# Calculation of organ-specific radiation quality factors for the radioprotection of astronauts on the Moon: a microdosimetric approach

**M. J. Large**[1], J.W. Archer[1], D. Bolst[1], S. Peracchi[2], A.B. Rosenfeld[1,3] & S. Guatelli[1]

1 CENTRE FOR MEDICAL RADIATION PHYSICS, UNIVERSITY OF WOLLONGONG, WOLLONGONG, NSW, AUSTRALIA

2 AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION (ANSTO), LUCAS HEIGHTS, AUSTRALIA

3 ILLAWARRA HEALTH AND MEDICAL RESEARCH INSTITUTE, UNIVERSITY OF WOLLONGONG, WOLLONGONG, NSW, AUSTRALIA

# Overview

- **Introduction**
  - Primary GCR Environment & G4 Parameters
  - Lunar Surface Geometry
    - ICRP145 Human Phantoms
- **Results**
  - Organ Specific Radiation Quality Factors
    - Microdosimetric Approach
    - LET-based Approach
  - Daily Lunar Surface Dose Calculations
  - Benchmarking of Results
- **Conclusions**


**ACKNOWLEDGEMENTS**

NCI AUSTRALIA

SRN NSW Space Research Network

AINSE THE AUSTRALIAN INSTITUTE OF NUCLEAR SCIENCE AND ENGINEERING

Australian Government

ANSTO

UNIVERSITY OF WOLLONGONG AUSTRALIA

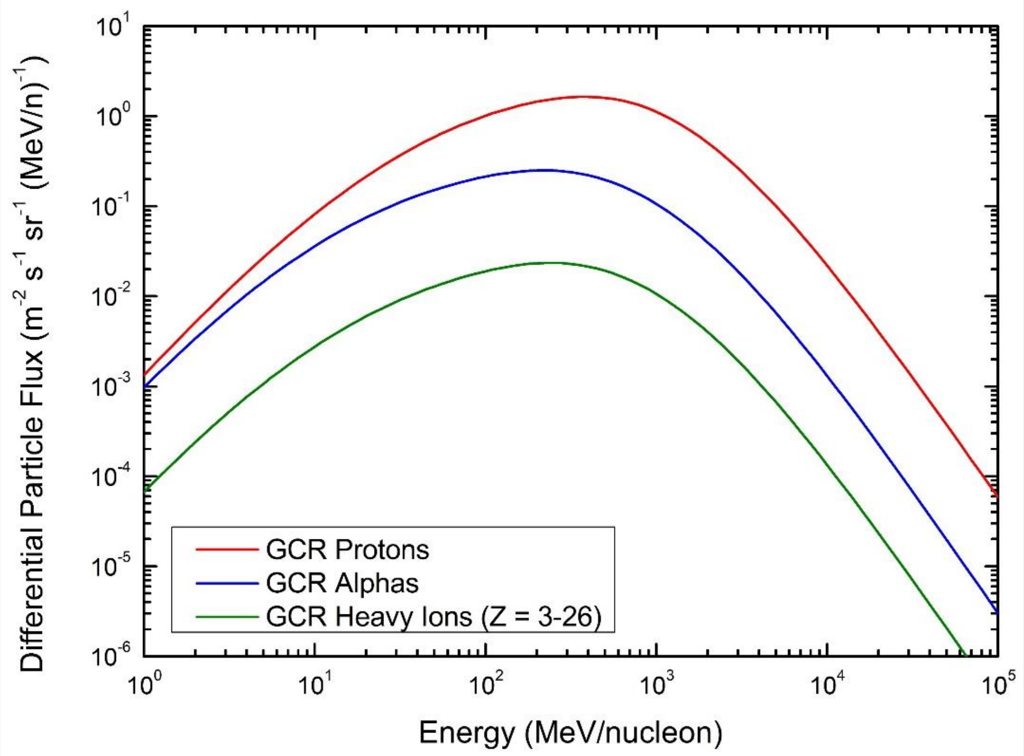
CENTRE FOR MEDICAL RADIATION PHYSICS

# Primary GCR Spectra

## Calculated via SPENVIS

**(4.6.10 – released May 4, 2018)**

- Near-Earth Interplanetary Space (1 AU from Sun)
- GCR model: ISO-15390 (standard)
- Solar activity data: Solar Minimum (late 2009 )
  - Calculated within SPENVIS using 12-Month averaged Wolf Number of 4.8)
- GCR spectra generated from incident Protons to Fe ions
  - Generated for particle energies from $10^0$ to $10^5$ MeV/nucleon with a resolution of 20 points per decade



# Geant4 Modelling

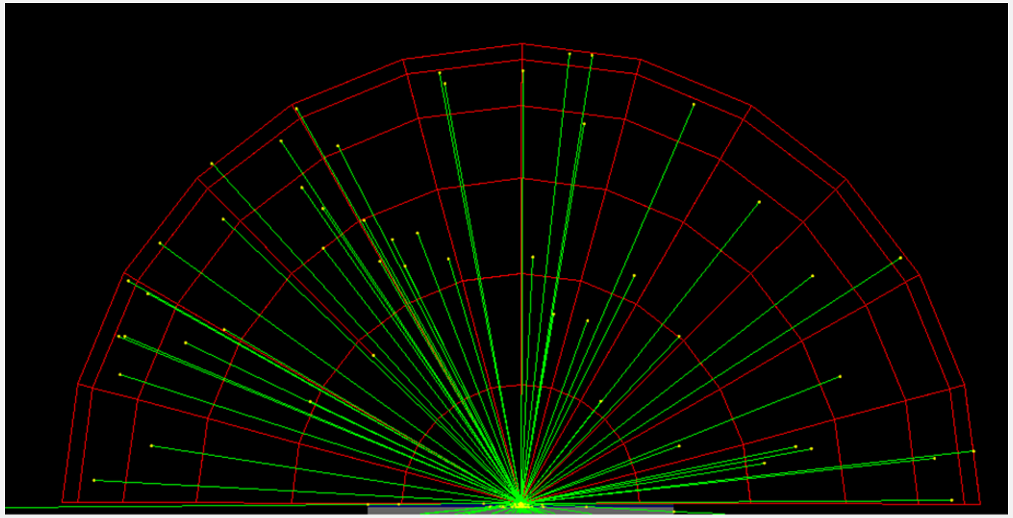
- Geant4 (version 11.0.01)
- Built-in physics list FTFP_BERT_HP adopted to model particle propagation, interaction and energy deposition within lunar soil. Physics list includes:
  - Fritiof model (particle energies > 10 GeV)
  - Bertini cascade model (particle energies < 10 GeV)
  - High Precision neutron model (G4NDL4.6 – neutron energies < 20 MeV)
- Primary GCR particles from Protons, Alpha, Carbon, Oxygen and Iron
  - Incident energies in range 1-$10^5$ MeV/n
  - Account for 99.63% of GCR falling incident on the Lunar surface

Agostinelli, S. et al. (2003). DOI: 10.1016/s0168-9002(03)01368-8

# Simulation Geometry

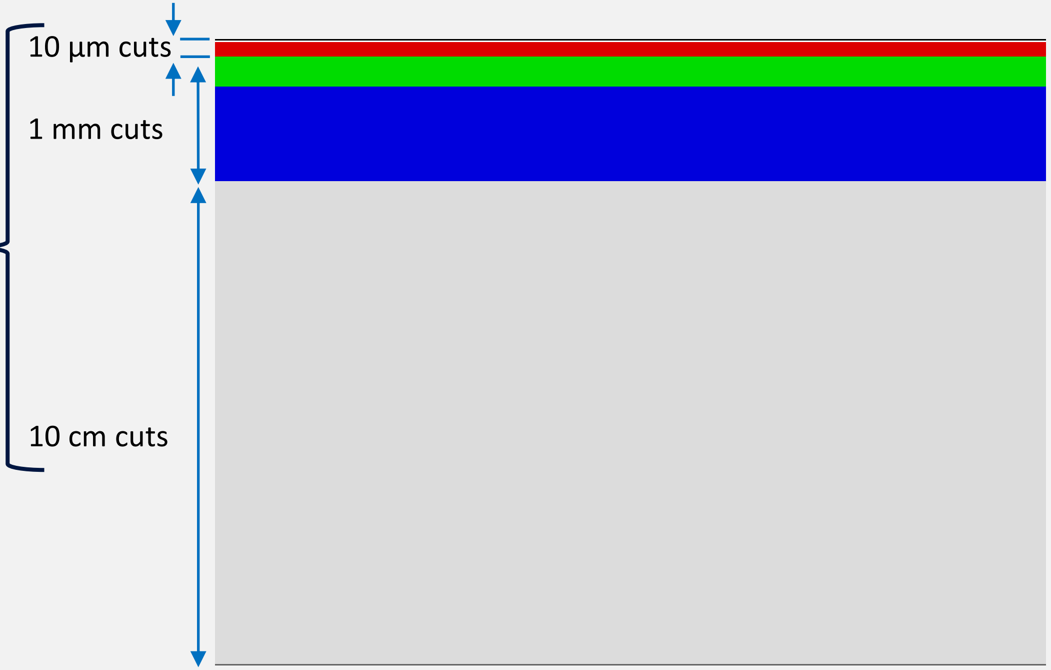
**TABLE:** Elemental composition of the Lunar Surface as implemented in Geant4. Layer compositions are presented as mass percentages, based on LNPE Borehole data following the works of McKinney *et al.* (2006) and Mesick *et al.* (2018).

| | Layer 1 | Layer 2 | Layer 3 | Layer 4 |
|---|---|---|---|---|
| Depth: | 0 – 22 cm | 22 – 71 cm | 71 – 224 cm | >224 cm |
| Density: | 1.76 g/cm$^3$ | 2.11 g/cm$^3$ | 1.78 g/cm$^3$ | 1.79 g/cm$^3$ |
| O | 41.739% | 41.557% | 42.298% | 42.636% |
| Si | 19.026% | 18.955% | 19.668% | 20.218% |
| Fe | 13.496% | 14.030% | 12.277% | 11.688% |
| Ca | 7.541% | 7.668% | 8.020% | 7.707% |
| Al | 6.061% | 5.977% | 7.384% | 7.598% |
| Mg | 6.162% | 6.026% | 6.156% | 6.091% |
| Ti | 5.144% | 4.905% | 3.380% | 3.198% |
| Na | 0.292% | 0.313% | 6.026% | 0.346% |
| Cr | 0.287% | 0.309% | 0.264% | 0.255% |
| Mn | 0.176% | 0.178% | 0.152% | 0.146% |
| K | 0.067% | 0.074% | 0.086% | 0.109% |
| Gd | 0.004% | 0.004% | 0.004% | 0.004% |
| Sm | 0.003% | 0.003% | 0.003% | 0.003% |
| Th | 0.001% | 0.000% | 0.001% | 0.001% |
| Eu | 0.001% | 0.001% | 0.001% | 0.000% |



"Cuts" = Minimum/threshold traversal length of secondaries in that medium

If secondary traversal < cut length, secondary particle will not be generated



# Isotropic Source Modelling with Directional Biasing

- G. Santin* describes the need for the emission of particles from surface of a sphere to follow a cosine-law angular distribution to simulate an isotropic radiation field at a desired target.

- The dose per particle can then be normalised to a dose per unit time in the "real world"

- Integrate over 2π emission angle with cosine biasing

$$\int_0^{2\pi} d\varphi \int_0^{\pi/2} d\theta cos\theta sin\theta = \pi$$

- Number of particles per unit "real time" from hemisphere ($2\pi R^2$ surface)

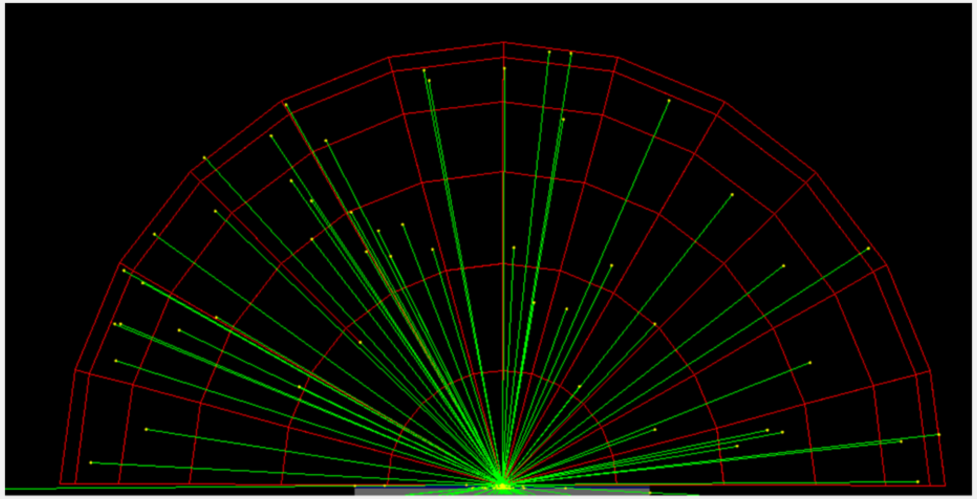
$$N_r = \Phi * 2\pi R^2 * \pi,$$ Φ = integral flux ($cm^{-2}$ $s^{-1}$ $sr^{-1}$)

- With directional biasing ($\theta_{min} < \theta < \theta_{max}$)

$$N_r = \Phi 2\pi^2 R^2 (\sin^2 \theta_{max} - \sin^2 \theta_{min})$$

- Dose per unit "real time":

$$D_r = D_s \left(\frac{N_r}{N_s}\right)$$



R = 1000m ; $\theta_{max} = 0.0573^O$

*Santin, G. (2007). *Normalisation modelling sources* [PowerPoint presentation]. Geant4 tutorial, Paris, 4-8 June 2007. URL: http://geant4.in2p3.fr/2007/prog/GiovanniSantin/GSantin_Geant4_Paris07_Normalisation_v07.ppt

# ICRP145 Human Phantoms

Anatomically accurate computational human phantoms

- Male: 73 kg, 176cm tall
- Female: 60 kg, 163 cm tall
- 186 organs/tissues constructed by over 8 million tetrahedrons

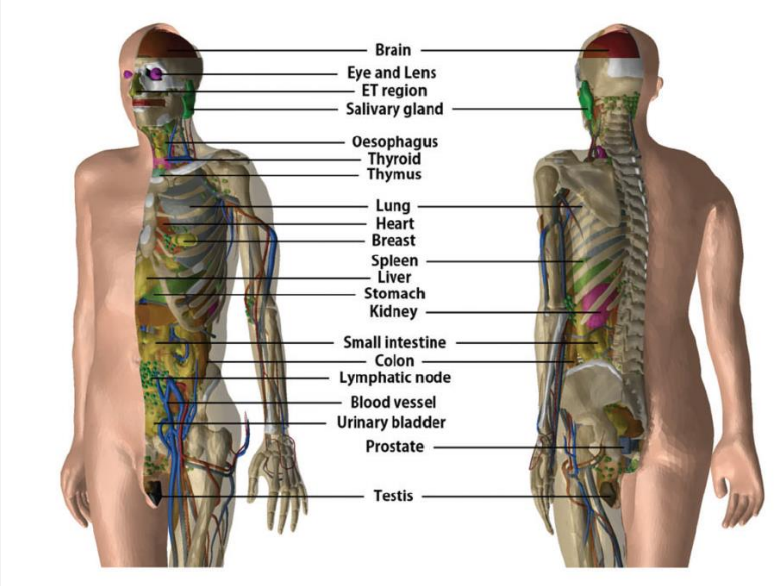
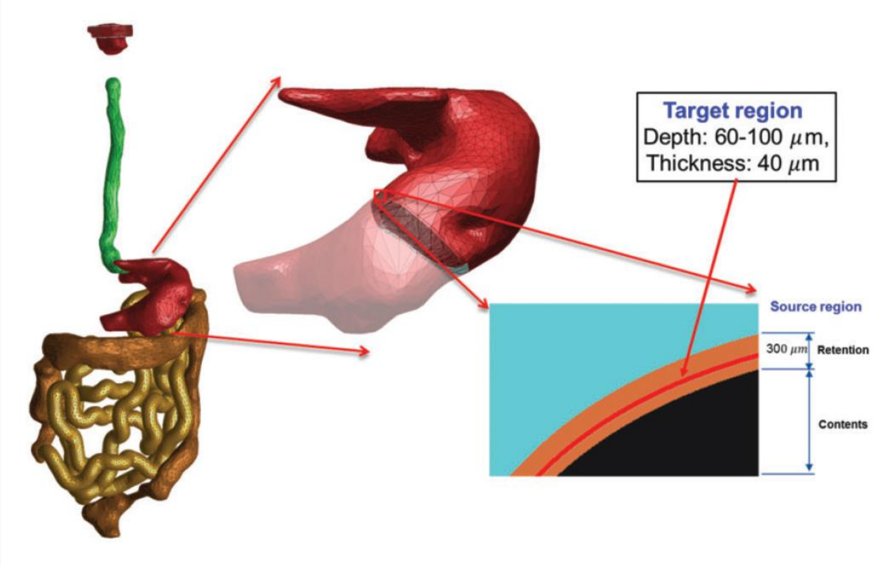
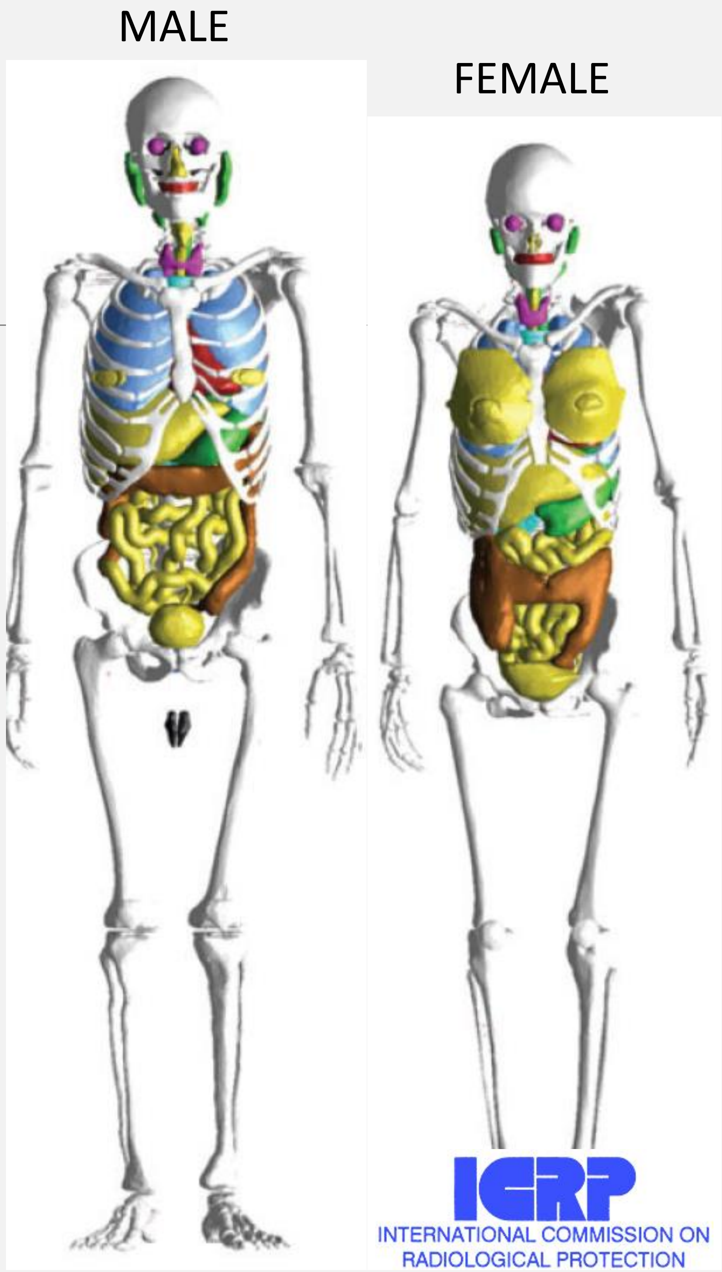



Fig. 6.1. Mesh-type ICRP adult male reference phantom.




Images from Kim, C.H. *et al.* 2020. ICRP publication 145: adult mesh-type reference computational phantoms. Annals of the ICRP, 49(3).

# Organ Specific Radiation Quality Factors

Comparison of 2 Methods

- Microdosimetry  (ICRU 40, )
- LET (ICRP 60, 1991)

# Q-Factor Calculation Methods

## MICRODOSIMETRIC APPROACH

Convolution of absorbed dose as a function of lineal energy d(y) with the distribution of Q(y), as described in ICRU's Report 40 (ICRU, 1986).

$$Q(y) = \frac{a_1}{y}[1 - \exp - a_2 y^2 - a_3 y^3]$$

With coefficients $a_1$ = 5510, $a_2$ = 5E-5 and $a_3$ = 2E-7. The av Q in each organ is calculated via

$$\bar{Q} = \int Q(y) d(y) dy$$

## LET APPROACH

As described in ICRP Publication 60 (ICRP, 1991).

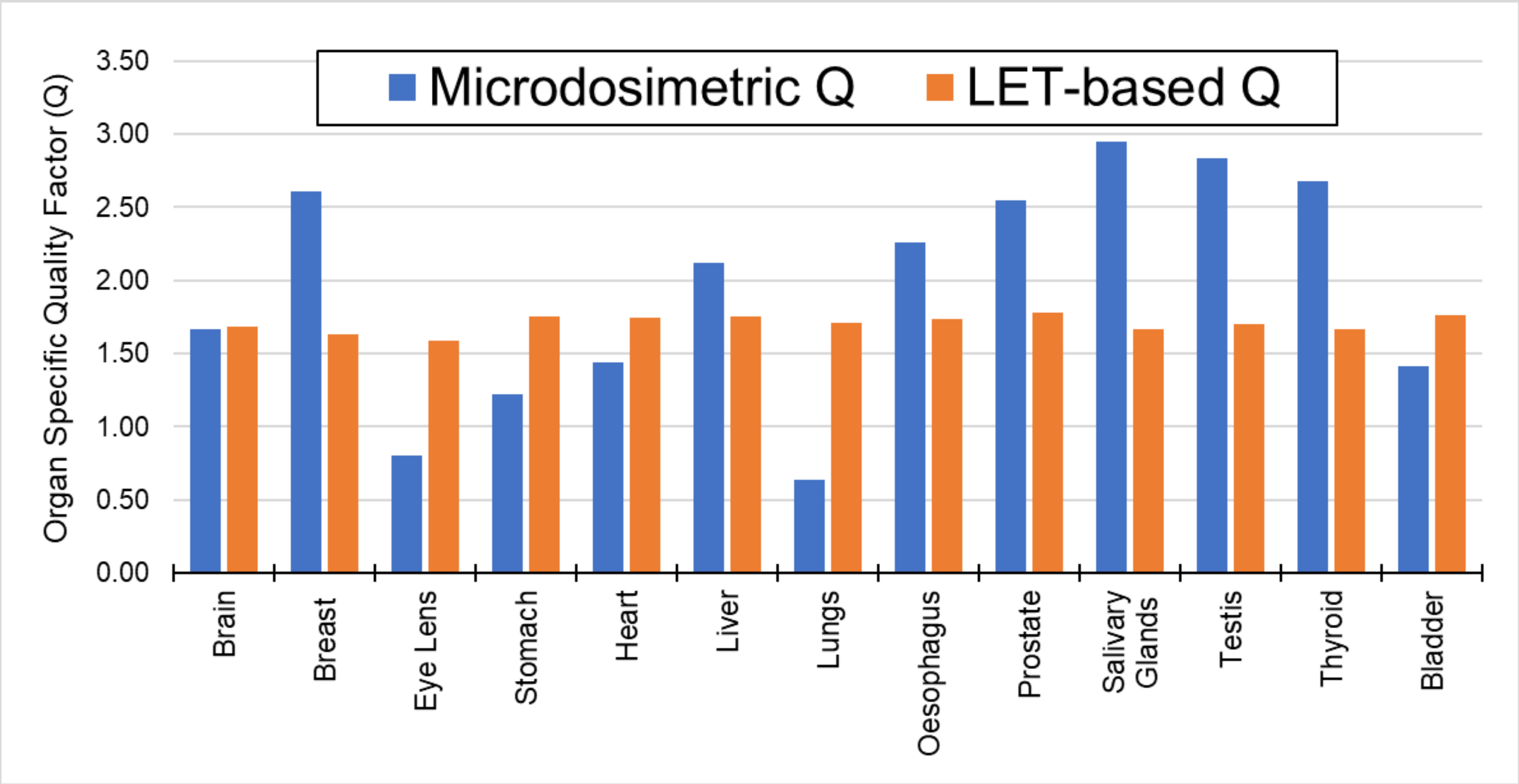
$$Q(L) = \begin{cases} 1 & L < 10\ \mathrm{keV}/\mu\mathrm{m} \\ 0.32L - 2.2 & 10 \leqslant L\ 100\ \mathrm{keV}/\mu\mathrm{m} \\ 300/\sqrt{L} & L > 100\ \mathrm{keV}/\mu\mathrm{m} \end{cases}$$

The radiation quality factor, Q, at a point in tissue is given by

$$Q = \frac{1}{D}\int_{L=0}^{\infty} Q(L) D_L \, \mathrm{d}L$$

D - absorbed dose at that point in tissue,
DL - distribution of absorbed dose with respect to linear energy transfer L,
Q(L) - quality factor at the point of interest for a given L.

# Comparisons: Q-Factor Calculations

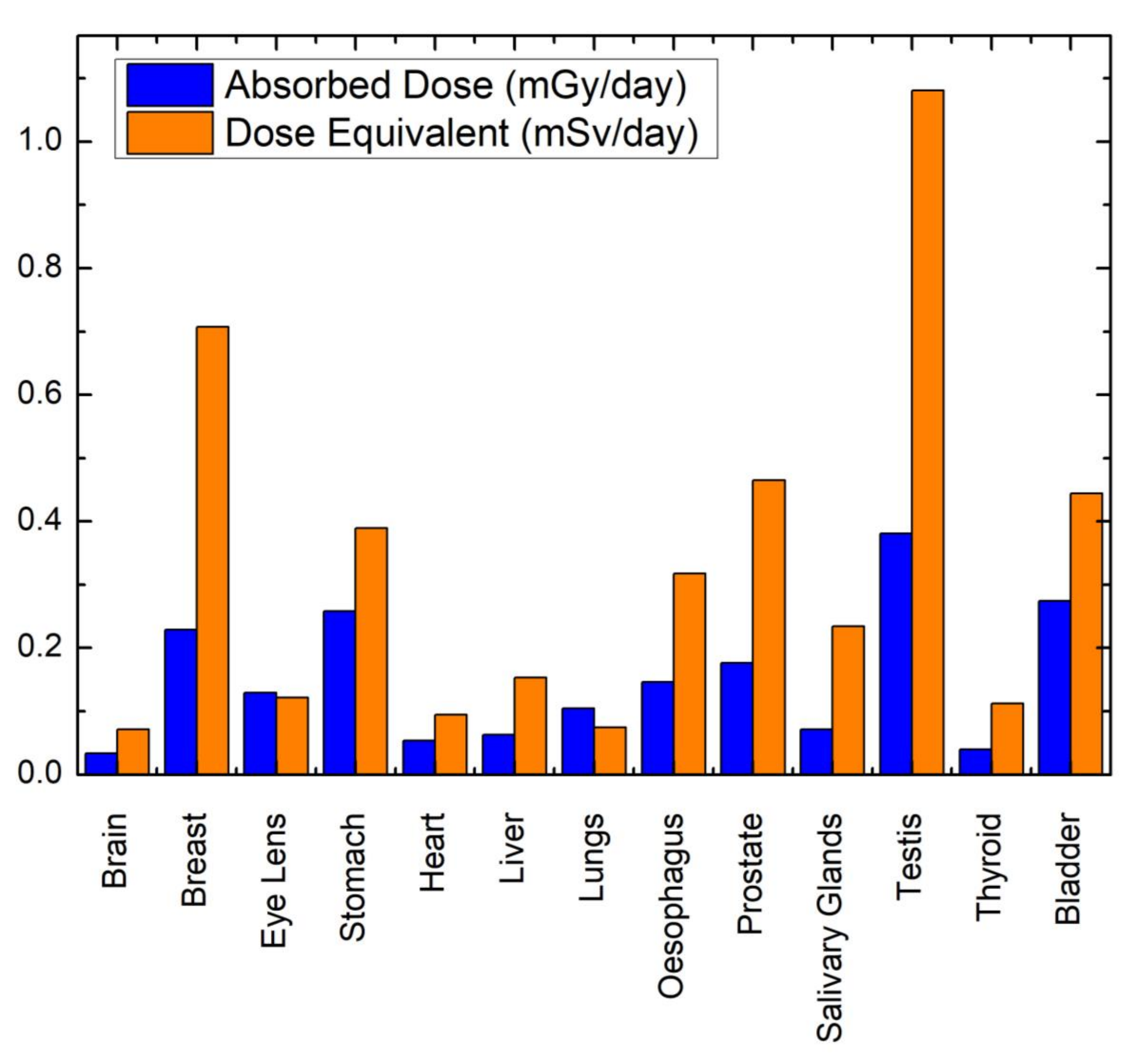



| Organ/Tissue | Microdosimetry | LET | Diff (%) |
|---|---|---|---|
| **Brain** | 1.67 | 1.68 | 1% |
| **Breast** | 2.61 | 1.63 | 60% |
| **Eye Lens** | 0.80 | 1.59 | 50% |
| **Stomach** | 1.22 | 1.76 | 30% |
| **Heart** | 1.44 | 1.74 | 17% |
| **Liver** | 2.12 | 1.76 | 21% |
| **Lungs** | 0.63 | 1.71 | 63% |
| **Oesophagus** | 2.26 | 1.73 | 30% |
| **Prostate** | 2.55 | 1.78 | 43% |
| **Salivary Glands** | 2.95 | 1.67 | 77% |
| **Testis** | 2.84 | 1.70 | 66% |
| **Thyroid** | 2.68 | 1.67 | 61% |
| **Bladder** | 1.42 | 1.77 | 20% |

# Calculated Daily Organ Doses

For ICRP145 Male Phantom on the Lunar Surface

# Results: Daily GCR Dose on Moon

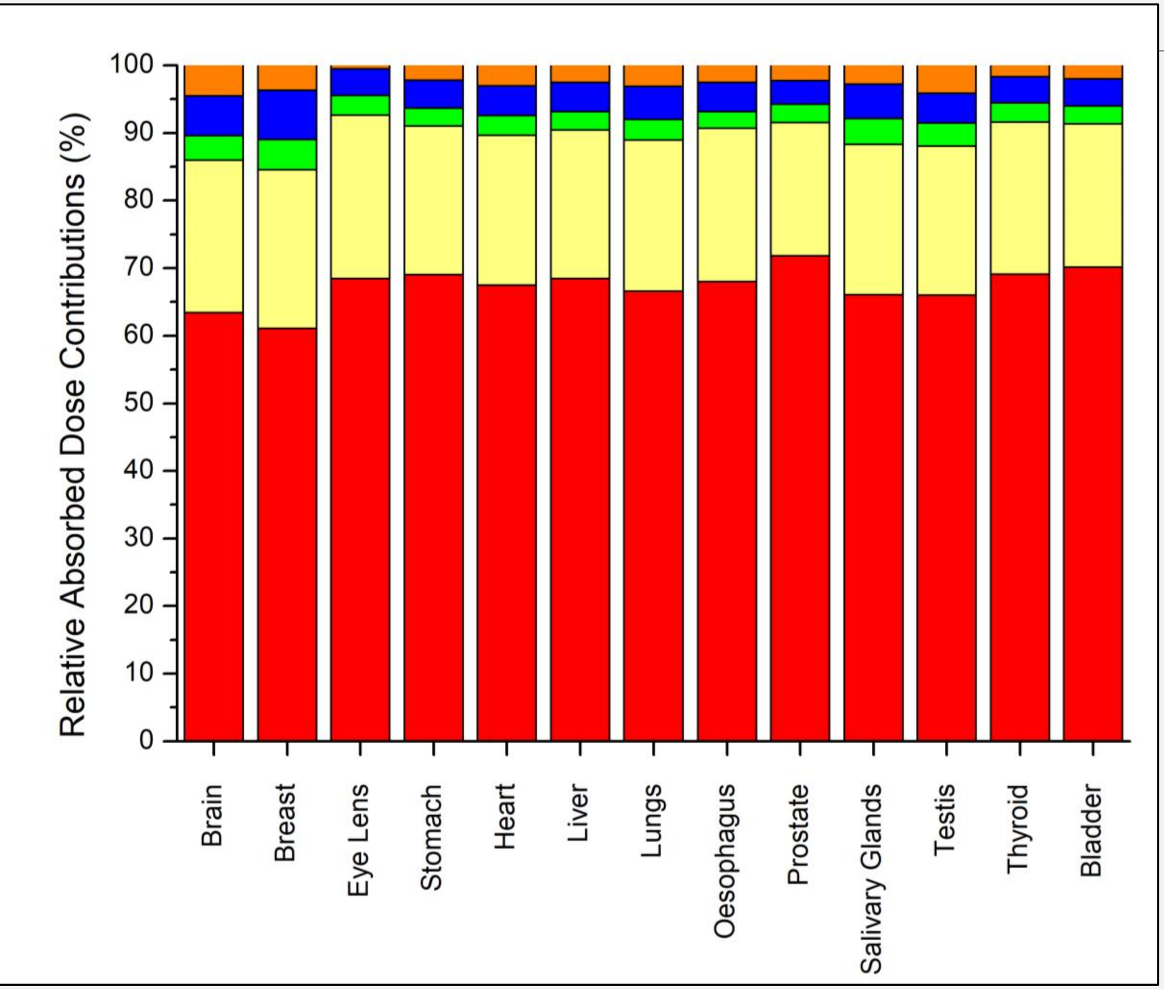



**Combined doses from daily fluences of GCR Protons, Alpha, Carbon, Oxygen and Iron ions.**

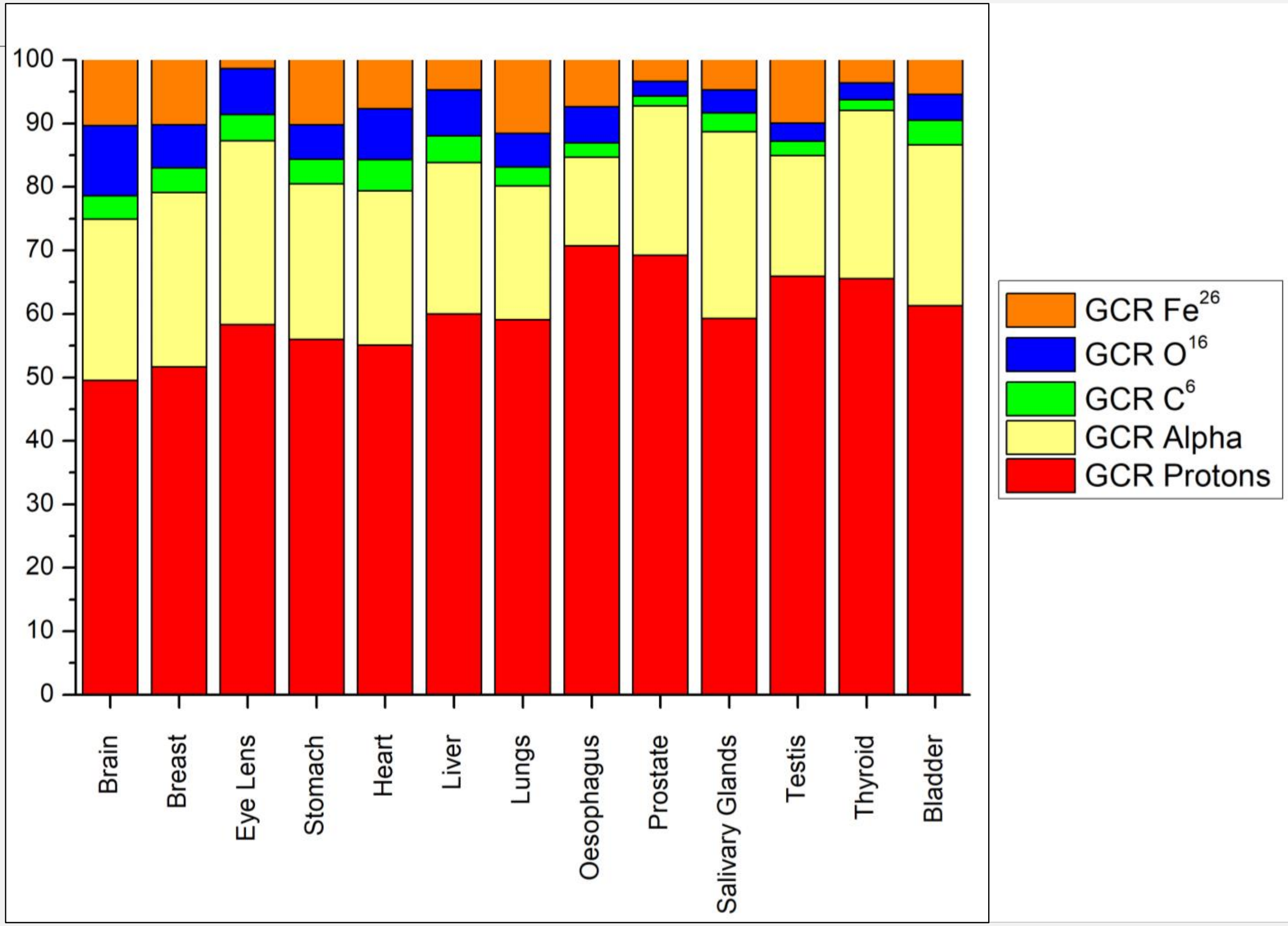
- Absorbed dose, **D** (mGy), to organs/tissues calculated as average energy deposited in each tissue divided by their respective weight.
- Average radiation quality factor, **Q**, calculated from microdosimetric spectra yd(y) vs y obtained within each organ/tissue.
- Dose equivalent, **H** (mSv), calculated as:
  - H (mSv) = D (mGy) * Q

# GCR Contributions

## ABSORBED DOSE




## DOSE EQUIVALENT



# Benchmarking of Results (Reitz *et al.*, 2012)

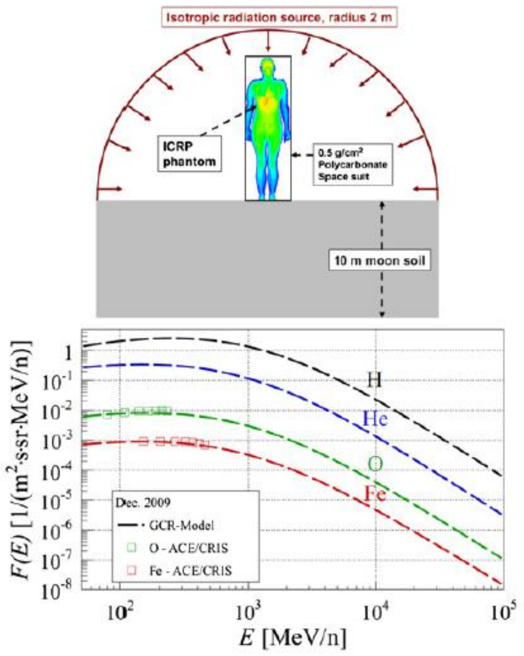



**Fig. 2.** Top—Simulation scenario for the estimation of the radiation exposure on the surface of Moon. Bottom—Galactic cosmic ray energy spectra (Matthiae et al., under review) for selected nuclei during solar minimum. The oxygen and iron spectra are compared to ACE/CRIS data during the very deep solar minimum in the end of 2009. (For interpretation of the reference to color in this figure, the reader is referred to the web version of this article.)

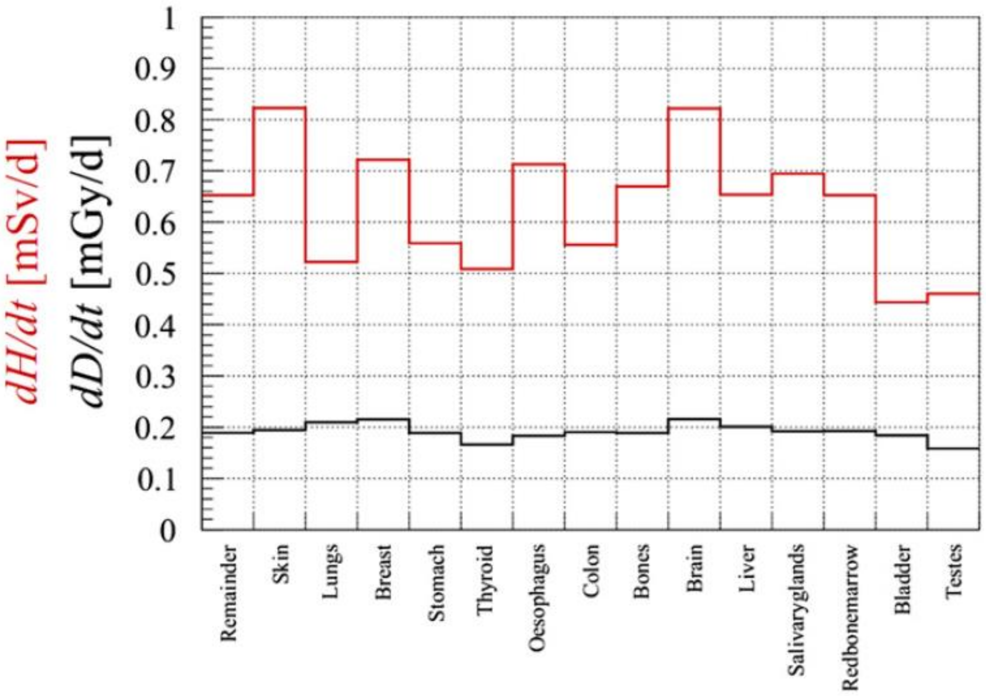
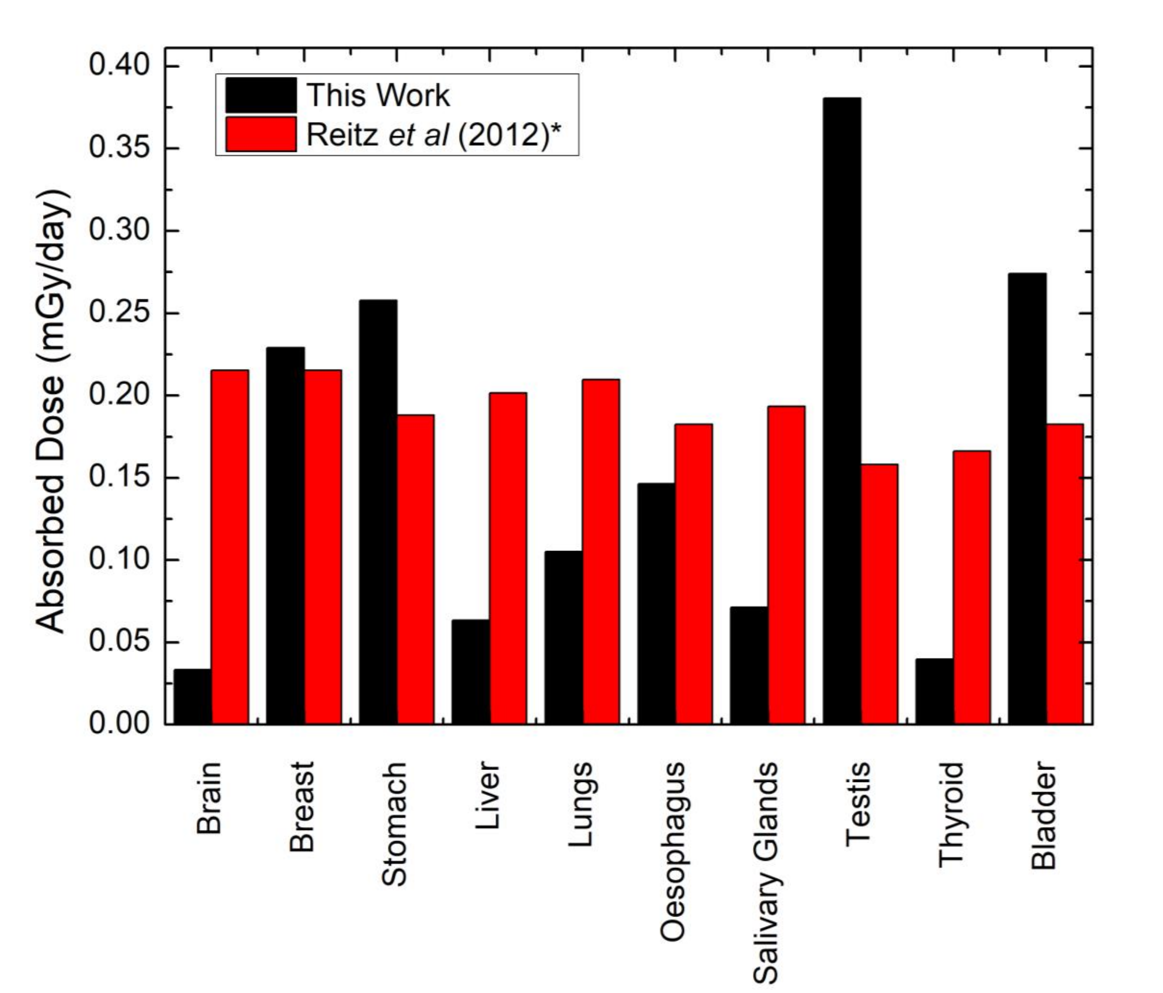


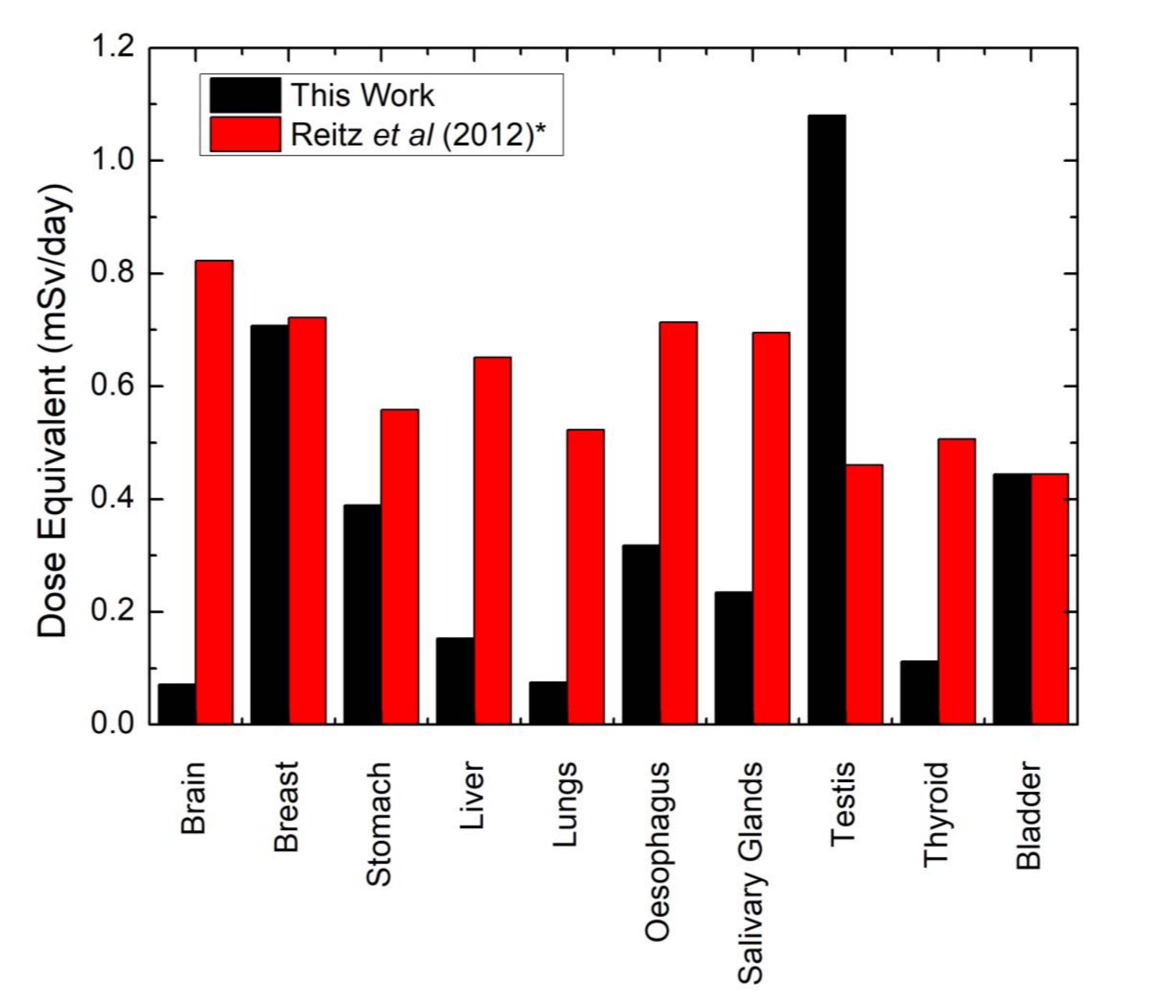

**Fig. 3.** Organ absorbed dose rates $dD/dt$ (lower line) and dose equivalent rates $dH/dt$ (upper line) from galactic cosmic rays for solar minimum conditions on the lunar surface.

Figures from Reitz, G., Berger, T. and Matthiae, D., 2012. Radiation exposure in the moon environment. *Planetary and Space Science*, 74**(1)**, pp.78-83.

# Benchmarking of Results (Reitz *et al.*, 2012)




**ABSORBED DOSE**




**DOSE EQUIVALENT**

# Benchmarking of Results (Reitz *et al.*, 2012)

| Organ/Tissue | Av Q (This Work) | Av Q (Reitz, 2012) | Difference (%) |
|---|---|---|---|
| **Brain** | 2.14 | 3.82 | -44% |
| **Breast** | 3.09 | 3.35 | -8% |
| **Eye Lens** | 0.94 | - | - |
| **Stomach** | 1.51 | 2.97 | -49% |
| **Heart** | 1.77 | - | - |
| **Liver** | 2.42 | 3.23 | -25% |
| **Lungs** | 1.71 | 2.49 | -32% |
| **Oesophagus** | 2.17 | 3.91 | -44% |
| **Prostate** | 2.64 | - | - |
| **Salivary Glands** | 3.29 | 3.59 | -8% |
| **Testis** | 2.84 | 2.91 | -3% |
| **Thyroid** | 2.83 | 3.05 | -7% |
| **Bladder** | 1.62 | 2.43 | -33% |

# Conclusions

- Comparisons of LET and Microdosimetry methods of Q-factor calculation show varying degrees of agreement (min 1%, max 77%).
- Microdosimetry method of Q-factor calculation adopted to investigate daily organ doses on lunar surface
- Benchmarking of results showed mixed results. The origins of these must be further investigated
- Organ Quality factors varied by less than 50% from the reference data
- Further investigations and validations of the data are required

# Thank you for your attention ☺

EMAIL: mjl970@uowmail.edu.au