# *In Memoriam Symposium*

# Celebrating the Life and Contributions of Jack Cunningham

D.W.O. Rogers
Carleton Laboratory for Radiotherapy Physics.
Physics Dept, Carleton University, Ottawa,
AAPM July 28, 2021



References after last page

# Jack and Sheila, everyone's friends

Boxing Day,
1998,

our living room

# *What's the fuss about $D_{med}$ or $D_{water}$?*

- many misleading statements in the literature but issue is important in modern radiotherapy
- this talk is a discussion of some related issues
- the following paper in June (2021) issue of Green journal

Report dose-to-medium in clinical trials where available; a consensus from the global Harmonisation group to maximize consistency Kry et al, Radiother. Oncol 15 (2021) 106-111

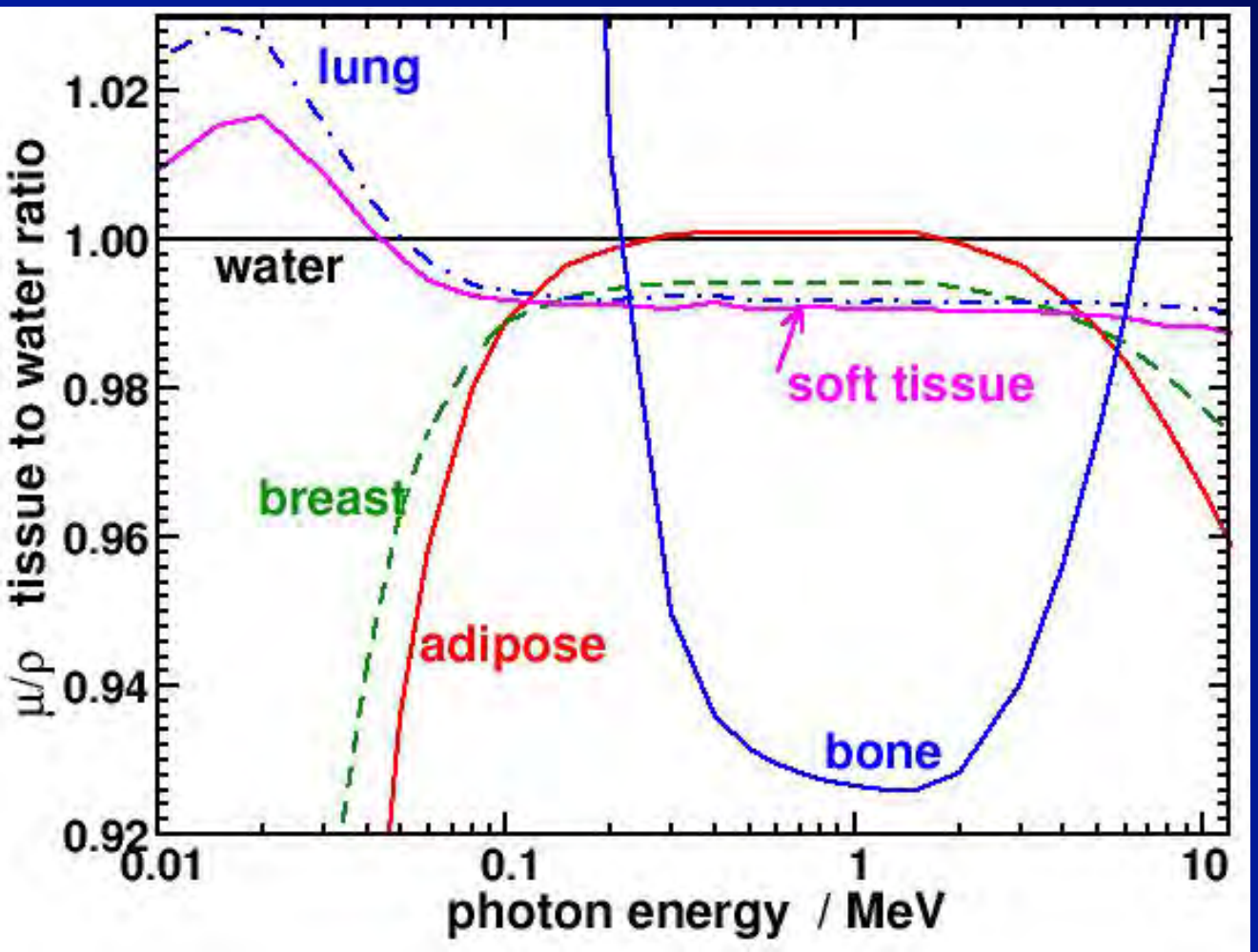
It outlines the issues accurately

# The underlying problem(s)

- modern TPSs calculate dose to medium
- early dose calculation algorithms, e.g., EQTAR developed by Cunningham, calculated dose based on scaling data for water using electron densities
- confusion in the literature about what dose convolution/superposition codes report
- reference dosimetry provides dose to water
- ICRU 83 and TG105 recommend reporting dose to a small mass of water in bone using stopping power ratios

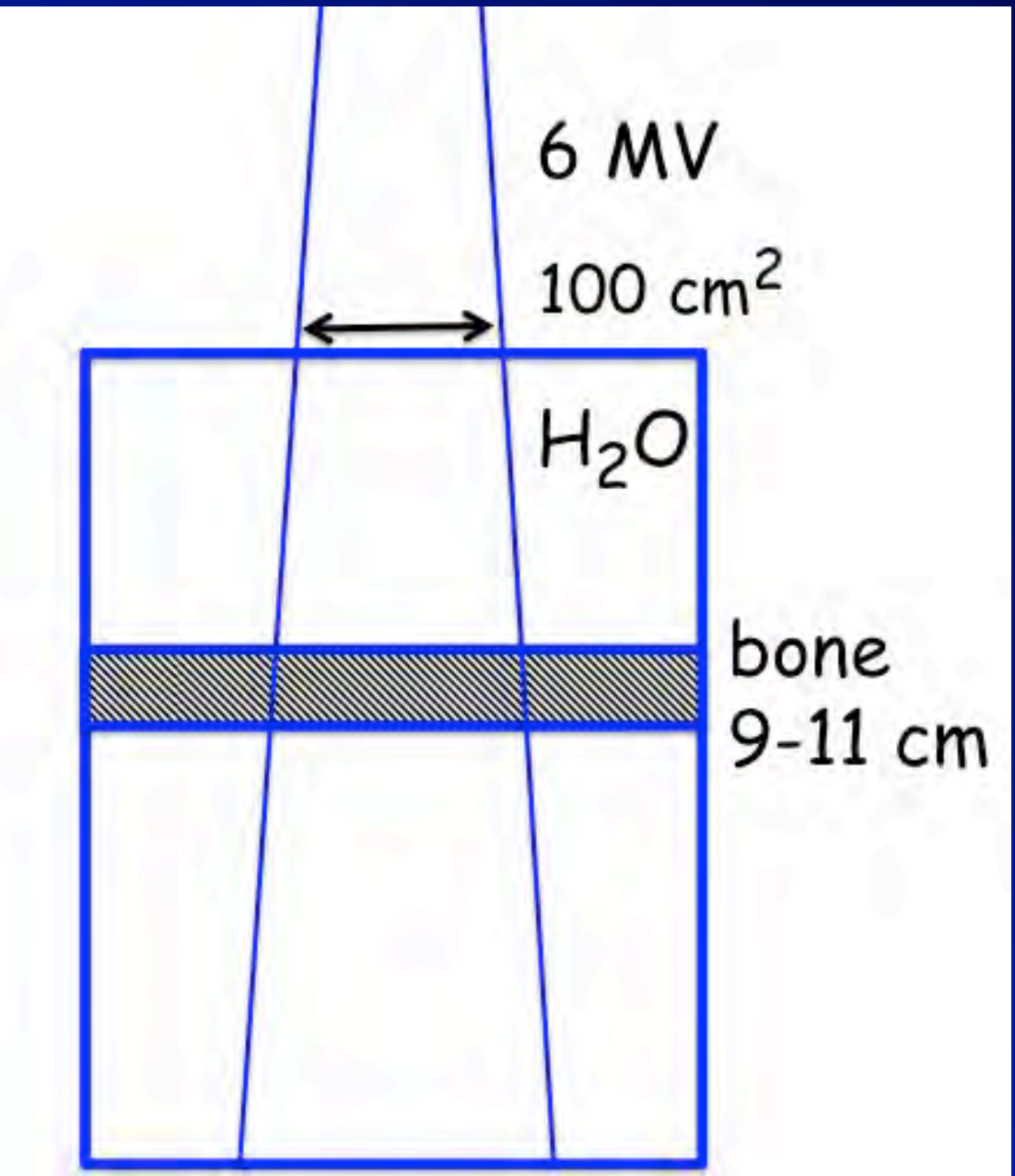
# *main issues involve bone*

- For most materials in body, $D_{med}$ & $D_{water}$ are very similar (in MV beams), except for bone



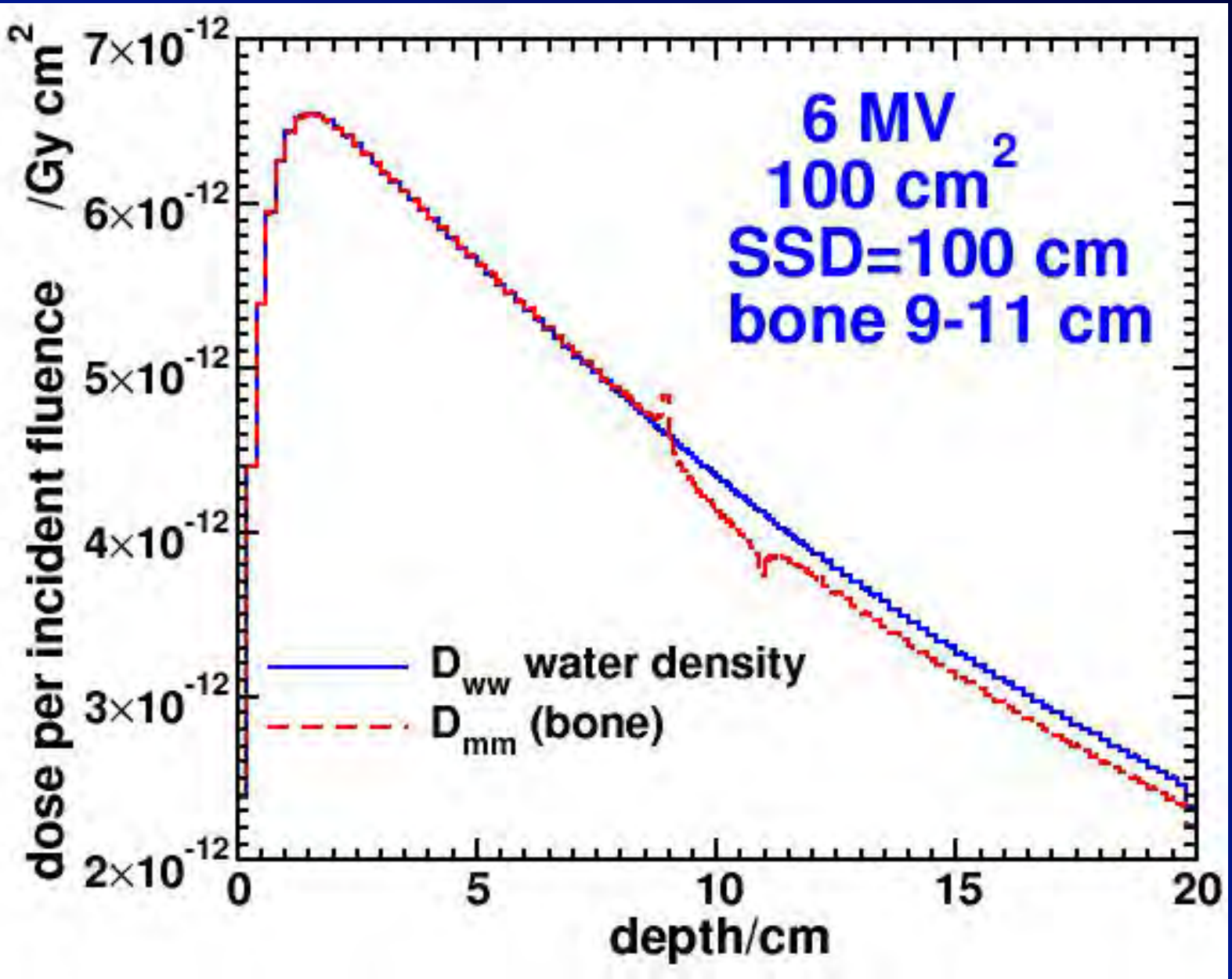

Also, sensitive cells are water-like, even in bone

# example calculations: bone slab in water

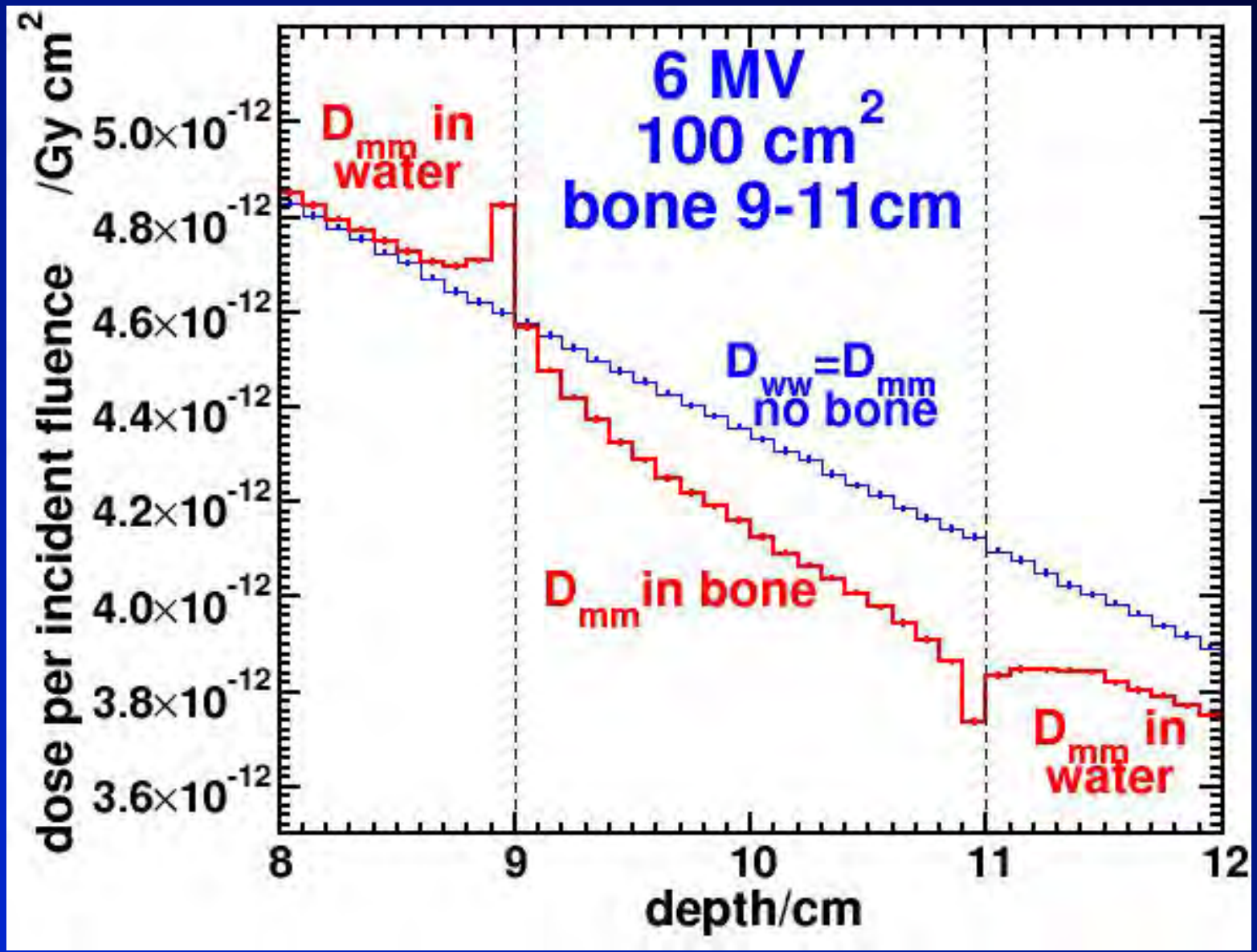



- cortical bone, 9-11 cm in a water phantom
- 6 MV beam, 100 $cm^2$
- $D_{mm}$ dose to med in med
- $D_{ww}$ dose to water in water
- $D_{wm}$ dose to water in medium

# $D_{mm}$ (with bone) and $D_{ww}$ (no bone)



# $D_{mm}$ (with bone) and $D_{ww}$ (no bone)




- backscatter from bone
- lack of backscatter at back of bone
- buildup past bone

Carleton UNIVERSITY
Canada's Capital University

# Correction based methods: eg. EQTAR

- for many years, planning systems used correction based methods such as Jack's EQuivalent Tissue Air Ratio method.

$$D_{\mathrm{hetero}}(z) = D_{\mathrm{homo}}(z)\frac{TAR(z', \hat{A})}{TAR(z, A)}$$

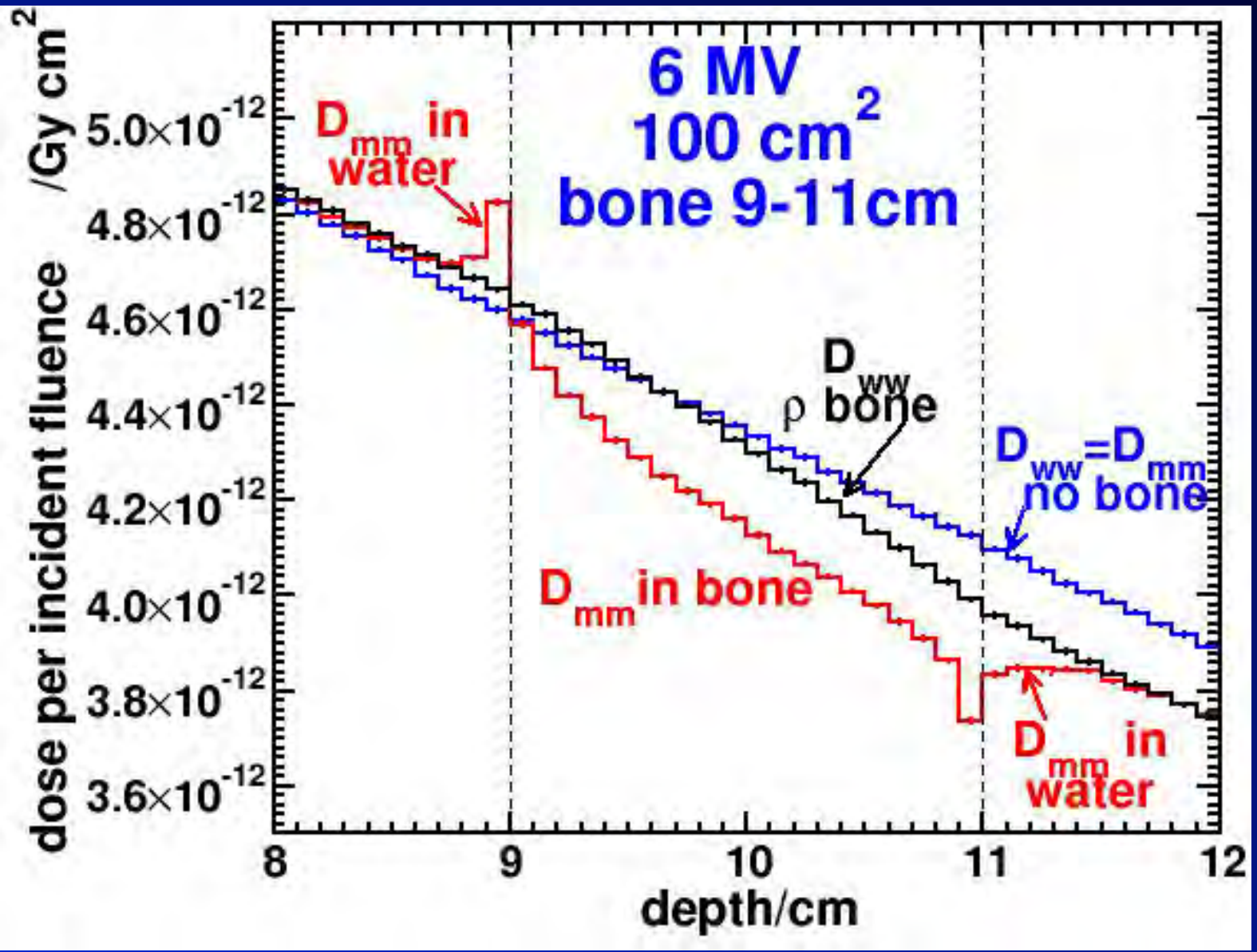
z = depth, z'= water equivalent depth

A = beam area at z, $\hat{A}$ is effective area $\hat{A} = \hat{\rho}A$

$\hat{\rho}$ is effective density

i.e. treats bone as high-density water

# $D_{ww}$ treating bone as high-density water




this fixes issues past bone

but

not issues in bone or at interfaces

# What about convolution/superposition

- some papers have suggested or implied that C/S codes, which report dose to water, are equivalent to using water with scaled densities
- but that is not what they do

$$D(\vec{r}) = \frac{1}{\rho(\vec{r})} \int_V \rho(\vec{r}\,')T(\vec{r}\,')A_\rho(\vec{r} - \vec{r}\,')\mathrm{d}V$$

$$T(\vec{r}\,') = \left(\frac{r_o}{r'}\right)^2 \left(\frac{\mu}{\rho}\right) \psi(\vec{r_o}) e^{-\int_{r_o}^{r'} \mu(\ell)\mathrm{d}\ell}$$

Water energy deposition kernel, $A_\rho$, is scaled by density, but Terma is material dependent

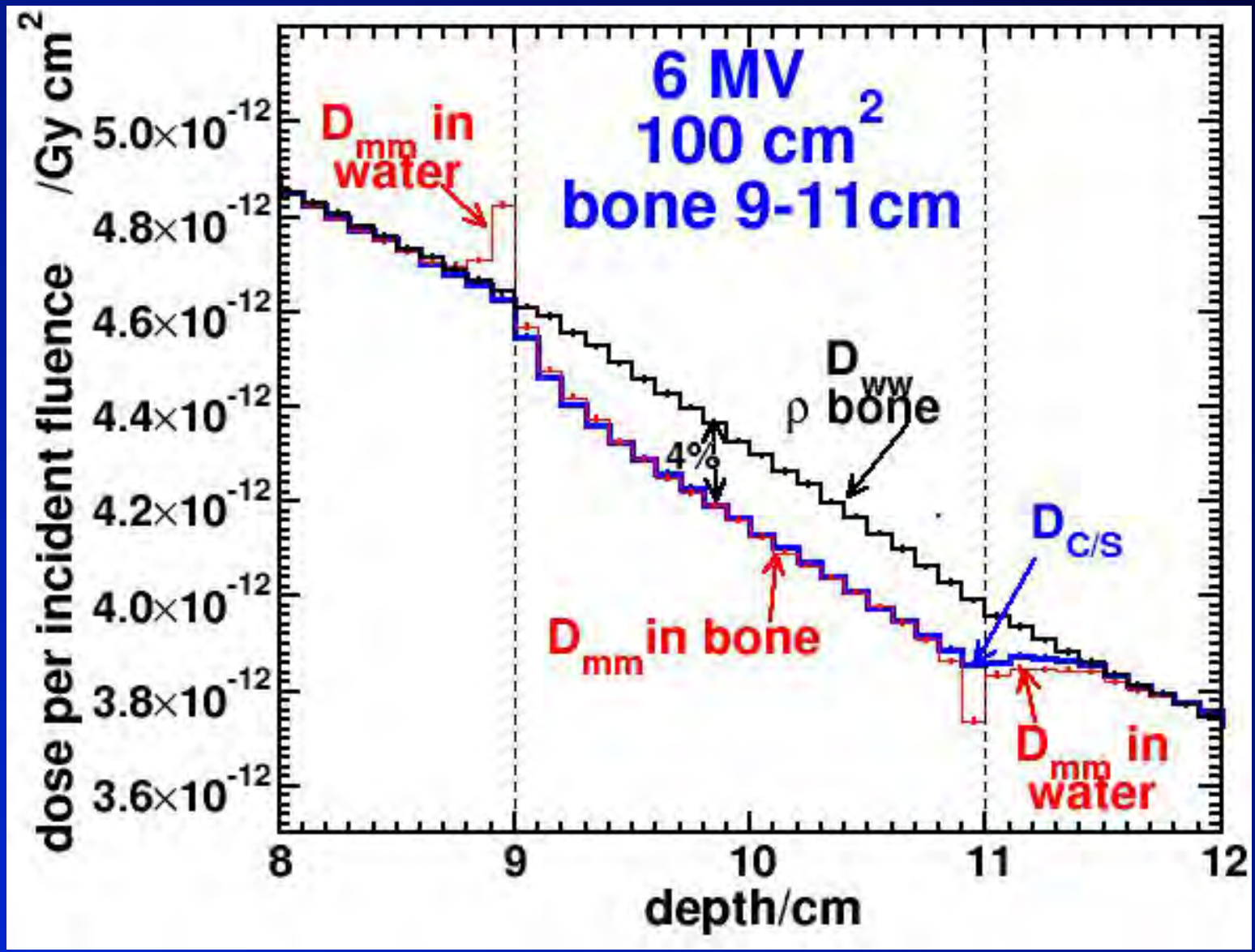
# How to emulate C/S with Monte Carlo?

- hack EGSnrc user code DOSRZnrc
  - use real geometry until location of interaction determined
  - then change all media to water with local e- density

- first step uses $\mu/\rho$ and the second creates a density scaled water-based EDK

- currently only handles slab geometries

# include the C/S result




as expected, remarkably close to Dmm

-except 4% off at interfaces

# summary so far

- Dmm is about 4% less than Dww when the water's density is scaled to that of bone
- $D_{C/S}$ is almost exactly the same as Dmm except at interfaces where it misses the 4% backscatter effects
- so the argument to use Dww to match previous clinical experience is invalid except for very old clinical data
- Dmm is generally in agreement with previous clinical data based on convolution superposition

# *what about water-like material in bone being the sensitive component?*

- damage to bone itself may be a limiting factor
  -then Dmm is what should be reported
- But often, dose of interest is to water-like bone surface cells or red bone marrow
- Hence ICRU 83's recommendation to report dose to a small mass of water in the medium

How to report/calculate that?

# cavity theory to the rescue

- for a small mass of water in a medium
- Bragg-Gray cavity theory where e- spectrum is in m

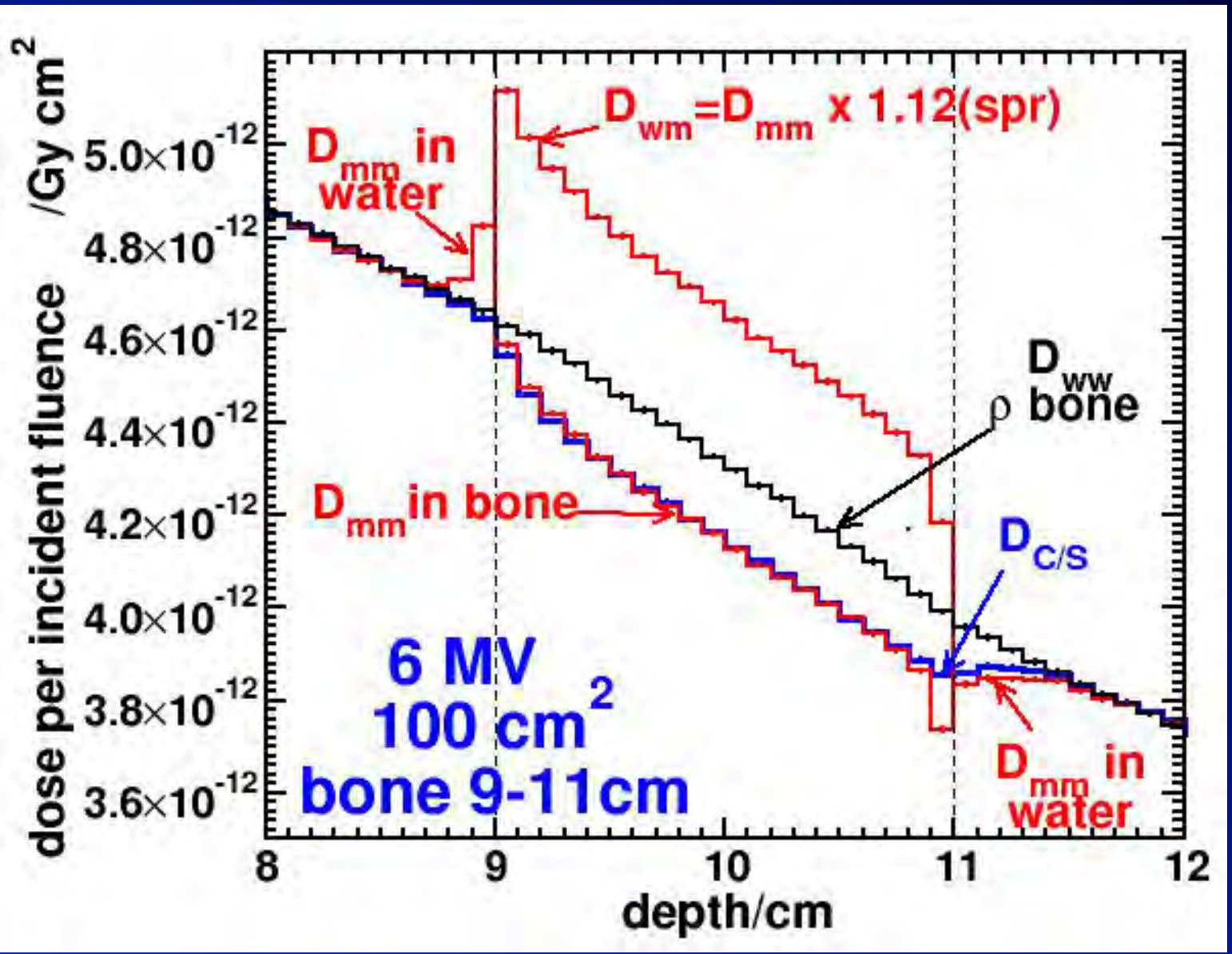
$$D_{mm} = D_{wm} \left( \frac{\overline{S}}{\rho} \right)_{w}^{m}$$

$$D_{wm} = D_{mm} \Big/ \left( \overline{S}/\rho \right)_{w}^{m} \approx D_{mm} \left( \overline{S}/\rho \right)_{m}^{w}$$

- Siebers et al (2000) calculated $\left( \overline{S}/\rho \right)_{m}^{w}$ using the e- spectrum in water
- showed that, throughout phantom,

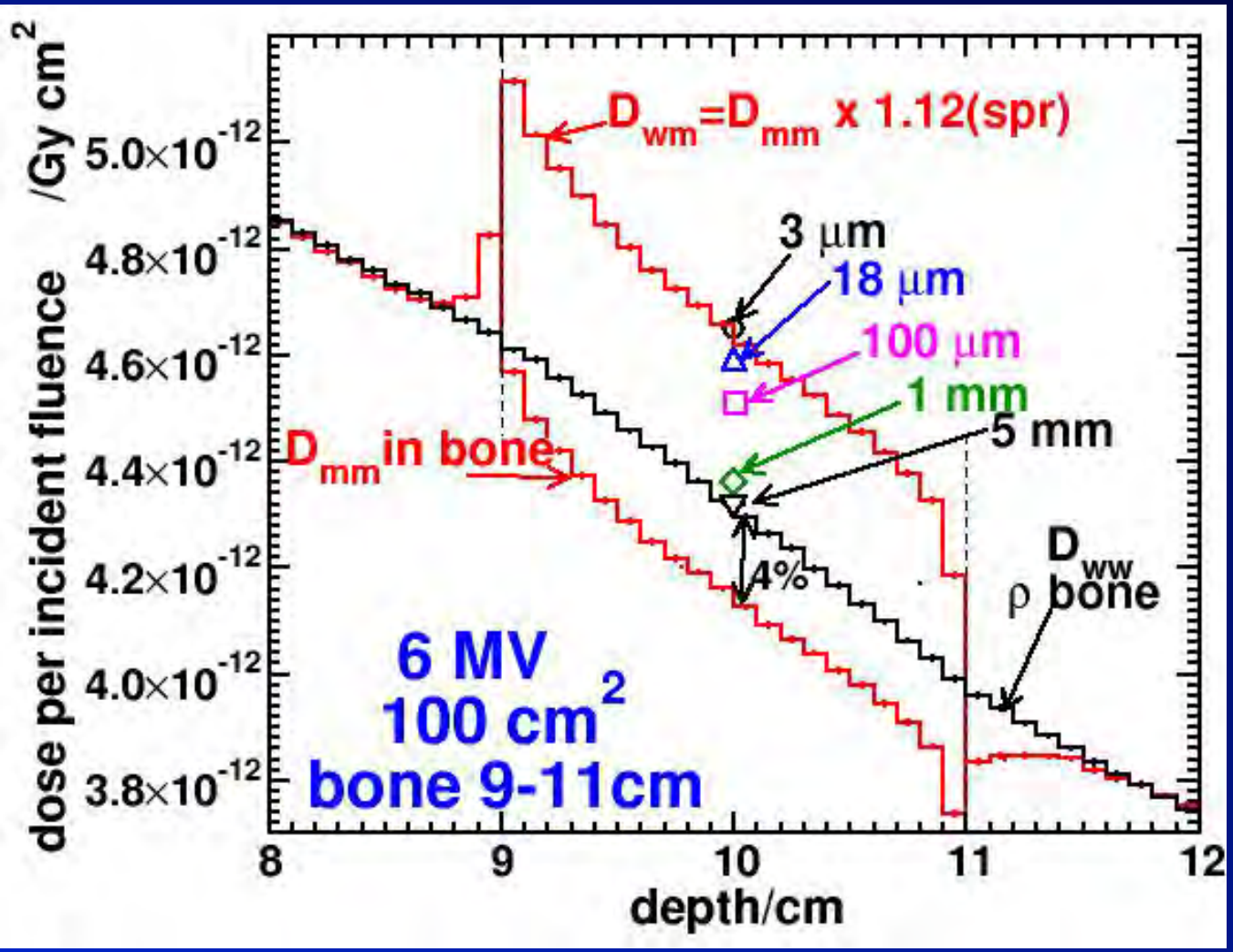
$$\left( \overline{S}/\rho \right)_{m}^{w} \approx \text{constant}$$

# consider Dwm=Dmm x spr




- nothing like Dww nor Dcs
- relevant if interest is dose to water-like material in bone

# calculate dose in thin slabs of water inside bone




- spr x Dmm agreement good for 3 μm slab
- by 5 mm slab looks like Dww
- Reynaert et al suggest $\mu_{en}/\rho$ ratios be used

**Problem:** value of $(\mu_{en}/\rho)^{water}_{bone}$ ? Reynaert et al 1.061

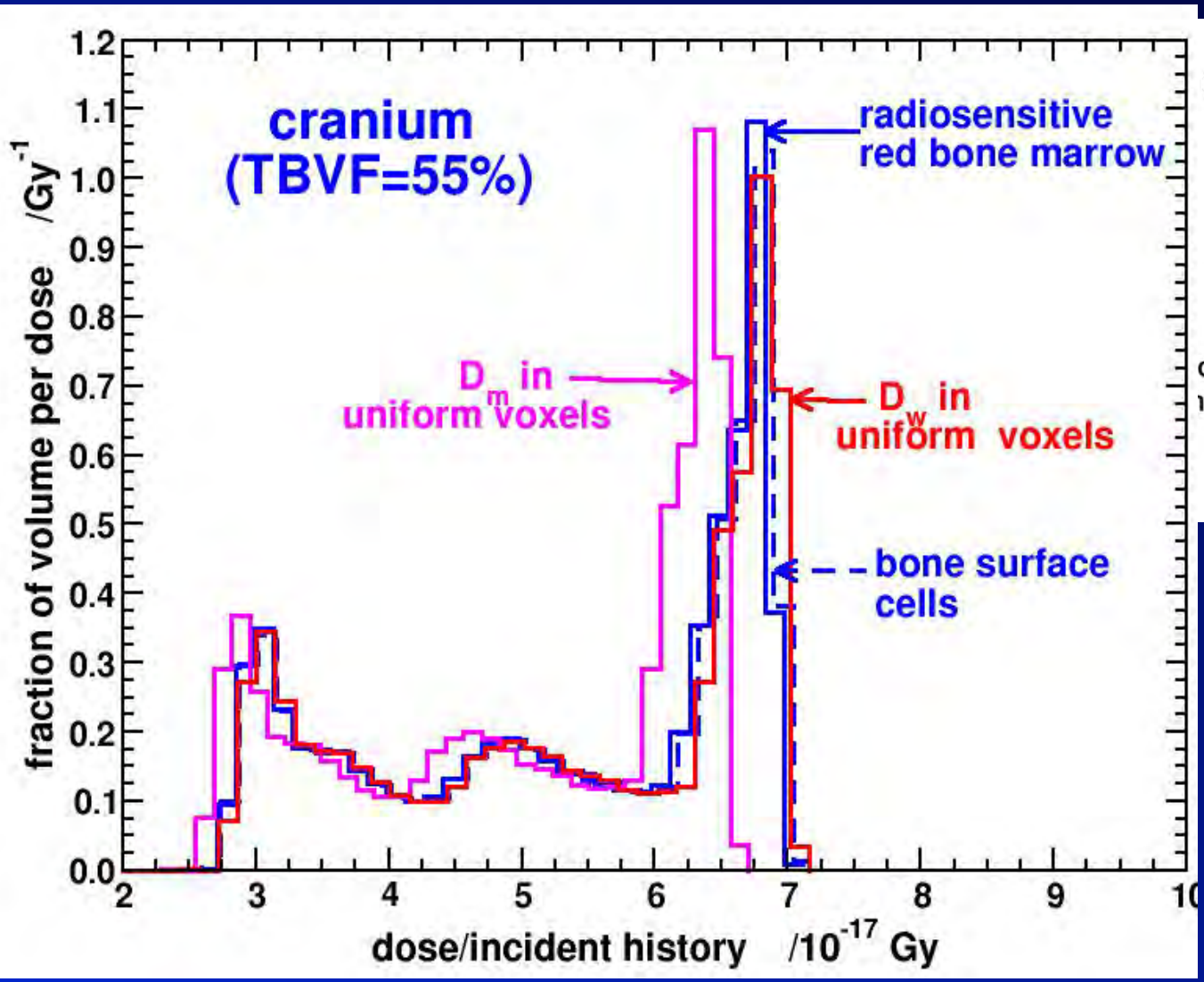
mine 1.017 in phantom, 1.053 incident:
Cunningham et al(1986). 1.026 in phantom

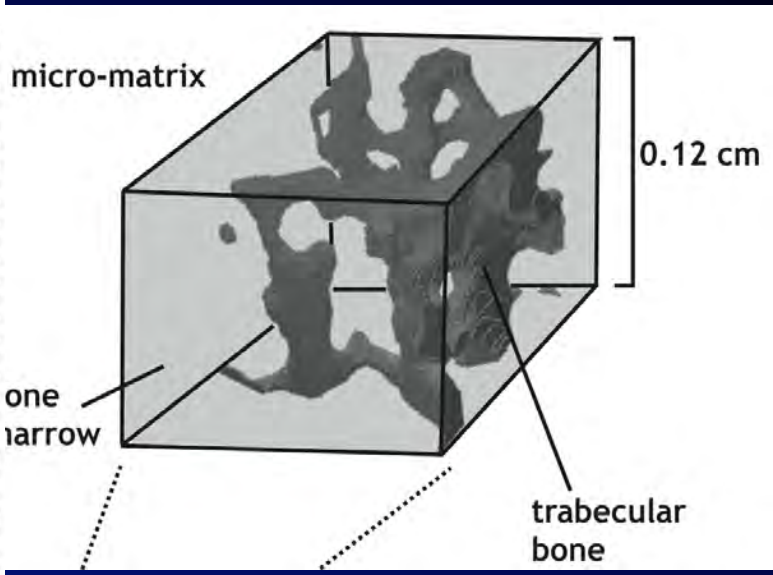
Carleton UNIVERSITY
Canada's Capital University

# *Where does this leave us?*

- Dmm from either MC or C/S are the same except at interfaces – so easiest to use
- if concern is a small mass of water in bone
  - spr correction not applicable for cell sized regions
    - Walters et al (2010) found spr worked but value very dependent on TBVF (trabecular bone volume fraction)
  - $\mu_{en}/\rho$ ratios subject to uncertainty
    - for larger regions, might as well calculate Dww (with varying $\rho$)

# Walters et al PMB 55(2010)4535 detailed bone model vs average material




$(18\mu m)^3$ voxels

calculated Dwm and Dmm on the fly
effective spr 1.07 and less as TBVF ↓

# Conclusions

- no simple answer
  - but good news is that Dmm, which is naturally calculated by Monte Carlo, Boltzmann transport solvers and in principle by C/S codes, is consistent with most clinical experience
- simplistic correction using stopping-power ratios to get dose to a small mass of water in bone is likely to lead to possibly big errors

# *In memory of Jack: a friend and giant in our field*

Carleton UNIVERSITY
Canada's Capital University

# references


- Report dose-to-medium in clinical trials where available; a consensus from the global Harmonisation group to maximize consistency: Kry et al, Radiotherapy& Oncology 159(2021)106
- Dose to medium versus dose to water as an estimator of dose to sensitive skeletal tissue: Walters et al PMB 55(2010)4535
- On the conversion of dose to bone to dose to water in radiotherapy treatment planning systems: Reynaert et al, Phys. Imaging in Rad.Oncol 5(2018)26
- Converting absorbed dose to medium to absorbed dose to water for Monte Carlo based photon beam dose calculation: Siebers et al, PMB 45 (2000) 983
- The Dependence of Mass Energy Absorption Coefficient Ratios on Beam Size and Depth in a Phantom: Cunningham et al, Med Phys 13 (1986) 496