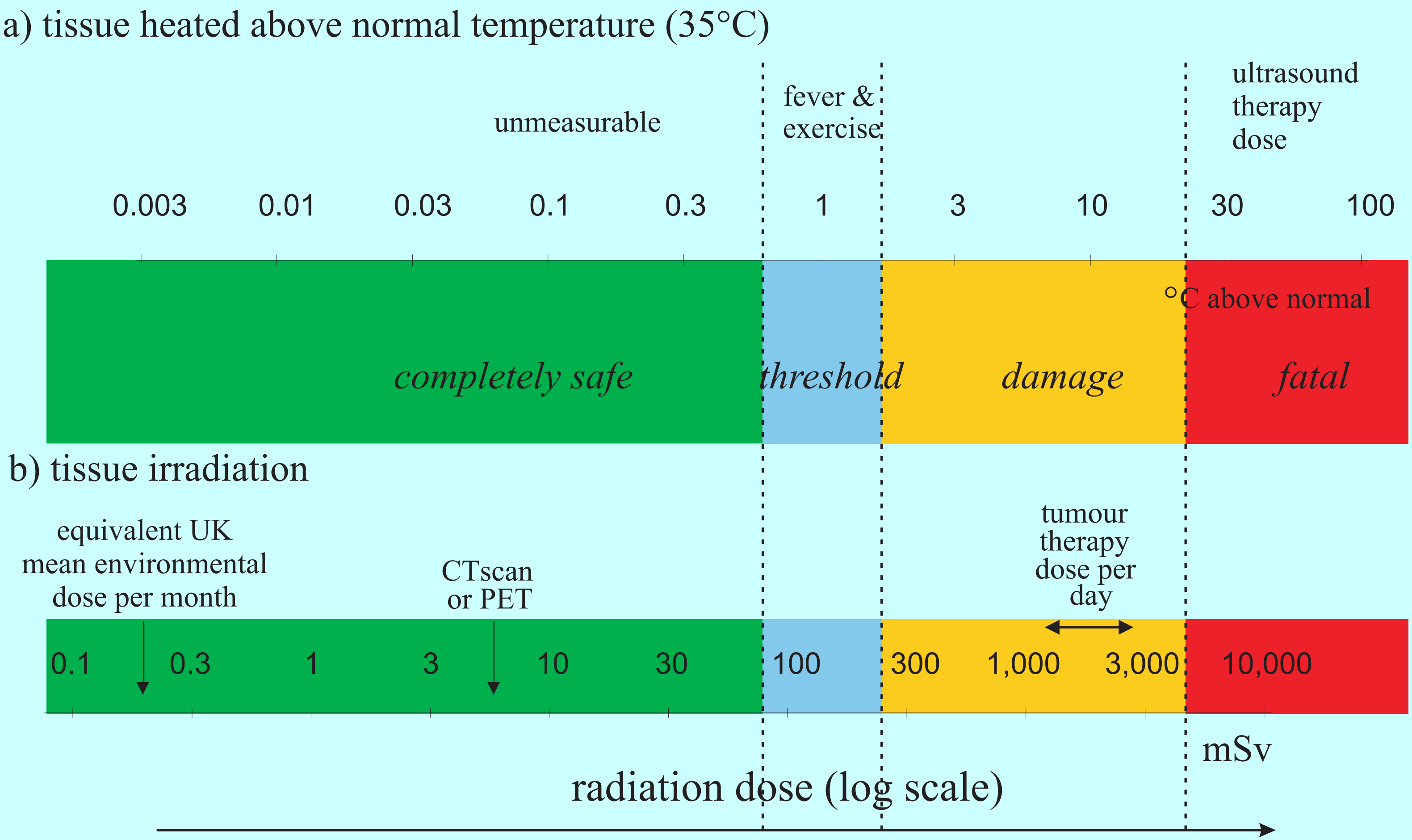
- belief that the default response model should be linear in spite of known repair mechanisms.
  Too much faith in simple maths,
  not enough faith in simple biology.
- misuse of linearity in the interpretation of radon and smoking data
- that if damage is a function of two parameters (dose, population) it is therefore a function of their product (collective dose)

# General conclusions

- Low doses cause no damage
- threshold of damage (100-200mSv),
  an order of magnitude below fatality (5000mSv),
  similar to other hazards
- Regulations should be relaxed. A single dose of 100mSv and a dose rate of 100mSv per month for short periods is harmless
- Above threshold, permanent damage (scar tissue) results
  - such scar tissue may remain benign, or later become malignant, like other scars

[some data show that damage is actually reduced by previous low radiation dose, like vaccination – this needs more study]

# on a log scale...




Current environmental safety levels are insignificantly small

# Message for public understanding...

- Climate change may be the largest threat. Prepare to take risks for the health of your planet in the same way as for your own health
- Nuclear radiation is only one danger of many. Nuclear power - and renewables - should be adopted. If safety regulations are sensible, costs should be sensible
- Society should be educated, co-ordinated and informed - ready to minimise any accident like Chernobyl.

- Free silicon radiation detectors for children and teach them - let people ‘see’ radiation (without clicks!)
- Free iodine tablets ready in every home
- For further examination
  - Terrorists? De-value the fear, the currency of their threats
  - Nuclear weapons? As bad as biological weapons, but not much worse
  - Waste? Not the size of problem sometimes suggested. Resources are available to do the job

For more details, slides, references, links, popular accounts, etc. see

http://www.physics.ac.uk/nuclearsafety

and also textbook
"Fundamental Physics for Probing and Imaging"
Wade Allison, OUP (2006)