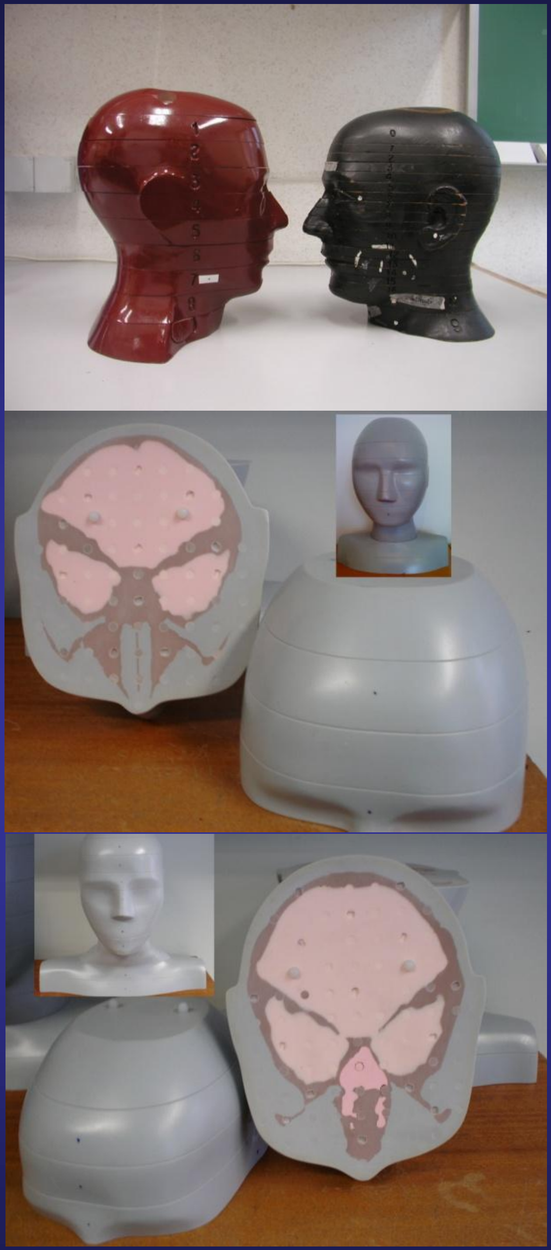
# Dosimetry

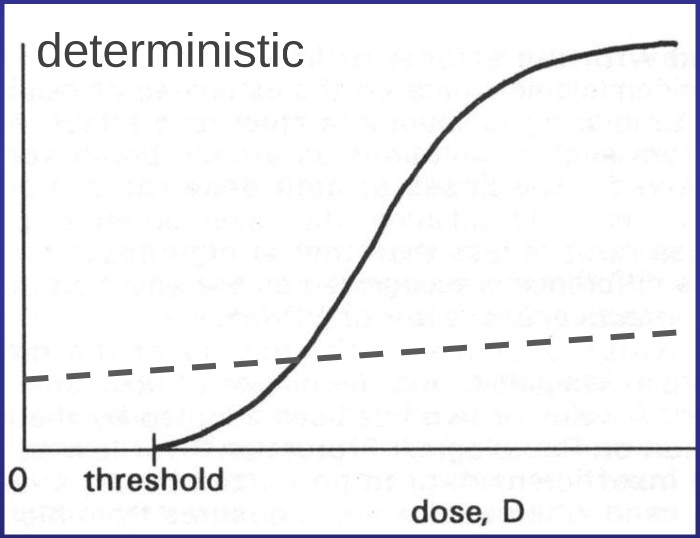
# of dental CBCT

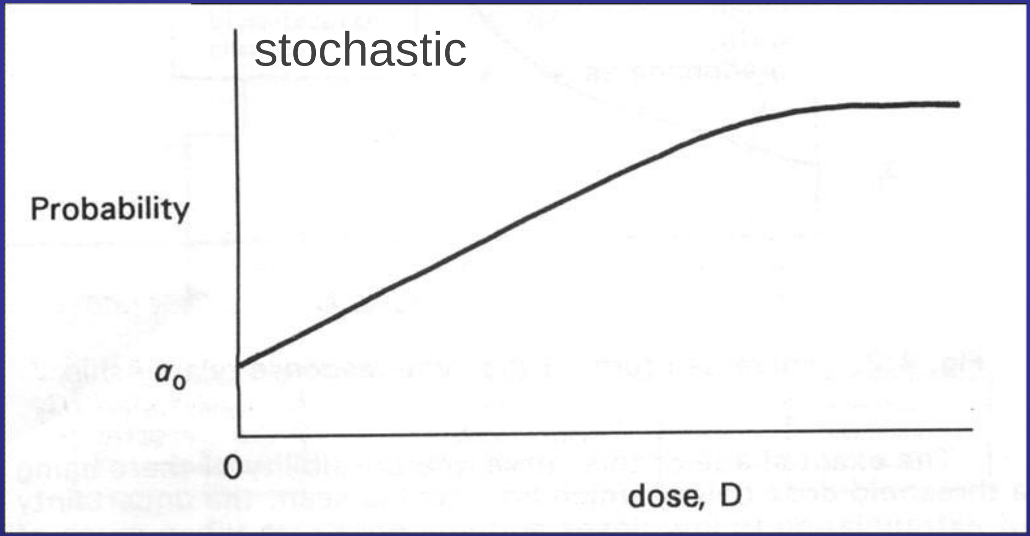


# Why dosimetry?

X-rays $\rightarrow$ ionizing radiation

$\rightarrow$ deterministic and stochastic effects



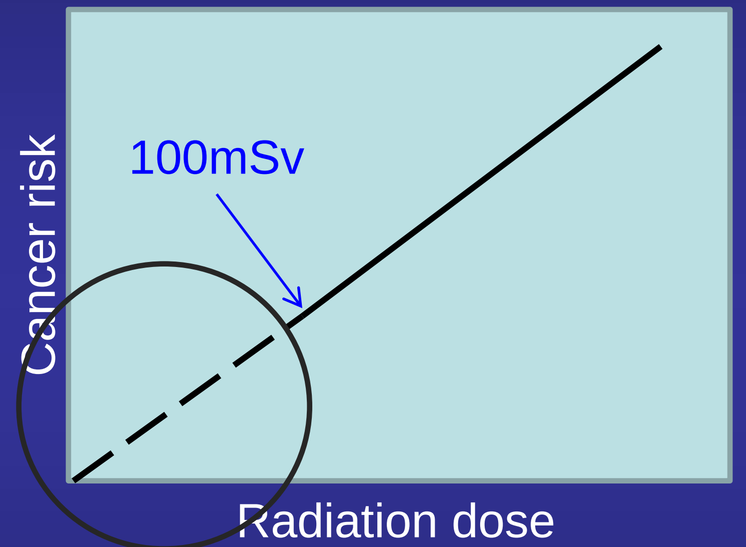



# Why dosimetry?

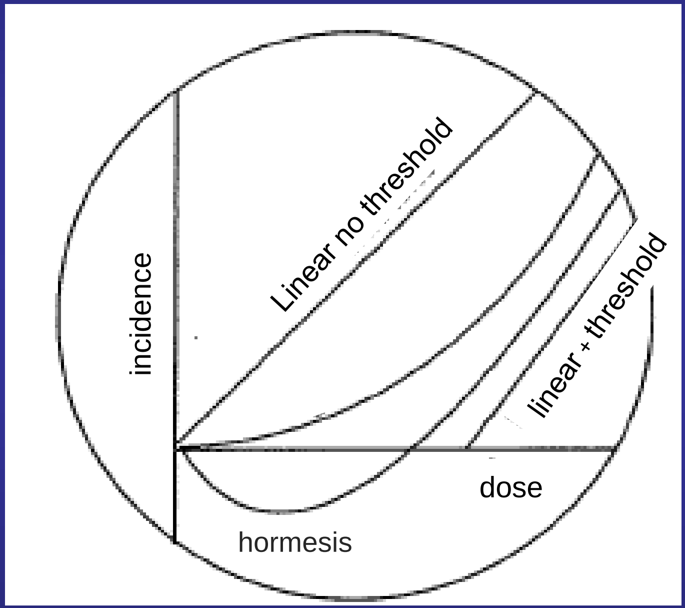
## Cancer risk?

International Commission on Radiological Protection[1]

French Academies Report, 2005[2]




*"linear no-threshold" model*

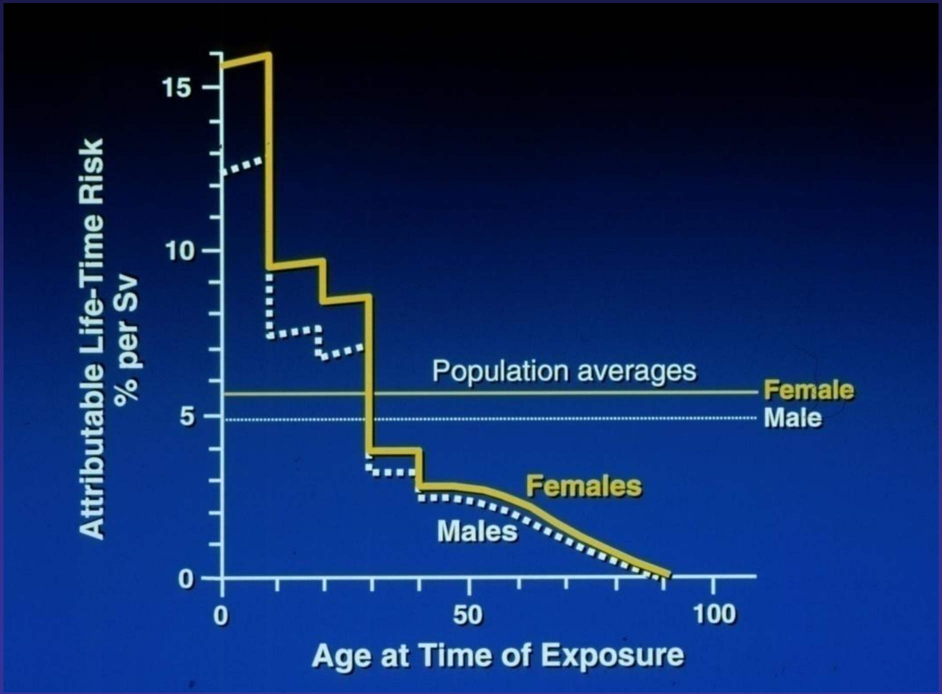



*[1]ICRP103: The 2007 Recommendations of the International Commission on Radiological Protection . Annals of the ICRP Vol 37 (2007)*

*[2]French Academies Report, 2005. La relation dose-effet et l'estimation des effets cancérogènes des faibles doses de rayonnements ionisants.*

# Why dosimetry?

## Risk of cancer and age

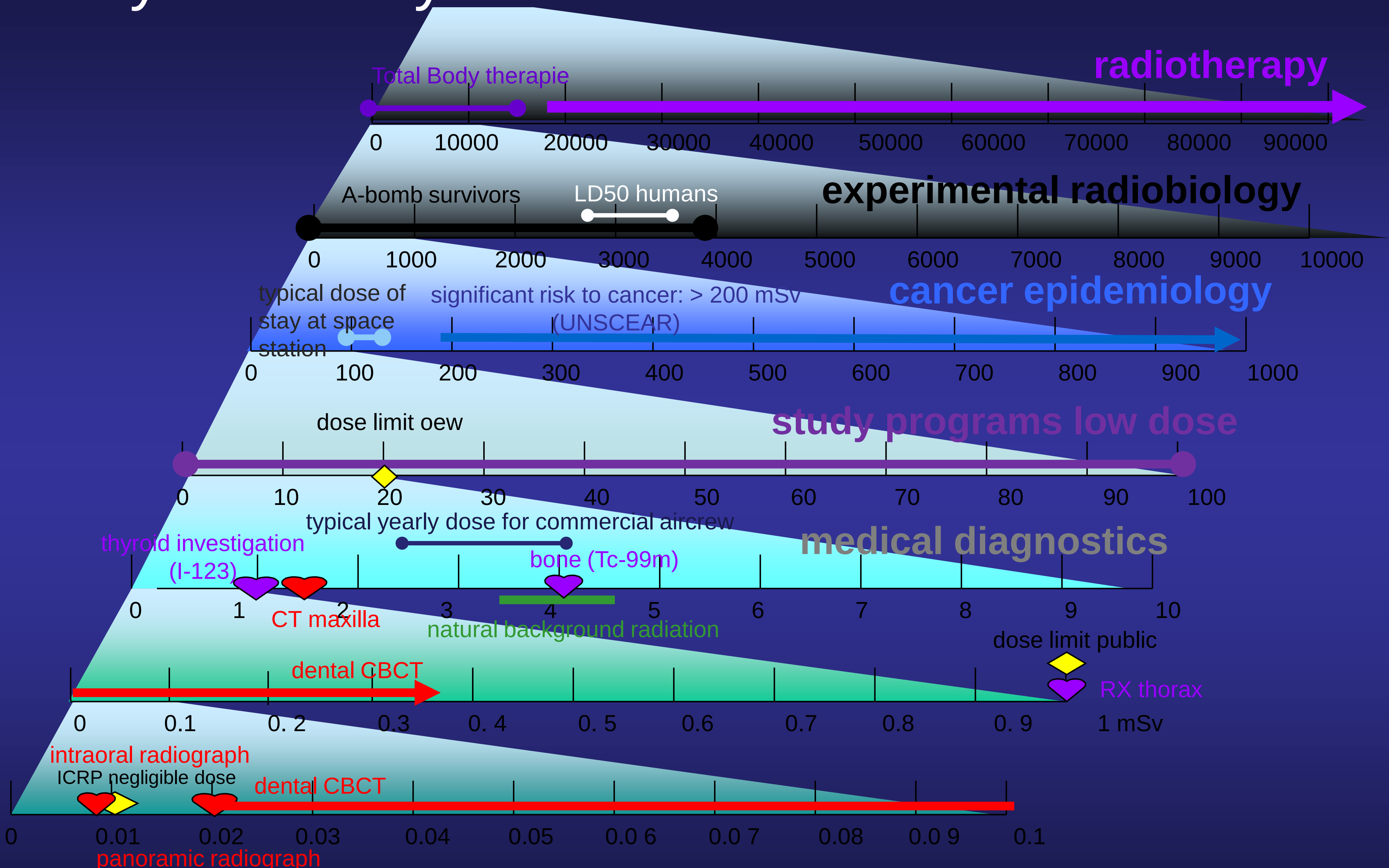



| Age group (years) | Multiplication factor for risk |
|---|---|
| <10 | x 3 |
| 10-20 | x 2 |
| 20-30 | x 1.5 |
| 30-50 | x 0.5 |
| 50-80 | x 0.3 |
| 80+ | negligible risk |

Multiplication factor at 30 years = 1

* Derived from International Commission on Radiation Protection Recommendations.[16]

# Why dosimetry? Effective dose ranges and dental investigations



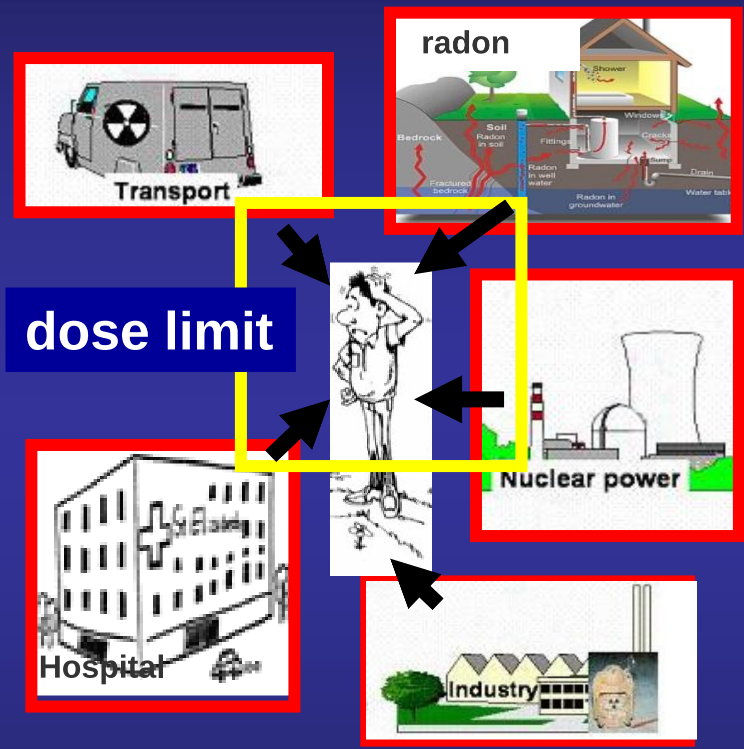

SEDENTEXCT

Workshop on dental Cone Beam CT

# Why dosimetry?

**The ICRP basis for radiation protection: patient and personnel protection policy**

European Directive 97/43 Euratom



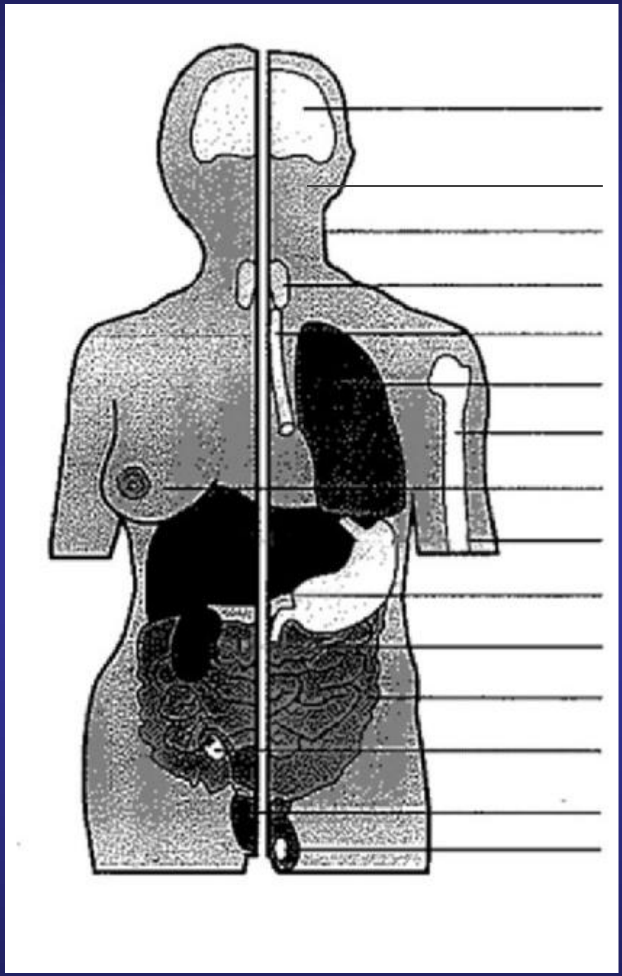


ALARA

Basic principles: 'individual related' ICRP 60
vs 'source related' ICRP 103

# Why dosimetry?

## Patient dose and technical dose characterization

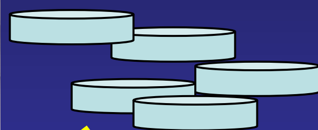


| | $w_T$ value ICRP103 |
|---|---|
| ***Brain*** | 0.01 |
| ***Salivary glands*** | 0.01 |
| ***Skin*** | 0.01 |
| ***Thyroid*** | 0.04 |
| Oesophagus | 0.04 |
| Lung | 0.12 |
| ***Red bone marrow*** | 0.12 |
| Breast | 0.12 |
| ***Bone surface*** | 0.01 |
| Liver | 0.04 |
| Stomach | 0.12 |
| Colon | 0.12 |
| Ovary | 0.08 |
| Bladder | 0.04 |
| Testes | 0.08 |
| ***Remainder*** | 0.12 |

- effective dose
- skin dose

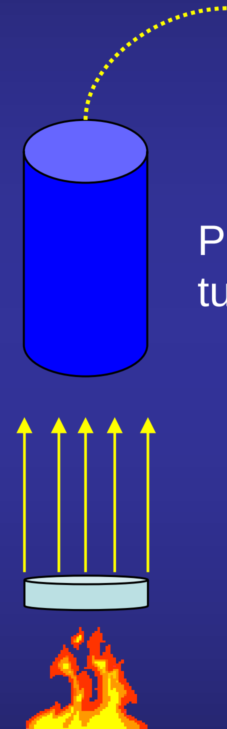
# Why dosimetry?

## Patient dose and technical dose characterization



TLDs exposed in the phantom. X-ray energy stored


Individually loaded into TLD reader



Photomultiplier tube detects light

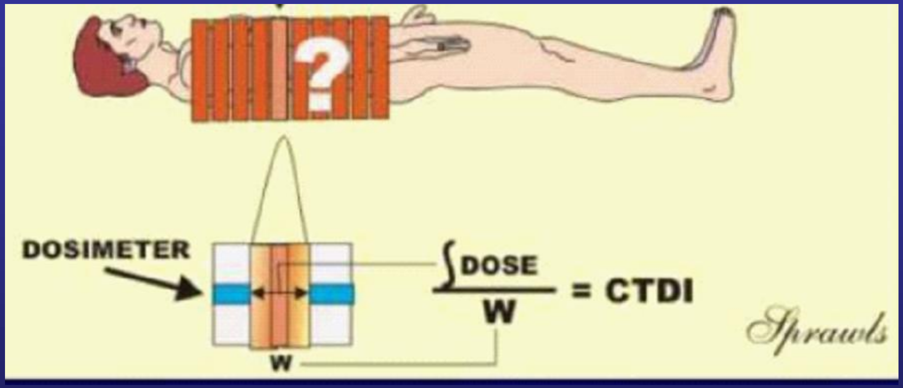
Energy released as light when heated

# Why dosimetry?

Patient dose and technical dose characterization

- effective dose is influenced by technical parameters as mAs and FOV
- definition of standard dose index that can be measured in a physical phantom during a routine medical physics quality control check
- candidates:
  - cfr. medical CT: Computed Tomography Dose Index, $CTDI_w$
    DLP (Dose Length Product)
    DAP

CTDI



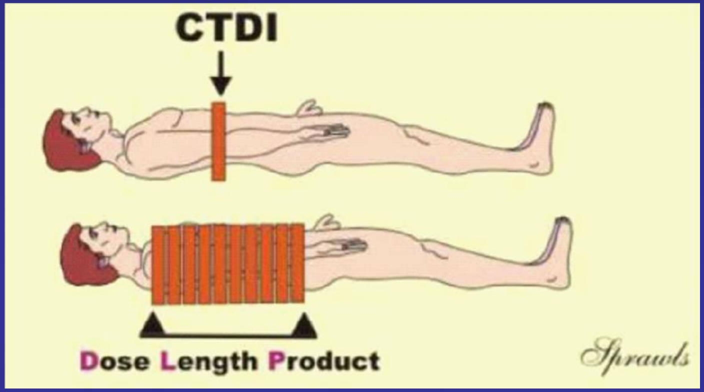

$$CTDI_{100} = \frac{1}{T}\int_{-50mm}^{50mm} D_a(z)dz$$

# Why dosimetry?

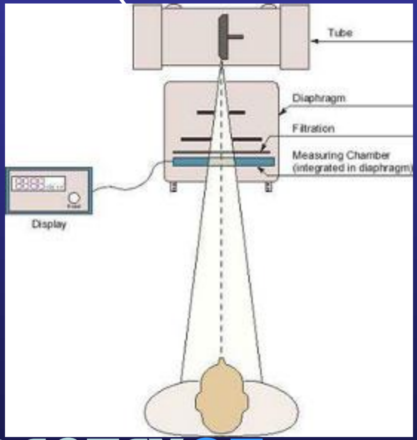
CTDI$_w$

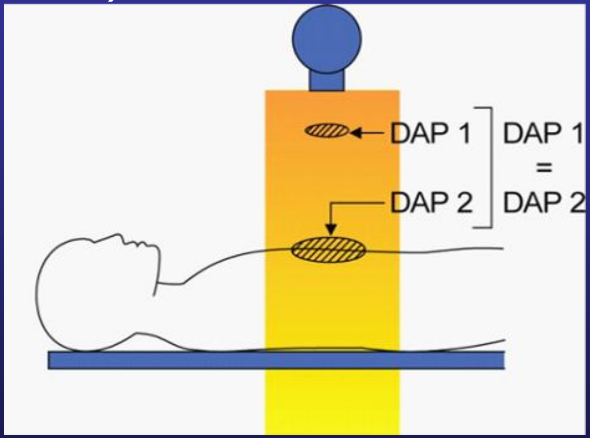
$$CTDI_w = \frac{1}{3}CTDI_{100}^{central} + \frac{2}{3}CTDI_{100}^{peripheral}.$$

DLP




DAP (Dose Area Product)




# Why dosimetry?

- determine conversion factors between technical quantities and effective dose:

the more dose determining factors that are included in the dose index, the more uniform the conversion factors will be:

dose conversion factors from mAs to effective dose will be different for different CBCTs and imaging protocols

dose conversion factors from a dose index including the influence of both mAs and FOV can possibly be the same for different CBCTs and imaging protocols

# Why dosimetry?

## Available knowledge at the start of SEDENTEXCT

- Few dosimetric studies

  ≠ anthropomorphic phantoms

  ≠ TLDs

  Limited number of TLDs & CBCT devices

- Few studies investigating CTDI and alternative indices for modern MSCT scanners
- No dose simulation studies for dental CBCT
- No reports on scattered dose in dental CBCT

# SEDENTEXCT dosimetry

KUL Leuven, UNIMAN Manchester, NKUA Athens, VU Vilnius, MAHOD Malmö, LTO Leeds

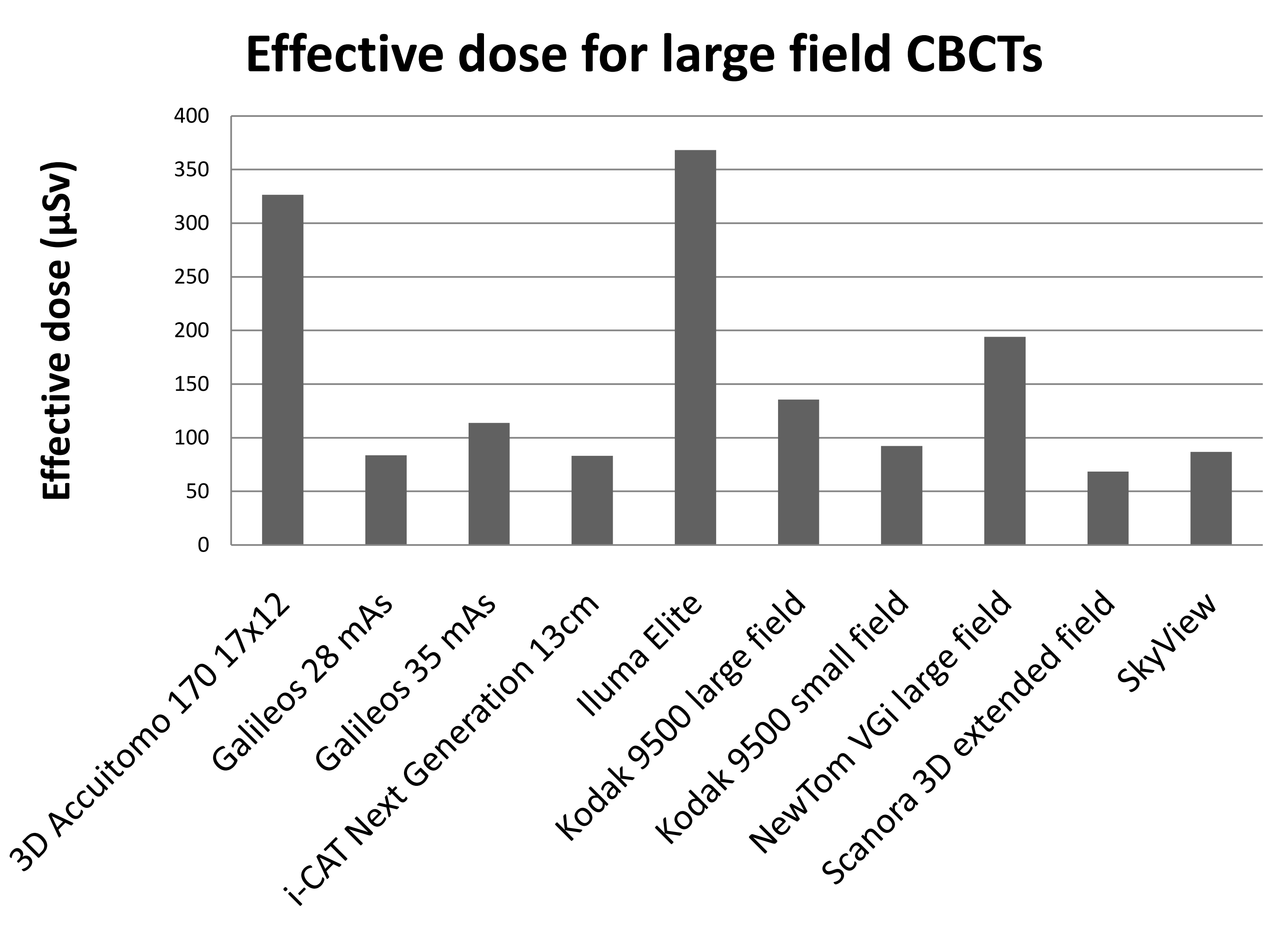
- Dental CBCT dose index
- Assessment of dental CBCT dose (adult & paediatric phantom, patients)
- Monte Carlo simulation framework for optimisation
- Personnel dose

# Measurement of the dose distribution in anatomical phantoms and subsequent calculation of effective dose

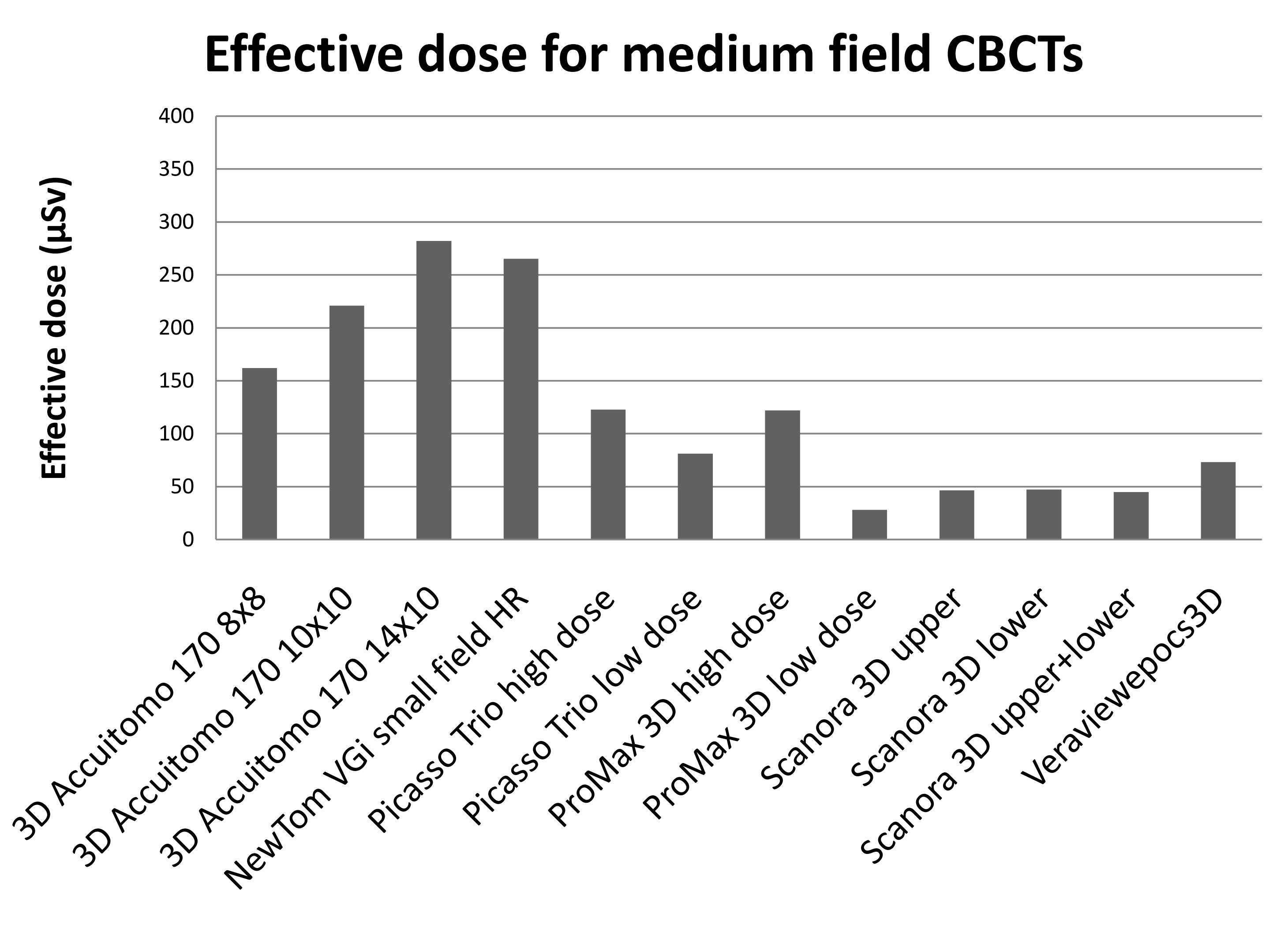
# Phantom dose

## Adult (Alderson) and paediatric (ATOM) phantoms

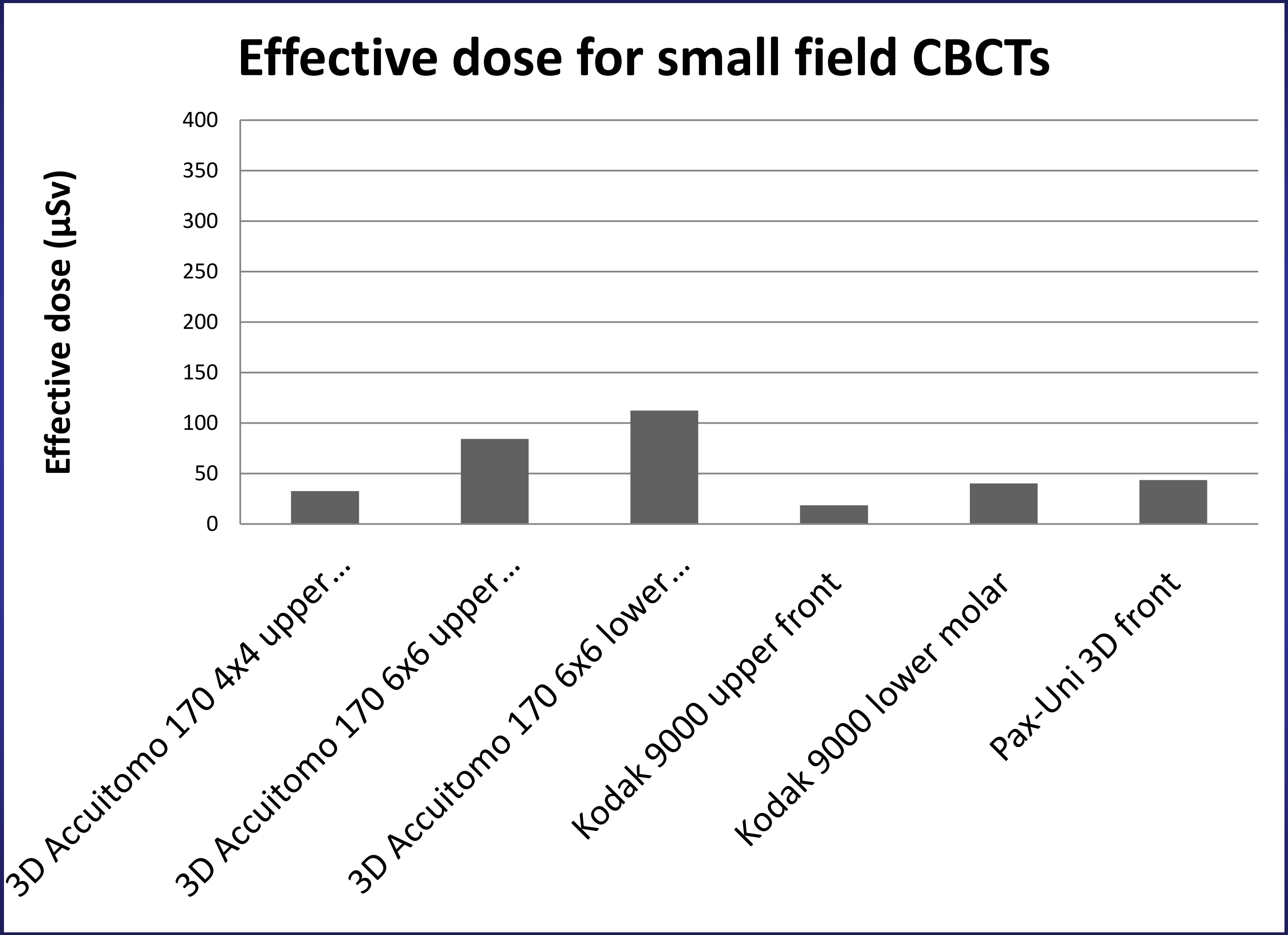

# Phantom dose: adult



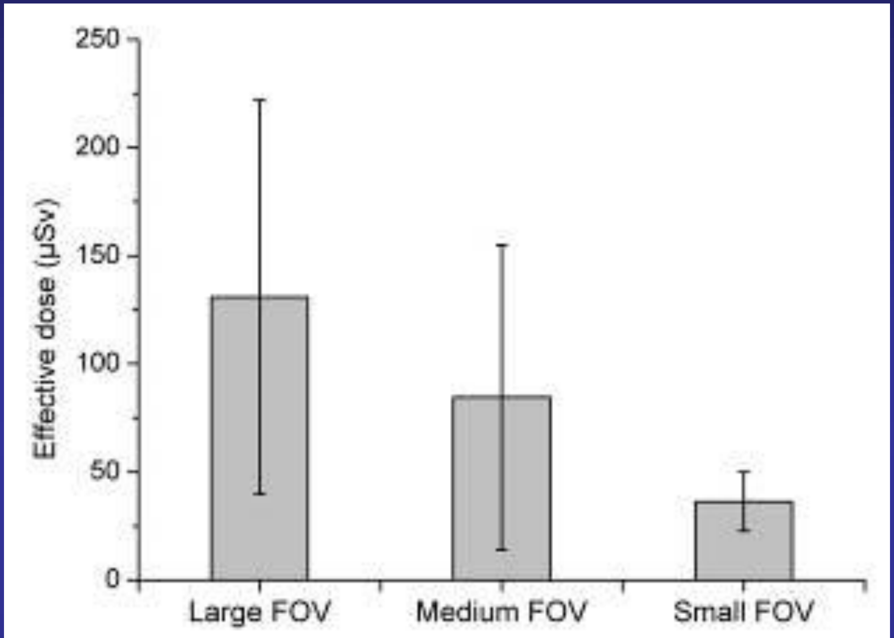
# Phantom dose: adult

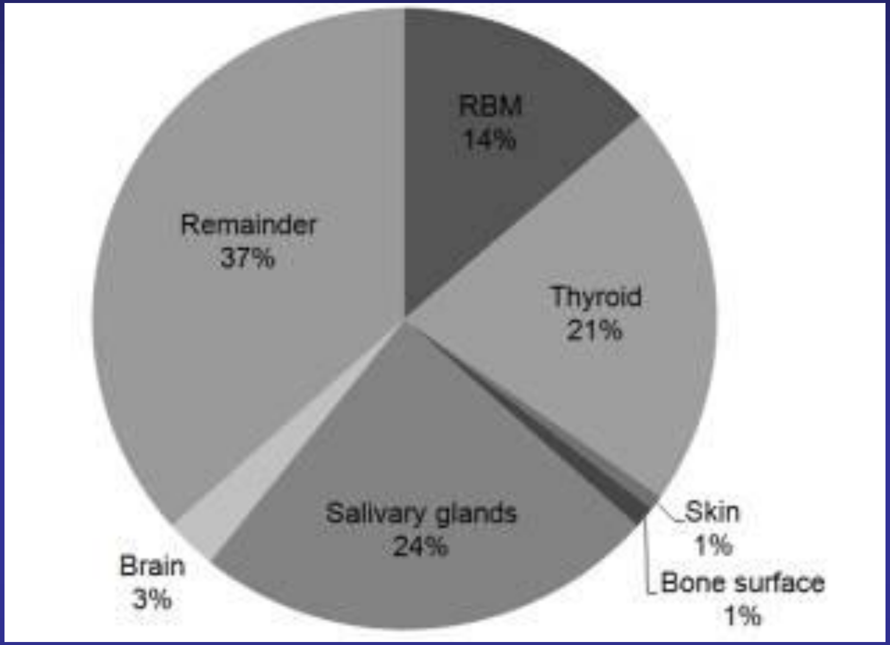


# Phantom dose: adult

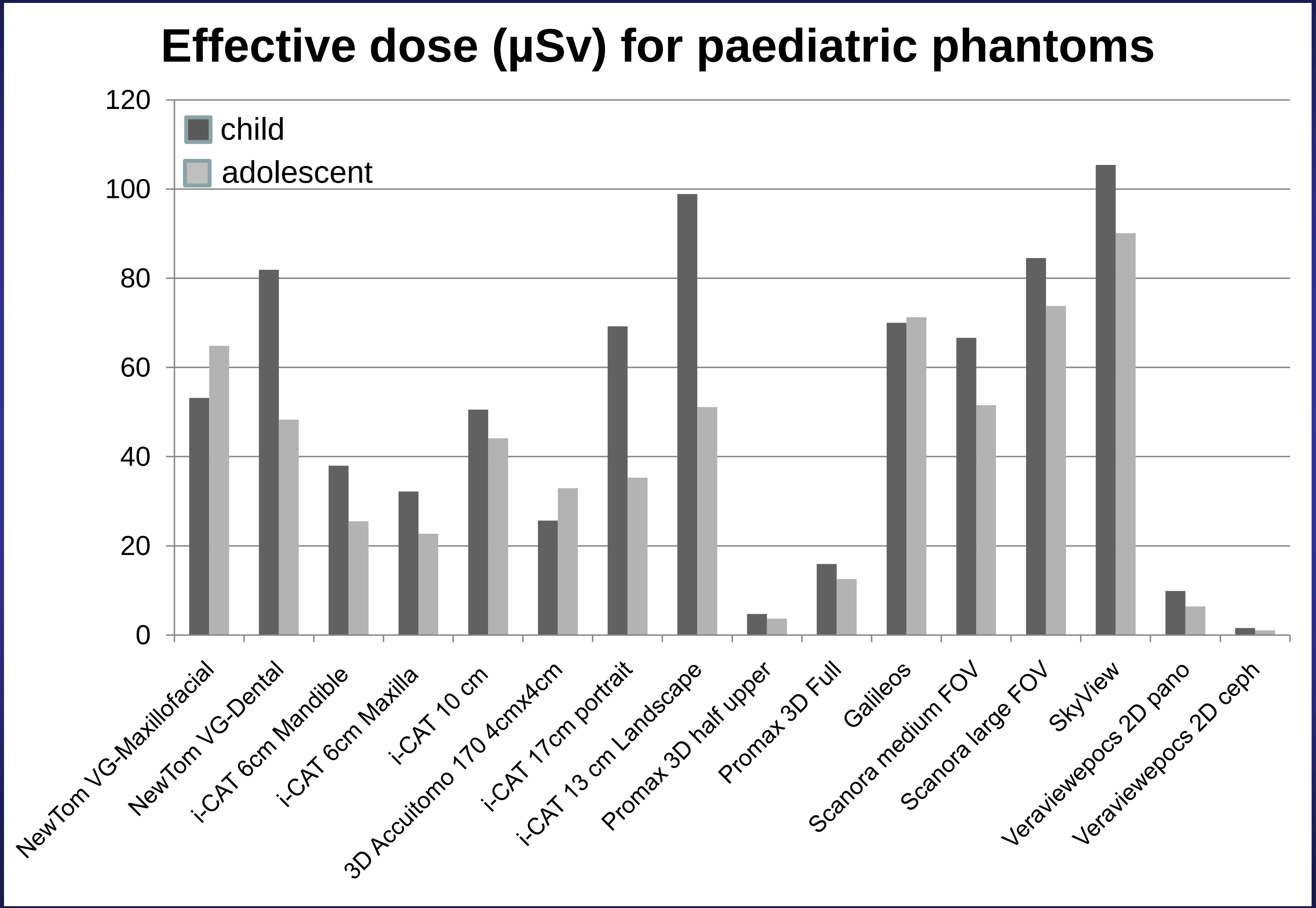


# Phantom dose: adult



# Phantom dose: paediatric



# Conclusions

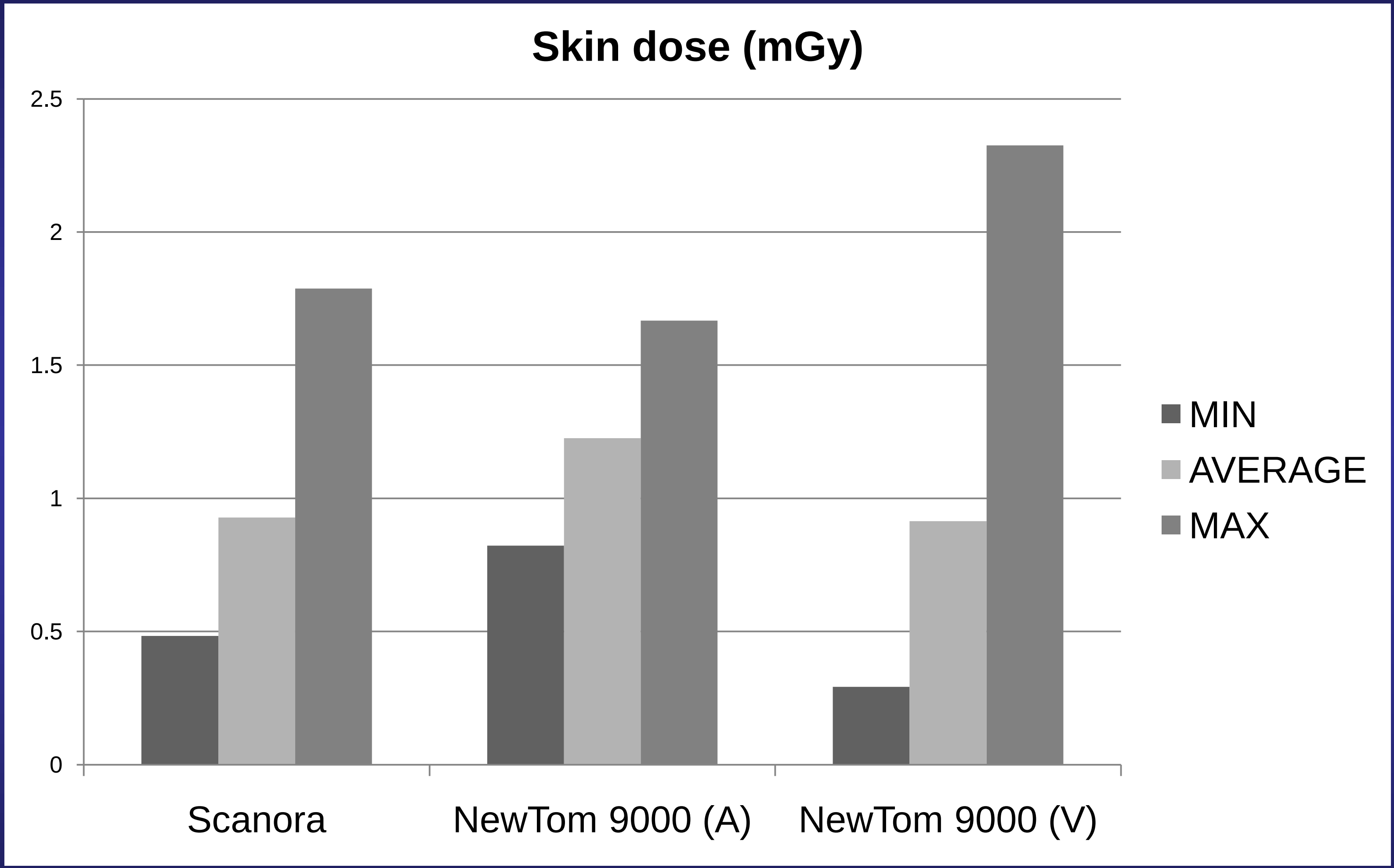
- Wide dose range (~20 μSv to 400 μSv: 20-fold)
- Main contributors: thyroid gland, salivary glands, ‘remainder’ (oral mucosa, extrathoracic airways)
- Clear effect of FOV size & position on effective dose
- Other differences between doses: interplay with image quality!
- Optimised (“customised”) patient dose: FOV selection based on region of interest + exposure selection based on image quality requirement

# In vivo dose measurements

# In vivo dose

| | KUL<br>Scanora 3D | | VU<br>NewTom 9000 | | NKUA<br>NewTom 9000 | |
|---|---|---|---|---|---|---|
| **Clinical indication** | **# Patients** | **Age** | **# Patients** | **Age** | **# Patients** | **Age** |
| Implant placement | 43 | 13-61 | 30 | 20-68 | 15 | 28-62 |
| Orthodontic planning | 4 | 10-13 | 0 | / | 1 | 13 |
| Impacted teeth | 8 | 10-20 | 43 | 10-83 | 10 | 18-33 |
| Maxillofacial trauma/ tumors/ development abnormalities | 1 | 20 | 29 | 11-49 | 0 | / |
| Sinus visualisation | 4 | 35-60 | 42 | 22-76 | 0 | / |
| Others | 10 | 10-54 | 0 | / | 8 | 24-62 |

# In vivo dose


Skin dose (mGy)
2.5
2
1.5
1
0.5
0
MIN
AVERAGE
MAX
Scanora
NewTom 9000 (A)
NewTom 9000 (V)

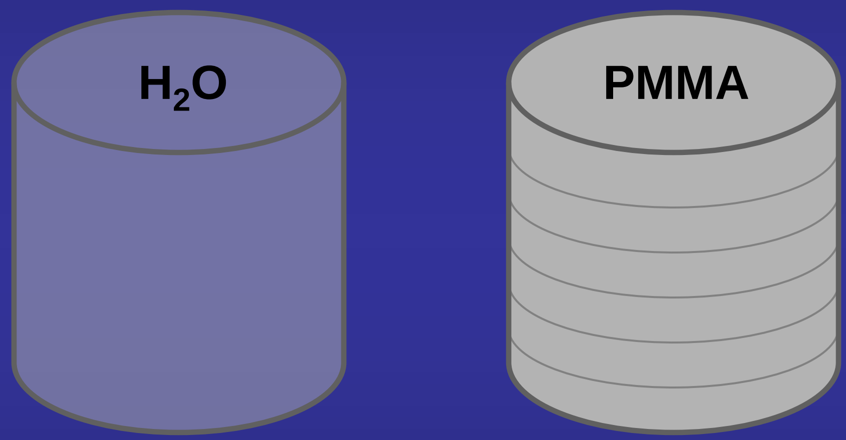
# Conclusions

- Wide range of in vivo doses due to difference in exposure and patient size
- Manual adjustment of exposure parameters ↔ Pre-set exposure protocols based on patient size ↔ Automatic exposure control

# Development of a standardised dose index to characterise dose distribution in dental CBCTs

# Dental CBCT dose index

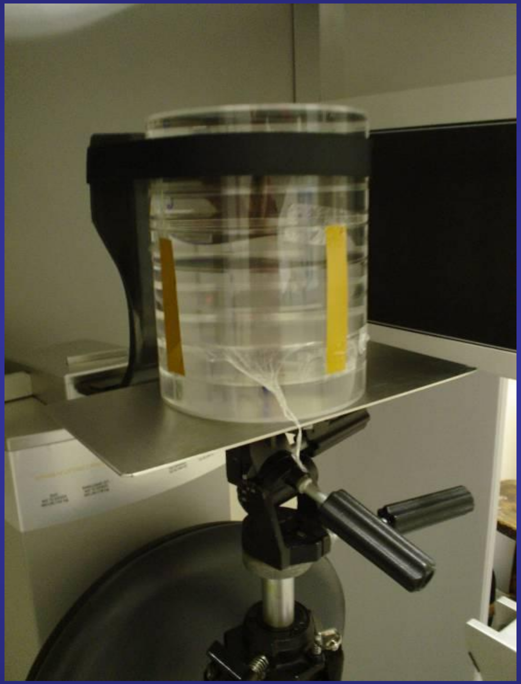
## Assessment of dose distribution




| KUL | UNIMAN & LTO |
|---|---|
| TLD<br>Ion chamber | TLD<br>Film |

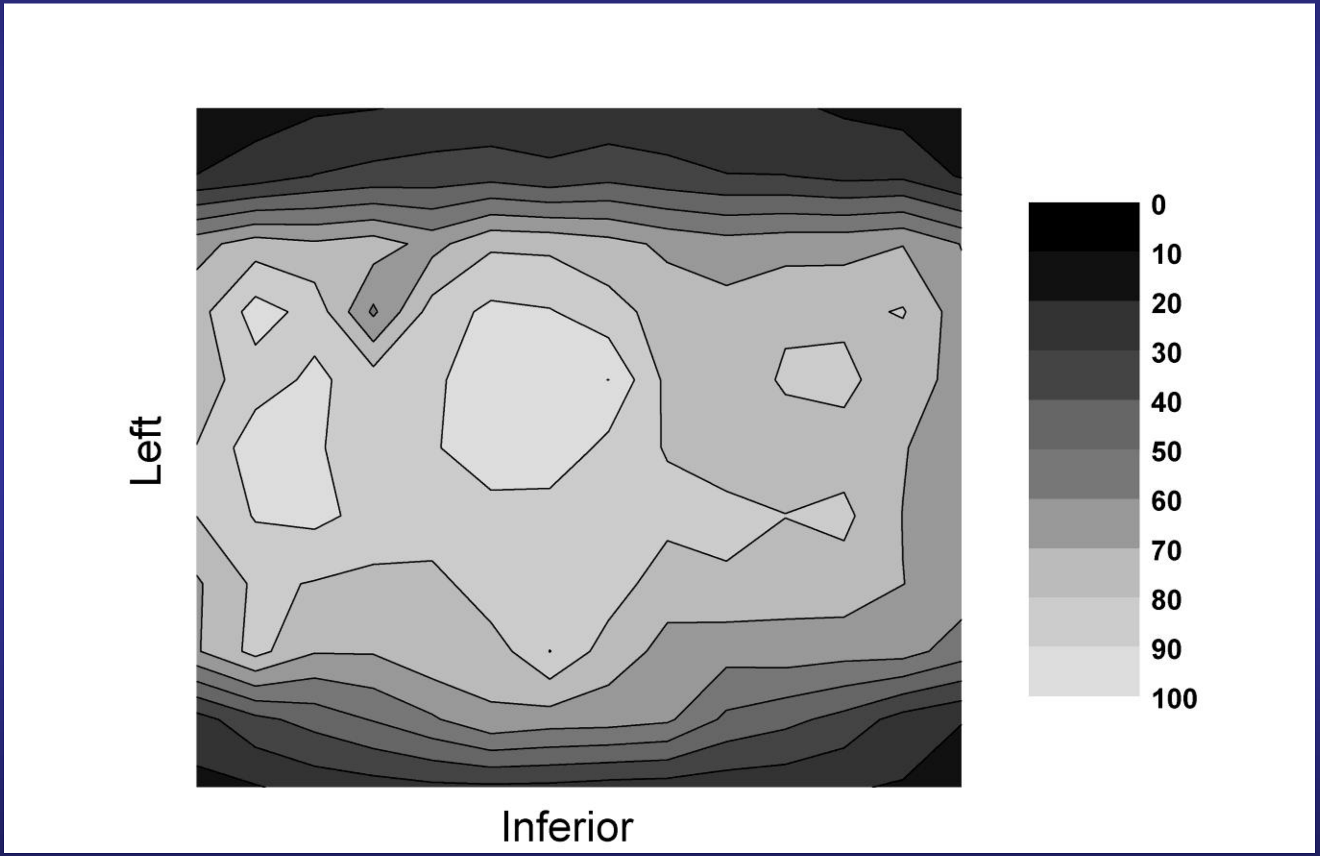
# Dental CBCT dose index

## Assessment of dose distribution



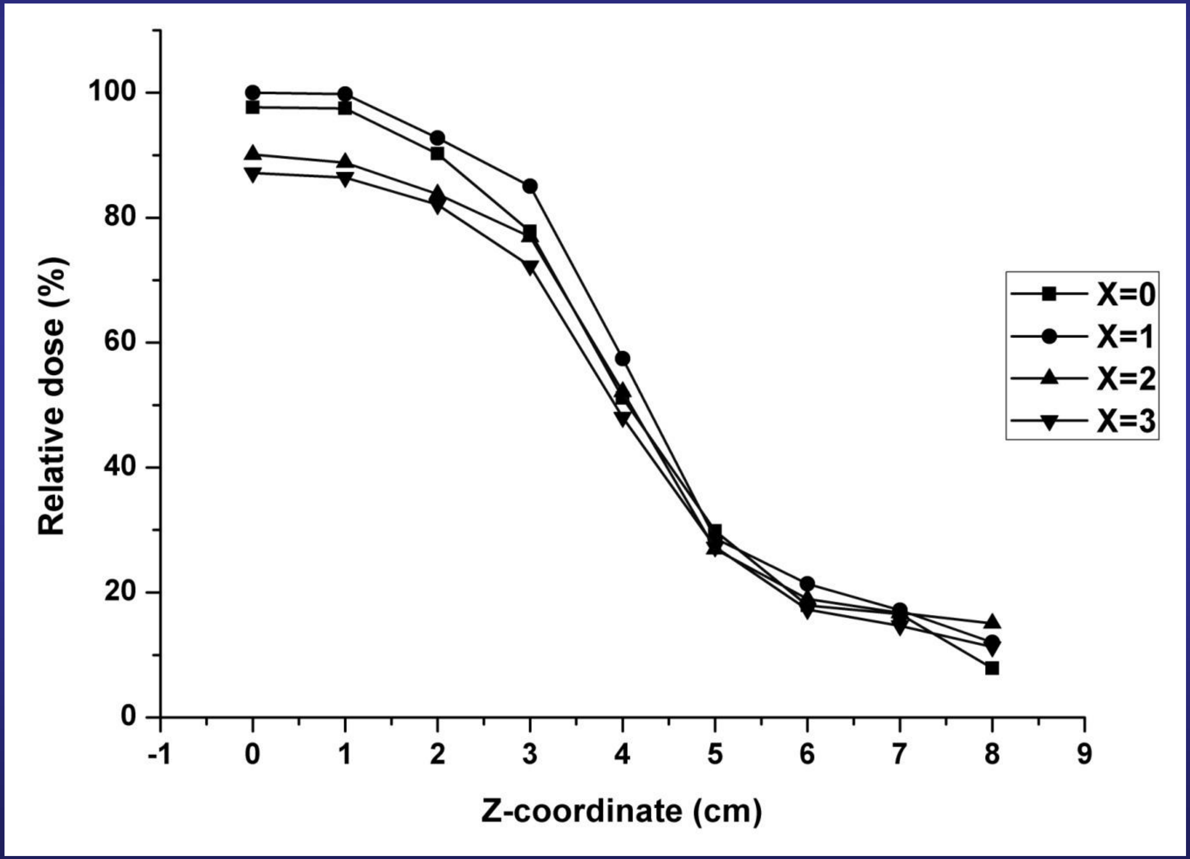
# Dental CBCT dose index

## Scanora 3D, TLDs in 'coronal' plane



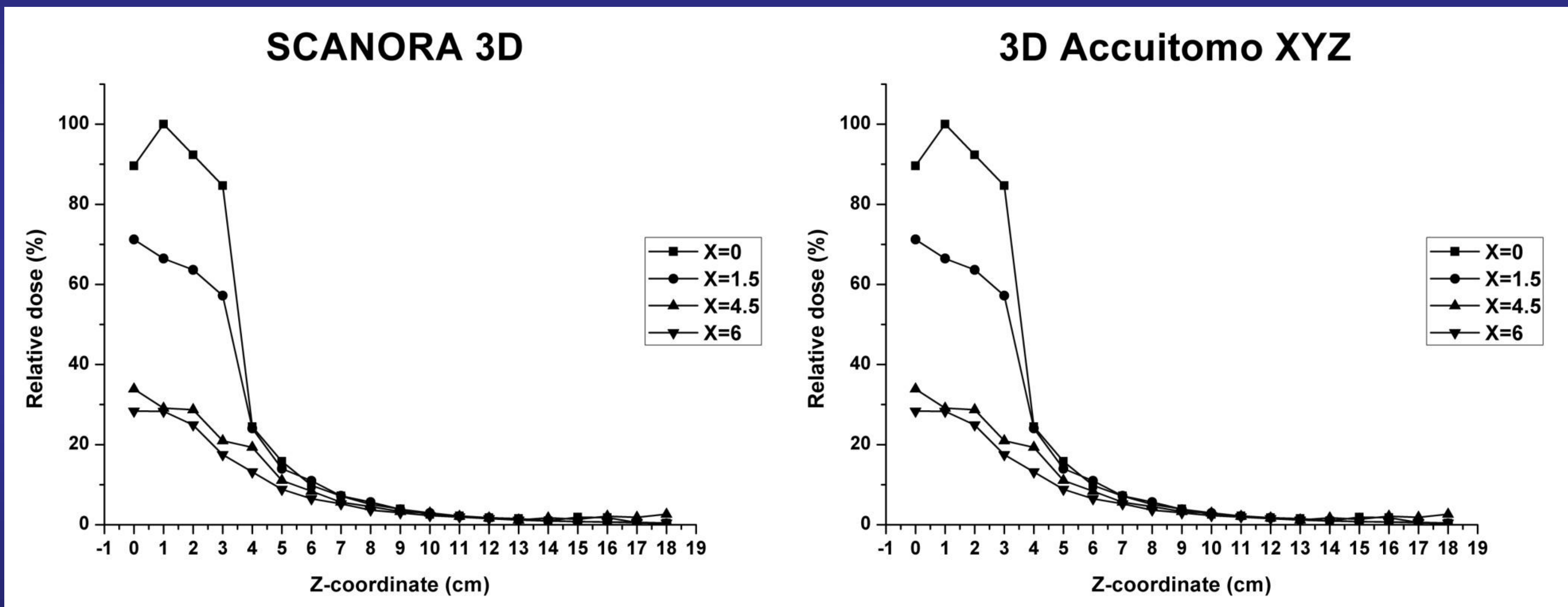
# Dental CBCT dose index

## Scanora 3D, ion chamber, along z-axis



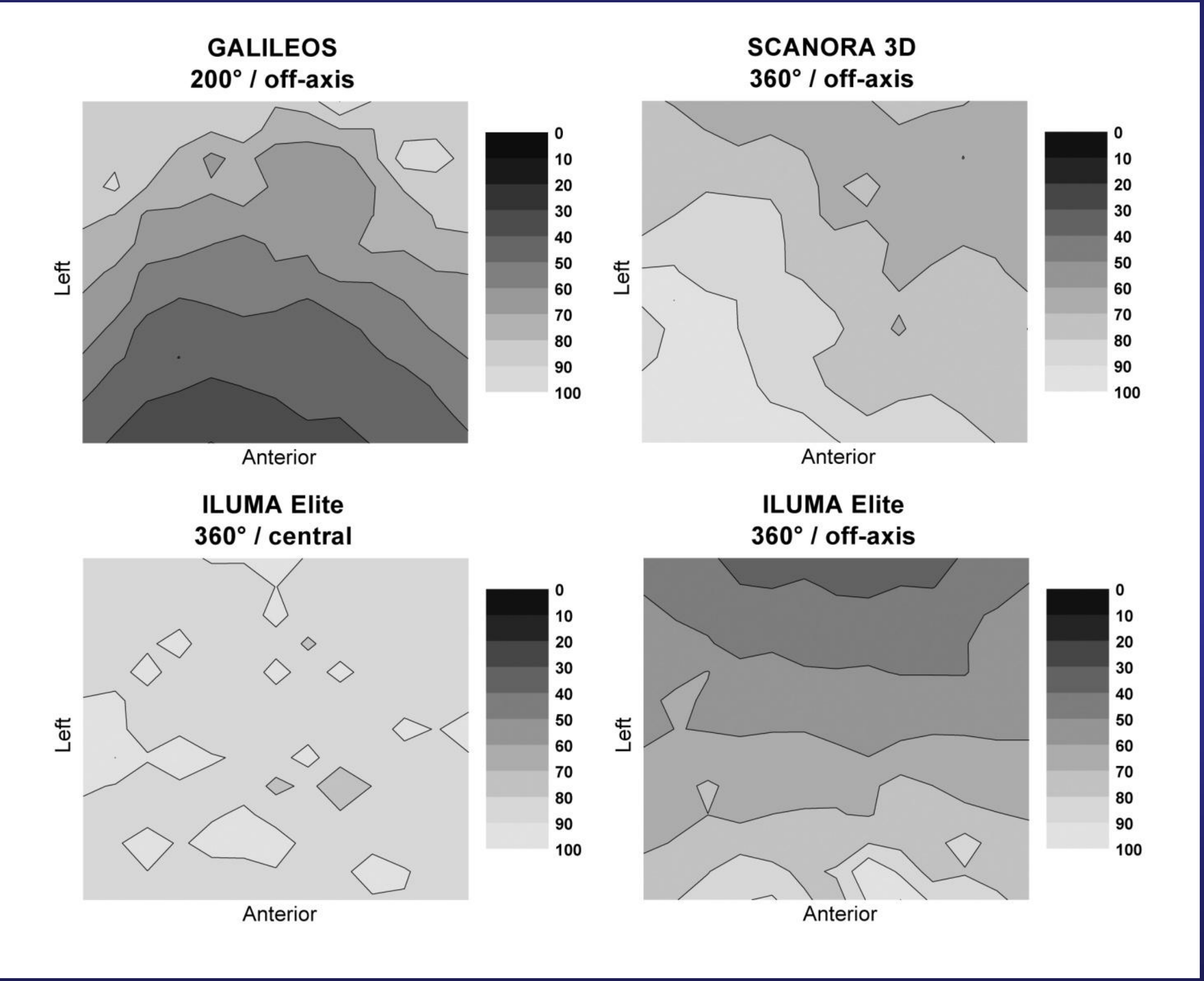
# Dental CBCT dose index

## TLDs, along z-axis



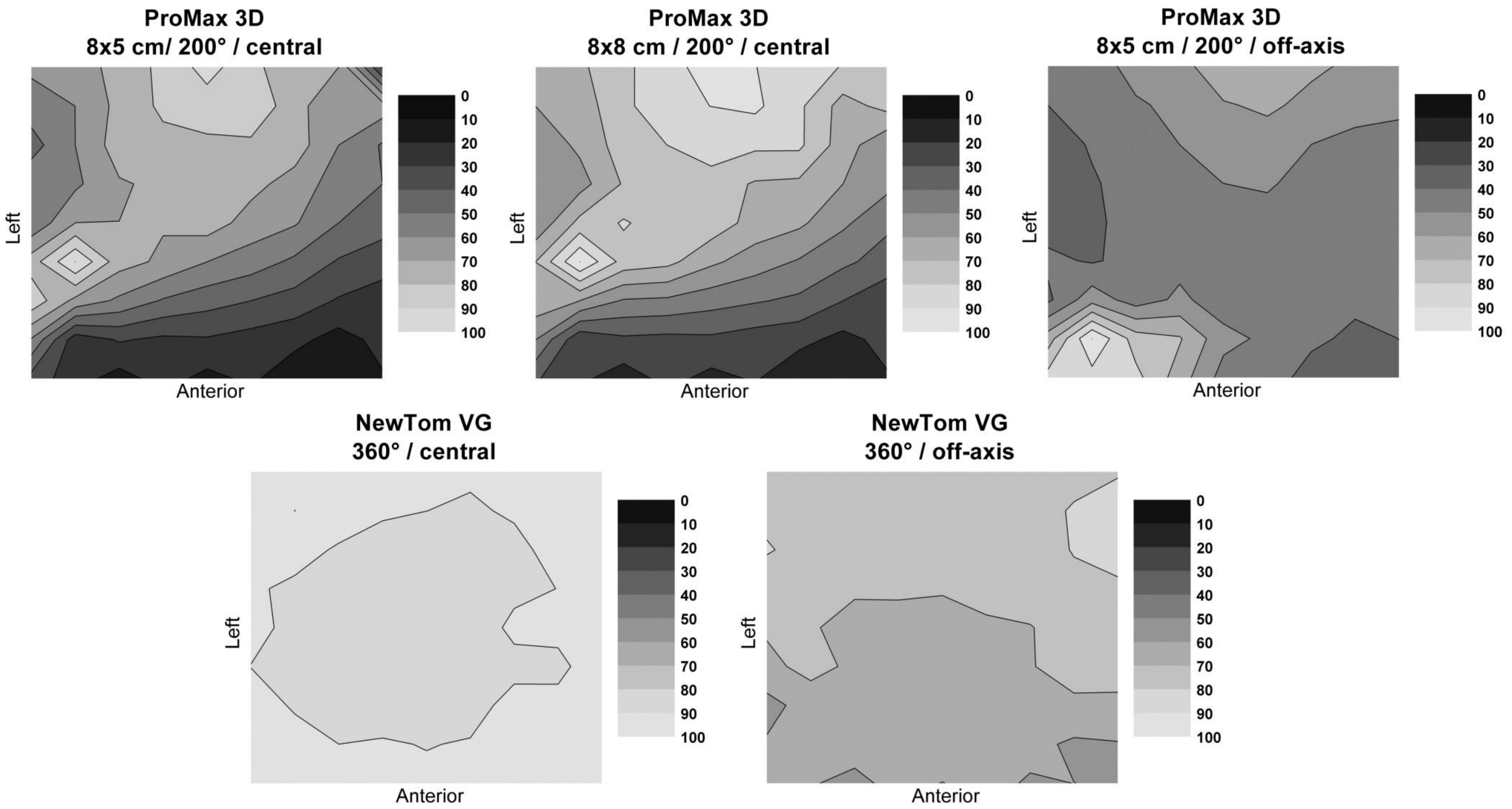
# Dental CBCT dose index

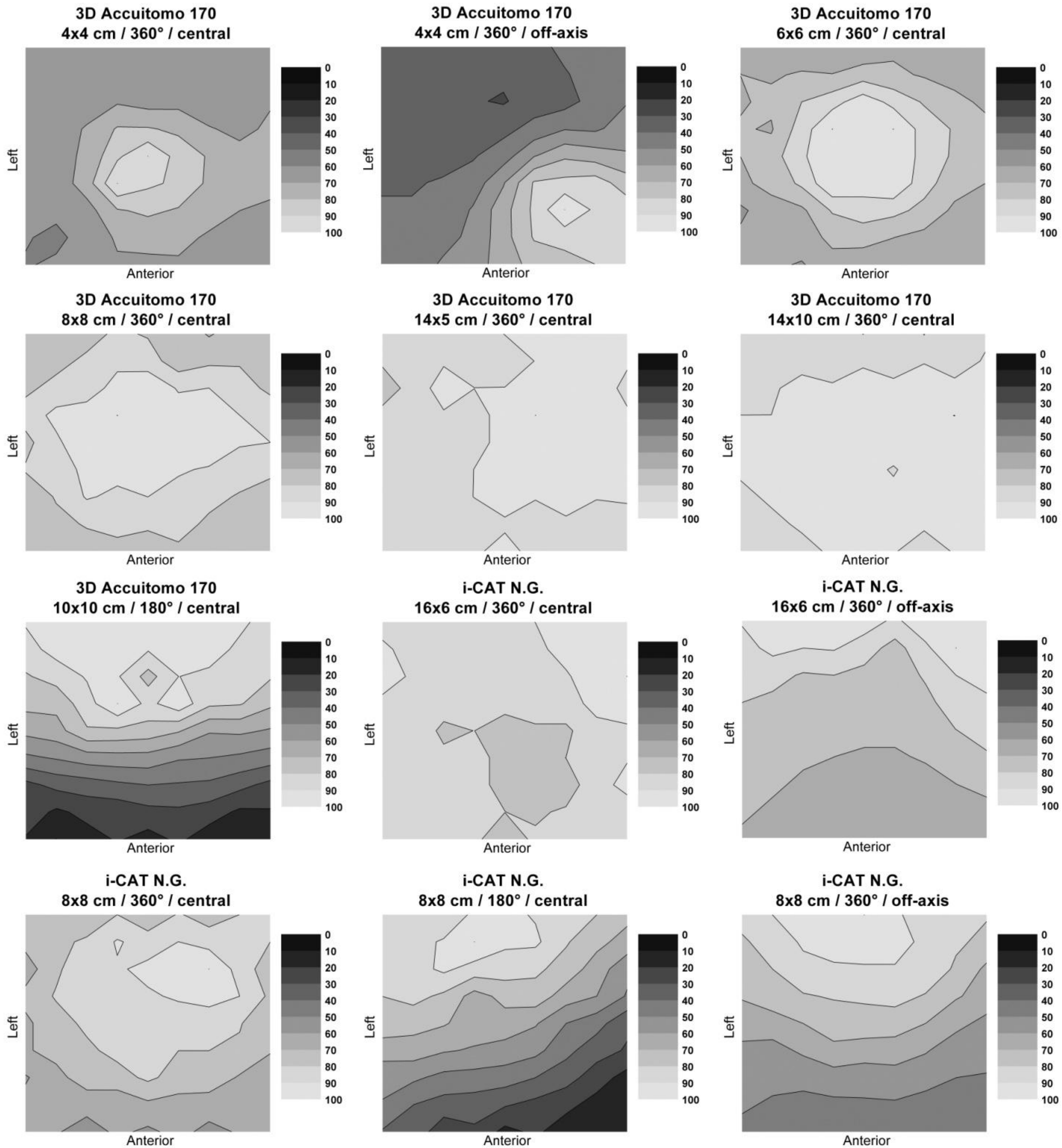
## TLDs, 'axial' plane




SEDENTEXCT

# Dental CBCT dose index



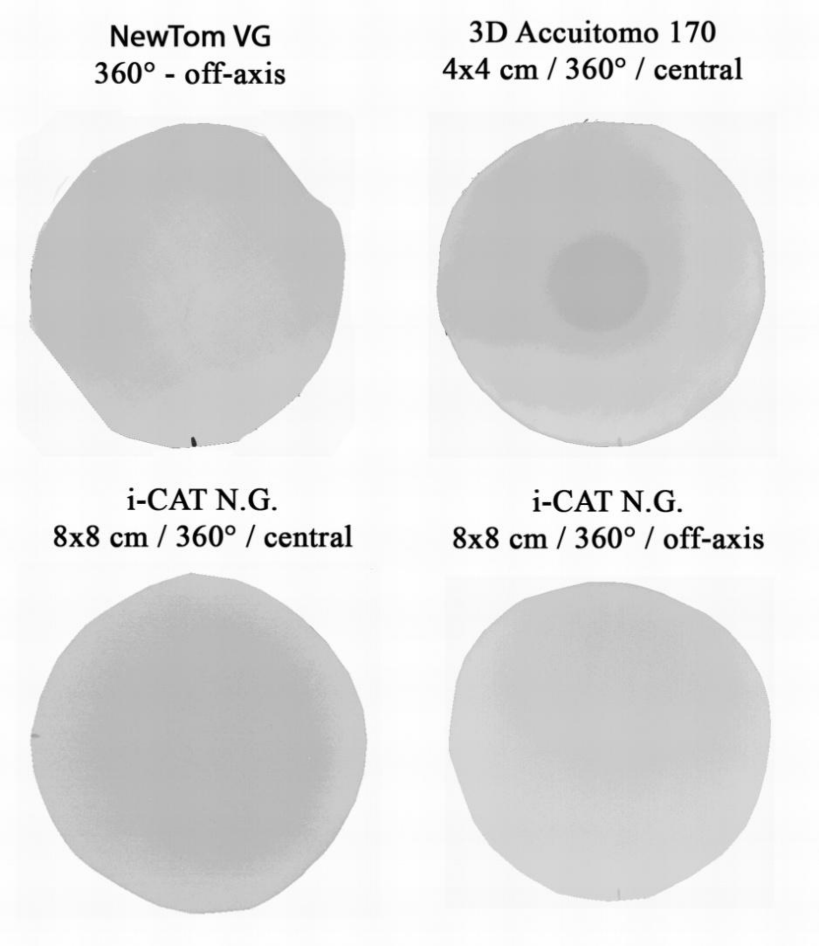

3D Accuitomo 170
4x4 cm / 360° / central
3D Accuitomo 170
4x4 cm / 360° / off-axis
3D Accuitomo 170
6x6 cm / 360° / central
3D Accuitomo 170
8x8 cm / 360° / central
3D Accuitomo 170
14x5 cm / 360° / central
3D Accuitomo 170
14x10 cm / 360° / central
3D Accuitomo 170
10x10 cm / 180° / central
i-CAT N.G.
16x6 cm / 360° / central
i-CAT N.G.
16x6 cm / 360° / off-axis
i-CAT N.G.
8x8 cm / 360° / central
i-CAT N.G.
8x8 cm / 180° / central
i-CAT N.G.
8x8 cm / 360° / off-axis
Left
Anterior
0
10
20
30
40
50
60
70
80
90
100

SEDEN

m CT

# Dental CBCT dose index

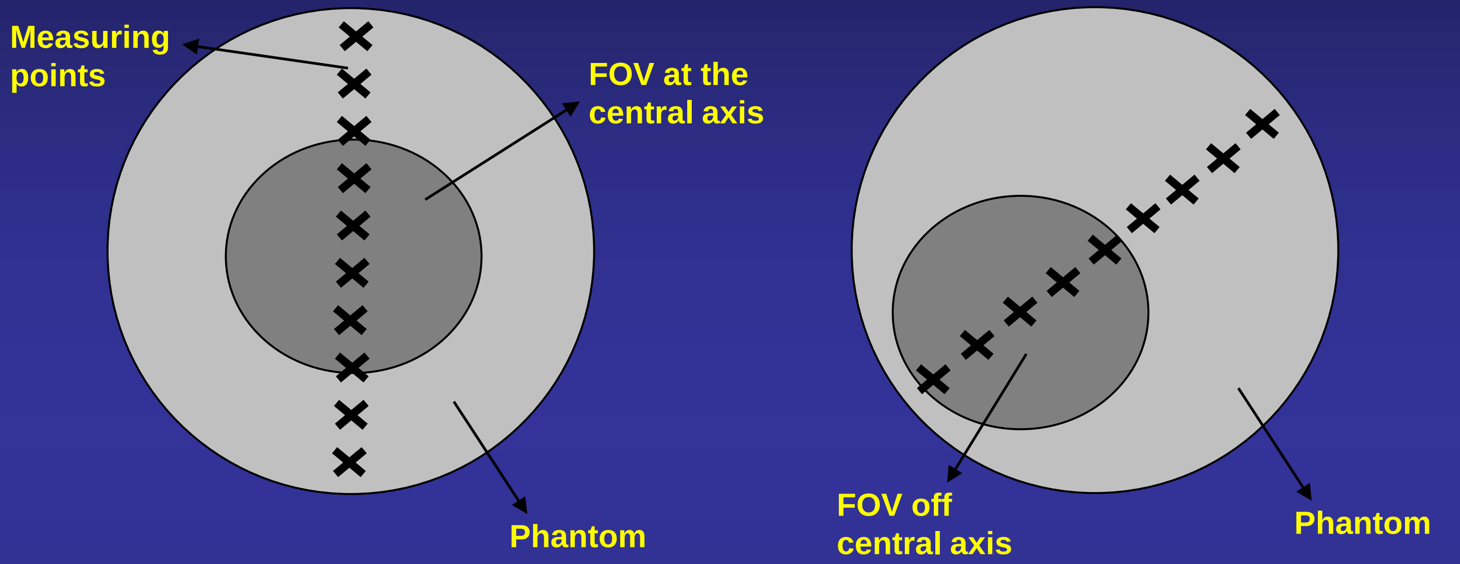
## Film measurements, ‘axial’ plane



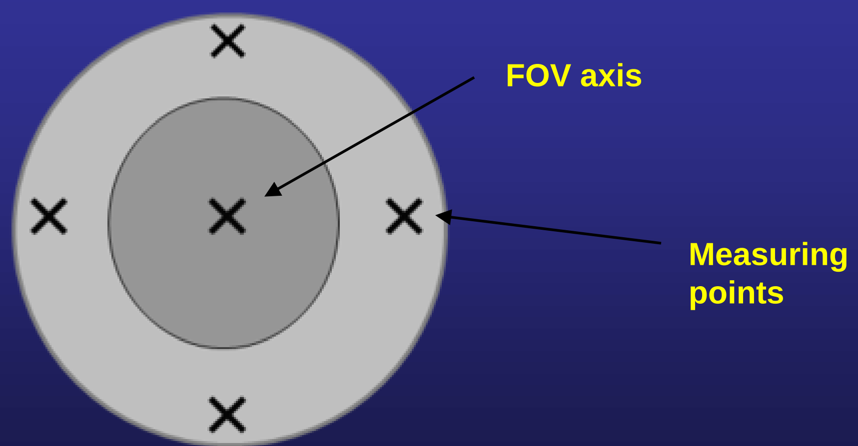
# Dental CBCT dose index

## Dose distribution → dose index definition

1




2

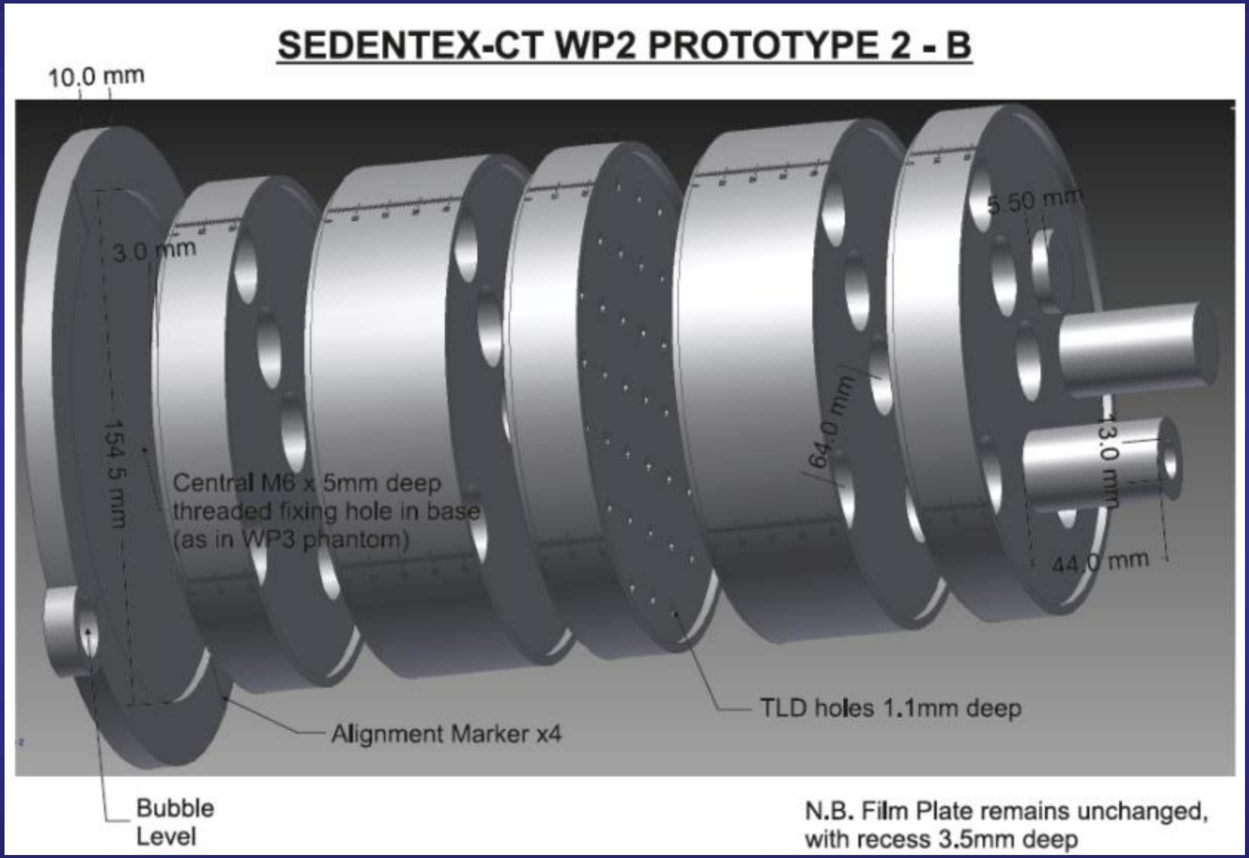


# Dental CBCT dose index

## Dose Area Product (DAP)?

# Dental CBCT dose index

## → Validation of indices




Leeds Test Objects Ltd

Dental CBCT dose index

→ Validation of indices

1) Measurement of indices in practice
2) Definition of correlation factors through Monte Carlo simulation

*Dose index measurements for the 3D Accuitomo 170*

| | Protocol | *Index1 (mGy)* AVG | STDEV | *Index 2 (mGy)* AVG |
|---|---|---|---|---|
| 17x12 | 90 kV, 5 mA, 17s, 360 | 8.8 | 0.4 | 8.8 |
| | 80 kV, 5 mA, 17s, 360 | 6.4 | 0.2 | 6.4 |
| | 70 kV, 5 mA, 17s, 360 | 4.3 | 0.2 | 4.3 |
| | 80 kV, 5 mA, 9s, 180 | 4.5 | 2.3 | 4.5 |
| 17x5 | 90 kV, 5 mA, 17s, 360 | 7.5 | 0.4 | 7.4 |
| 14x10 | 90 kV, 5 mA, 17s, 360 | 8.6 | 0.3 | 8.6 |
| 10x10 | 90 kV, 5 mA, 17s, 360 | 7.9 | 0.7 | 7.9 |
| | 90 kV, 5 mA, 17s, 360 | 7.4 | 2.4 | 7.3 |
| 8x8 | 90 kV, 5 mA, 17s, 360 | 6.4 | 2.3 | 6.5 |
| | 80 kV, 5 mA, 17s, 360 | 4.8 | 1.8 | 4.9 |
| | 70 kV, 5 mA, 17s, 360 | 3.3 | 1.3 | 3.4 |
| | 90 kV, 5 mA, 9s, 180 | 2.9 | 0.6 | 3.3 |
| | 80 kV, 5 mA, 9s, 180 | 2.2 | 0.5 | 2.5 |
| | 70 kV, 5 mA, 9s, 180 | 1.5 | 0.4 | 1.8 |
| 6x6 | 90 kV, 5 mA, 17s, 360 | 5.2 | 3.1 | 5.2 |
| | 80 kV, 5 mA, 17s, 360 | 4.0 | 2.4 | 3.9 |
| | 70 kV, 5 mA, 17s, 360 | 2.8 | 1.8 | 2.7 |
| | 90 kV, 5 mA, 9s, 180 | 2.1 | 0.2 | 2.7 |
| | 80 kV, 5 mA, 9s, 180 | 1.6 | 0.2 | 2.0 |
| | 70 kV, 5 mA, 9s, 180 | 1.1 | 0.1 | 1.4 |
| 4x4 | 90 kV, 5 mA, 17s, 360 | 3.4 | 3.0 | 3.7 |
| | 80 kV, 5 mA, 17s, 360 | 2.6 | 2.3 | 2.7 |
| | 70 kV, 5 mA, 17s, 360 | 1.9 | 1.7 | 1.9 |
| | 90 kV, 5 mA, 9s, 180 | 1.2 | 0.3 | 1.9 |
| | 80 kV, 5 mA, 9s, 180 | 0.9 | 0.2 | 1.4 |
| | 70 kV, 5 mA, 9s, 180 | 0.6 | 0.2 | 1.0 |

*Dose index measurements for the Scanora 3D*

| | Protocol | *Index1* (mGy) AVG | STDEV | *Index 2* (mGy) AVG |
|---|---|---|---|---|
| 14.5x7.5 | 24 mAs, central | 2.1 | 0.1 | 2.2 |
| 10x7.5 | 30 mAs, central | 2.2 | 0.1 | 2.3 |
| | 30 mAs, off-axis | 2.1 | 0.6 | 1.7 |
| 6x6 | 36 mAs, central | 1.8 | 0.4 | 2.0 |
| | 36 mAs, off-axis | 1.7 | 1.0 | 1.5 |

# Conclusions

- dose distributions in homogenous phantoms have been measured for different CBCTs and settings
- 2 CBCT dose indices have been proposed in addition to DAP
- validation measurements have been performed

# Development of mathematical models for dental CBCT dosimetry

# Monte Carlo simulations

- Development of computational models for dental CBCT dosimetry
- Calculation of conversion factors to effective dose using Monte Carlo (MC) simulations
- MC simulations are a class of computational algorithms that are based on repeated random sampling to compute the results
- MCNP5: a general purpose Monte Carlo N-Particle code

# Monte Carlo simulations

- Point sources with biased direction
- Arranged on a circle positioned at 10 degrees intervals
- A set of collimators to shape the beam
- ATOM 10 year old phantom
- ICRP male reference computational phantom
- ICRP female reference computational phantom (in progress)

# Monte Carlo simulations

→ Validation of the simulated CB geometry-Stage 1

- Simulated doses were compared against measured doses

    - PMMA cylinder on a 3D Accuitomo 170 CBCT scanner
    - Thermoluminescent dosimeters (<10% error)
    - Full and half rotation CB geometry
    - Range of tube voltages
    - Range of FOVs
    - Axis and off-axis

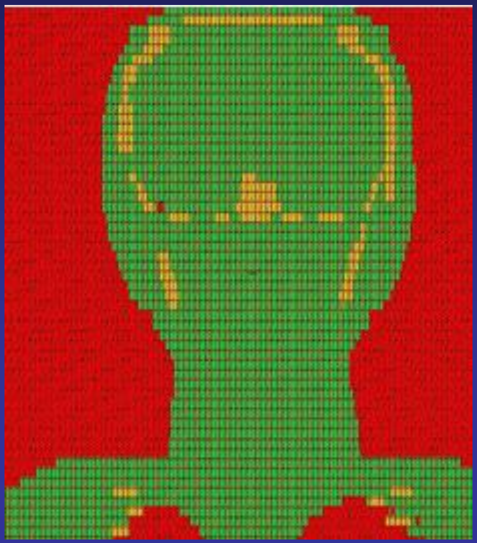
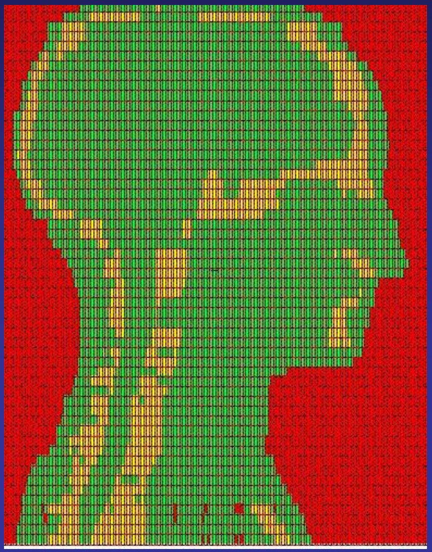
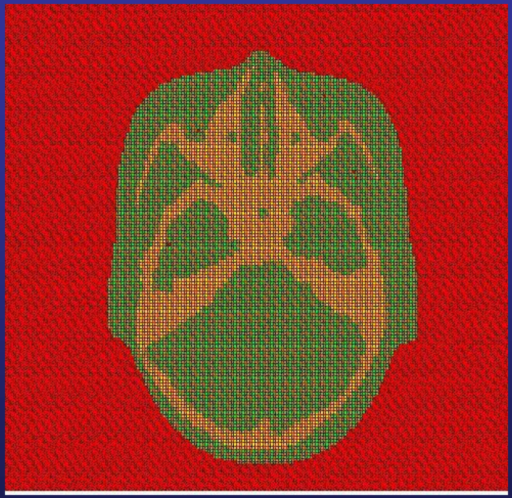
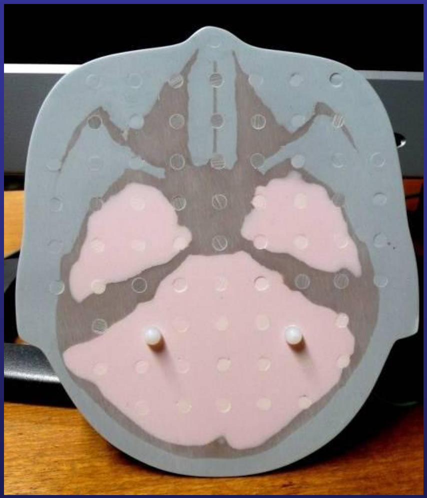
- % difference between simulated and measured normalised doses ranged between 7% to 19%

# Monte Carlo simulations

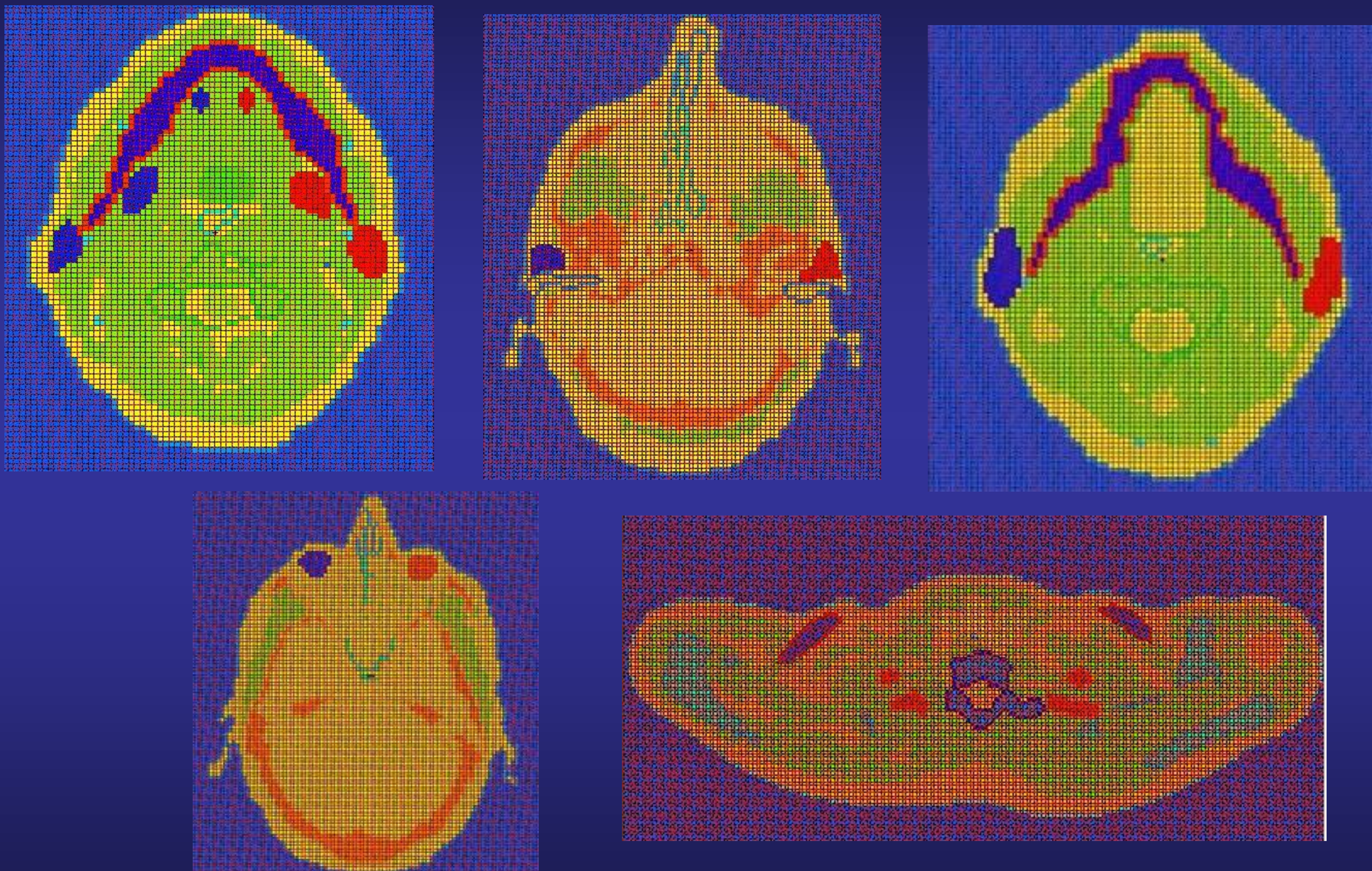
→ Validation of the simulated CB geometry-Stage 2

- Simulated doses were compared against measured doses
  - ATOM 10 year old anthropomorphic phantom
  - Thermoluminescent dosimeters (<10% error)
  - Range of CBCT machines
  - Range of FOVs
  - Range of clinical examinations
- % difference between simulated and measured effective doses ranged between 3% to 17%

# Monte Carlo simulations

# Monte Carlo simulations



# Monte Carlo simulations

## → Calculation of conversion factors (mSv/mAs)

- Three computational phantoms
- Range of FOVs, tube voltages, imaging protocols
- Range of machines
  - i-CAT NG
  - Kodak 9000 3D
  - Kodak 9500 3D
  - NewTom VG
  - NewTom VGi
  - NewTom 5G
  - NewTom QR DVT 9000
  - Galileos Comfort
  - Galileos Compact
  - 3D Accuitomo XYZ
  - 3D Accuitomo 170
  - Planmeca Promax 3D (in progress)
  - Planmeca Promax 3D Max (in progress)

# Monte Carlo simulations

| 3D Accuitomo 170- 10 year old phantom | | | |
|---|---|---|---|
| **Imaging protocol** | **Tube voltage** | **Rotation** | **Conversion factor** |
| 4Øcm x 4cm Maxillary Canine | 70/80/90 | 360 | 0.00028/0.00030/0.0.00031 |
| 10Øcm x 10cm | 70/80/90 | 360 | 0.00248/0.00255/0.00261 |
| 17Øcm x 5cm Mandible | 70/80/90 | 180 | 0.00252/0.00254/0.00256 |
| **i-CAT NG - ICRP male reference computation phantom** | | | |
| **Imaging protocol** | **Tube voltage** | **Rotation** | **Conversion factor** |
| 16Øcm x 6cm Maxilla | 120 | 360 | 0.00130 |
| 16Øcm x 6cm Mandible | 120 | 360 | 0.00189 |
| 16Øcm x 13cm Maxilla | 120 | 360 | 0.00299 |

# Conclusions

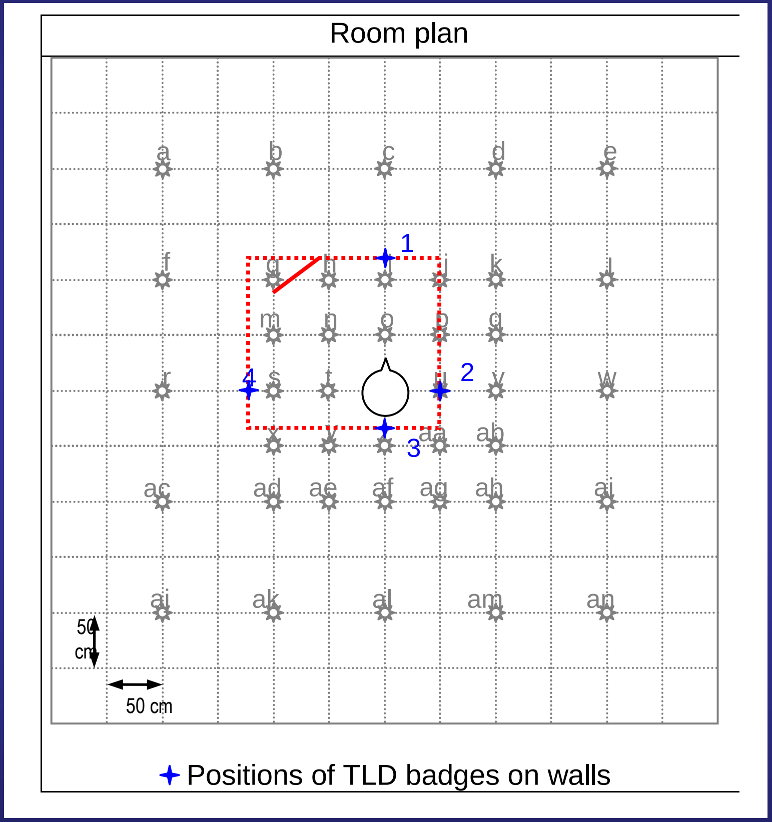
- a CBCT simulation model was set up and validated
- conversion factors from mAs to effective dose were calculated for a broad range of CBCTs
- relation between dose indices 1 and 2 and effective dose has been established but needs further elaboration
- the relationship with DAP needs to be stablished

# Measurements of scatter dose and radiation protection of personnel and helpers

# Personnel dose

## Protocol

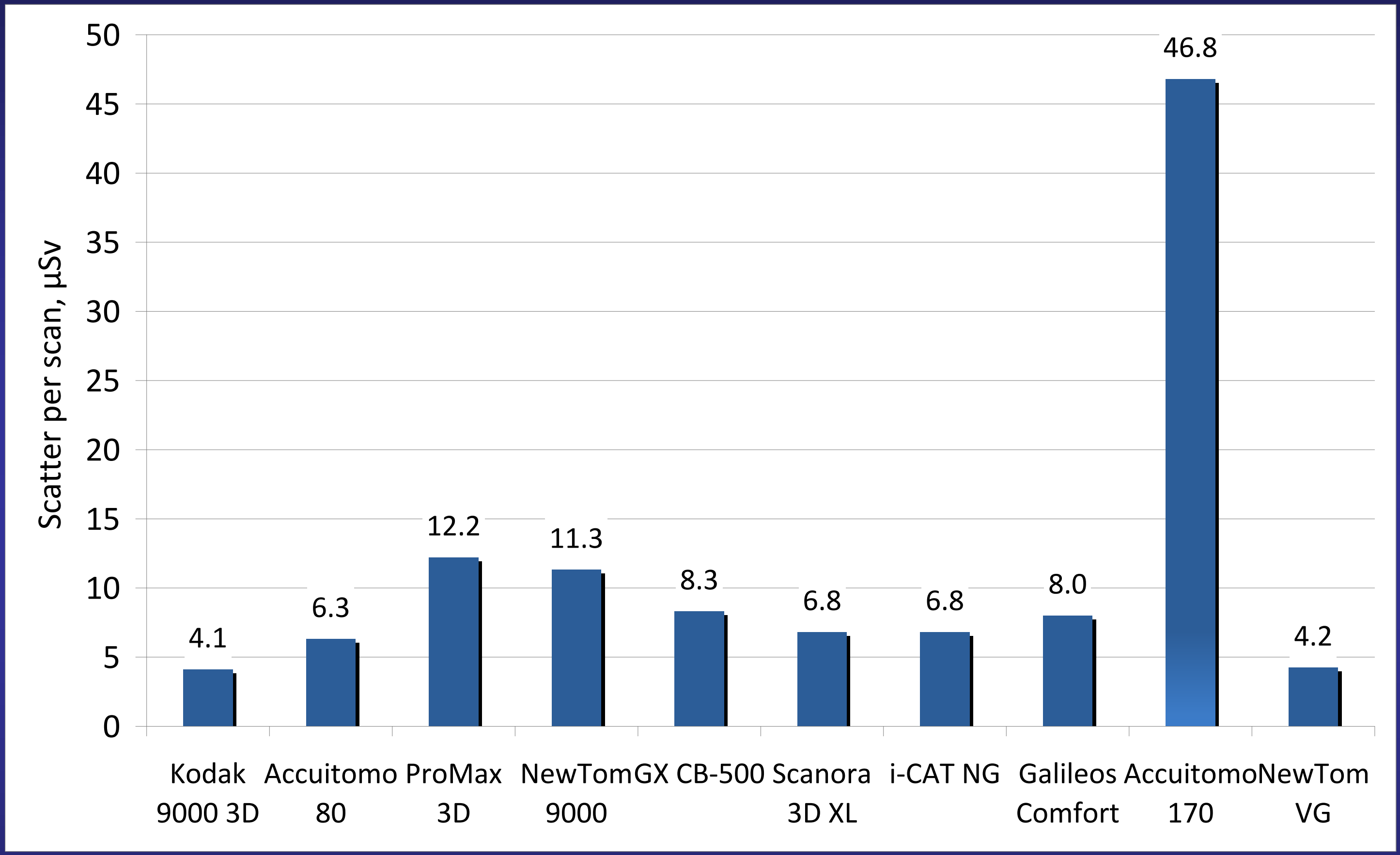
- Active measurements
  - Using ionisation chamber or dose rate meter
  - On standard measurement grid
- Passive dosimetry
  - High sensitivity TLD badges
  - In rooms where CBCT is sole X-ray source



# Personnel dose

| Model | Manufacturer | Active measurements | Passive measurements |
|---|---|---|---|
| Kodak 9000 3D | Kodak | ✓ | |
| Accuitomo 80 | J. Morita | ✓ | ✓ |
| ProMax 3D | Planmeca | ✓ | |
| NewTom 9000 | QR | ✓ | ✓ |
| GX CB-500 | Gendex | ✓ | |
| Scanora 3D XL | Soredex | ✓ | ✓ |
| i-CAT NG | Imaging Sciences International | ✓ | |
| Galileos Comfort | Sirona | ✓ | |
| Accuitomo 170 | J. Morita | ✓ | ✓ |
| NewTom VG | QR | ✓* | |

# Personnel dose




Active

# Shielding requirements

- For small FOVs, low workload and low occupancy of adjacent areas, additional shielding may not be required
- In most circumstances, 0.5-1.5mm Pb equivalence is required dependent on:
  - Average scatter per scan
  - Distance
  - Workload
  - Dose constraint

Personnel dose

# Conclusions

- Max scatter varies 4.1 to 46.8 μSv per scan
- Distance unlikely to be sufficient protection, shielding required up to about 1.5mm lead
- Advice of a qualified expert required
- Base calculations on maximum scatter and double expected workload
- Manufacturers should provide scatter data
- Keep scatter and workload under review
- Further work needed on workload and to assess new units

# Work beyond SEDENTEXCT?

Further focus on paediatric dose

‘Mathematical’ dose optimisation (simulations, reconstruction algorithms)

Long-term quality control of CBCT devices

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