The 15th Annual Scientific Meeting
Thai Medical Physicist Society, 1-3 March 2024

Pradub Atthakorn Memorial Lecture

Monte Carlo Simulation in Medical Physics

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Disclosure of COI

☑ Nothing to disclose

Contents

- Principles of Monte Carlo simulation

- Application of Monte Carlo simulation

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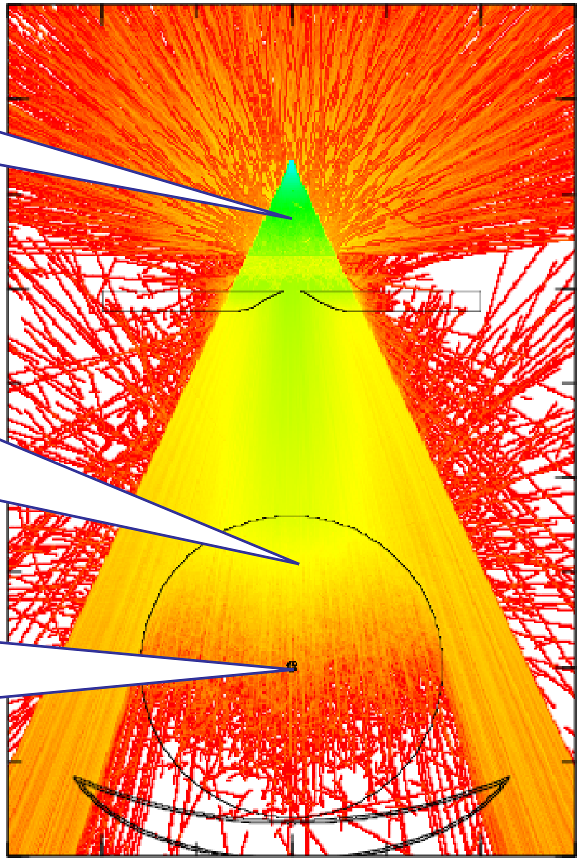
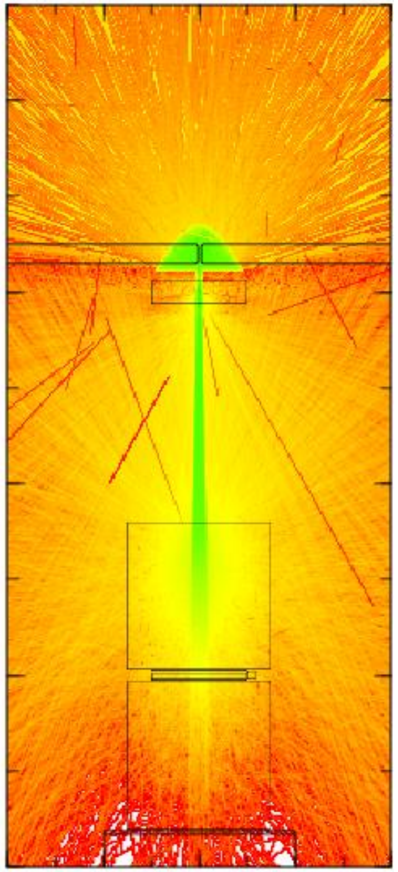
- Principles of Monte Carlo simulation
- Application of Monte Carlo simulation

Introduction

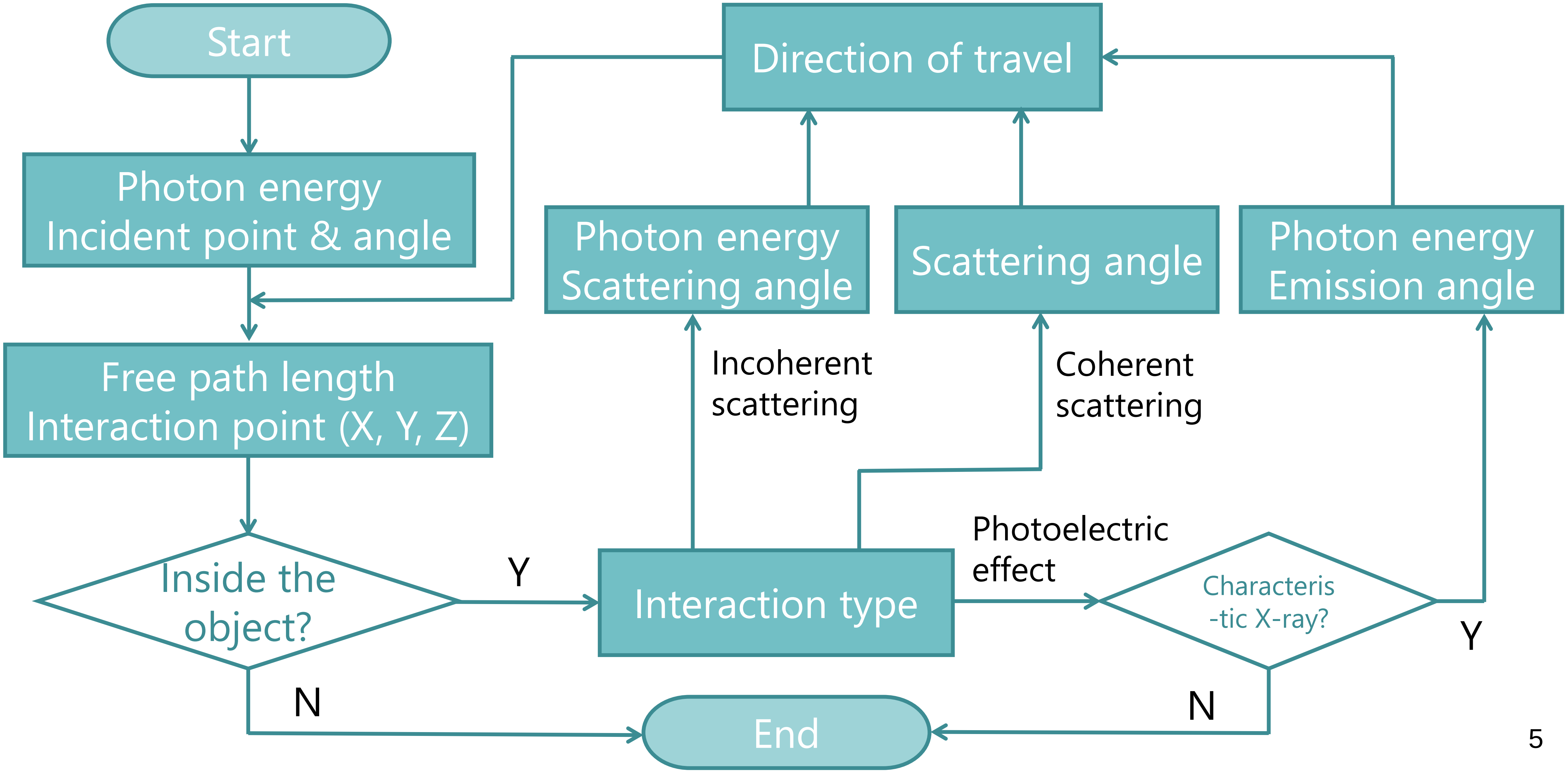
Monte Carlo (MC) simulations are the basis of all modern x-ray dosimetry methods in medical physics

1. **Track the trajectory** of individual x-rays
2. **Enter** the simulated patient/phantom and **undergo scattering and absorption events** (by pseudo-random real numbers)
3. **The amount of energy deposited** in the patient/phantom **is tallied** at each location

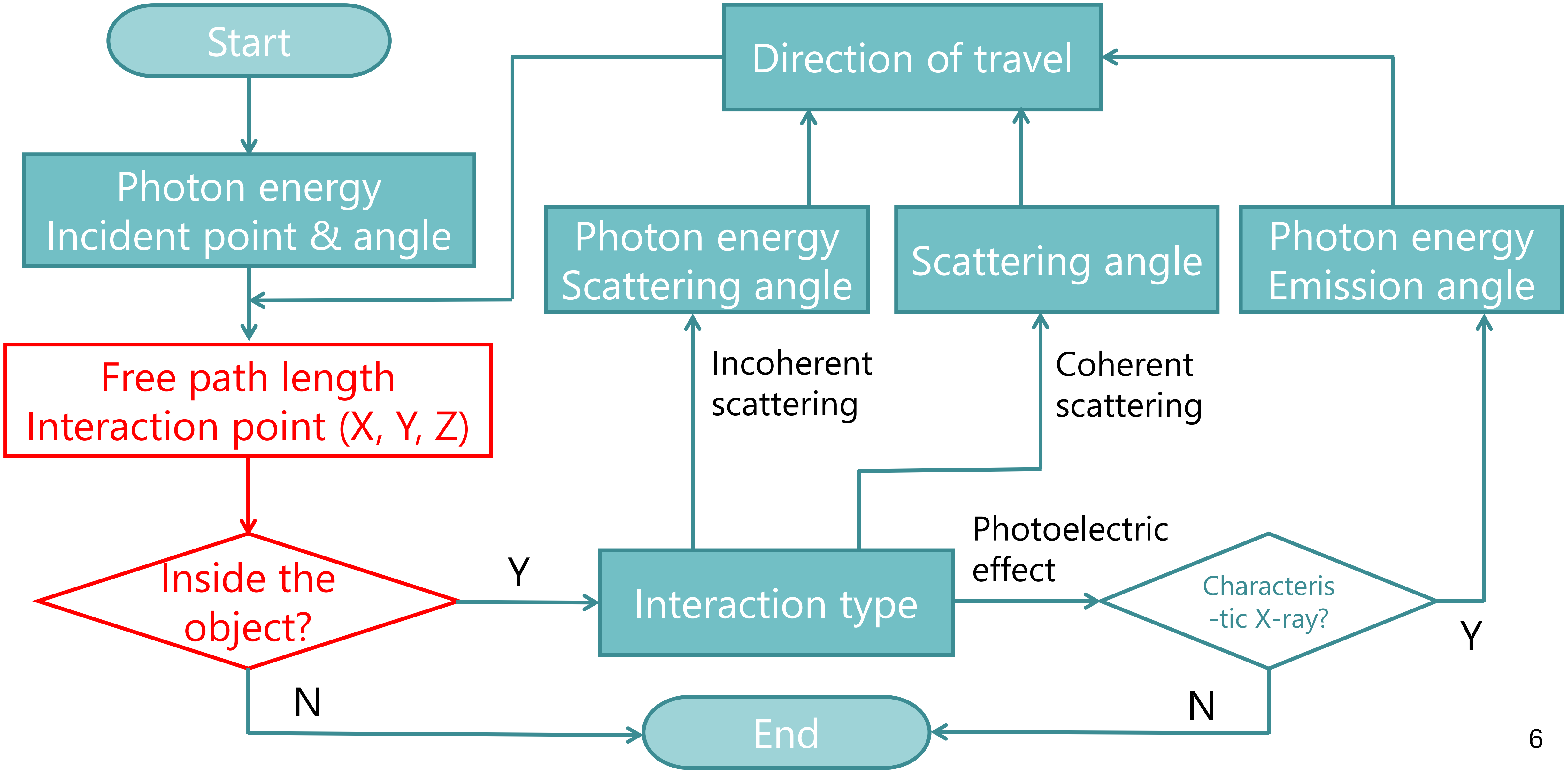




Flowchart (from incidence to exit of one photon)



Flowchart (from incidence to exit of one photon)



Random sampling of free path length

- The probability density function $f(L)$ that a photon will interact with material between depths L and $L + \Delta L$

$$f(L) = \mu \cdot e^{-\mu L} \qquad (\mu\text{: linear attenuation coefficient})$$

- Its distribution function $F(L)$:

$$F(L) = \int_0^L \mu \cdot e^{-\mu l} dl = 1 - e^{-\mu L}$$

- If $F(L)$ is a uniform random number r in the interval [0,1],

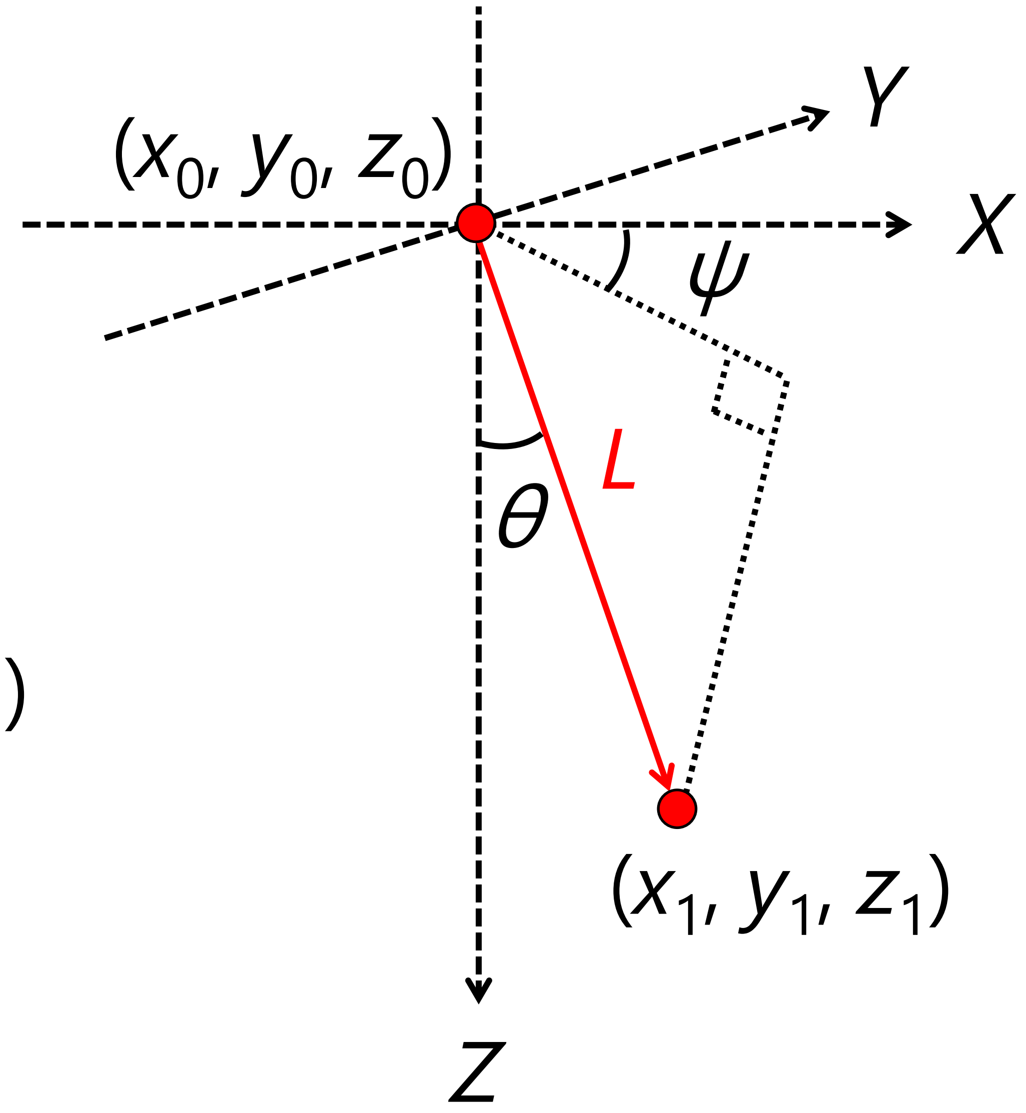
$$L = -\frac{1}{\mu}\ln(1 - r) = -\frac{1}{\mu}\ln(r) \qquad (r = 1 - e^{-\mu L})$$

Interaction point

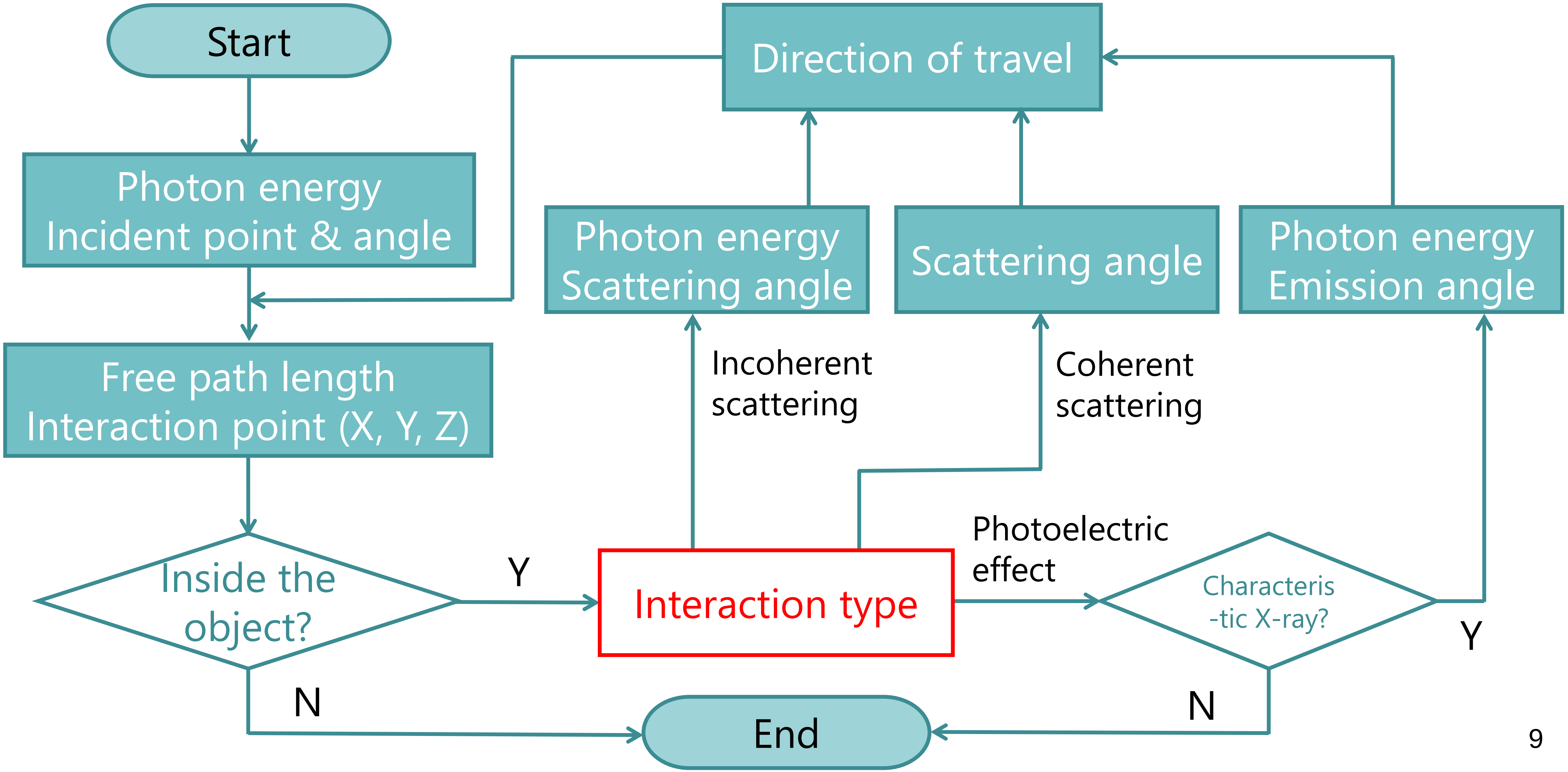
- Photon before scattering
  - Coordinate (x_0, y_0, z_0)
  - Scattering direction (θ, ψ)

- Free path length L

- Next interaction point (x_1, y_1, z_1)
  - $x_1 = x_0 + L \cdot \sin\theta \cdot \cos\psi$
  - $y_1 = y_0 + L \cdot \sin\theta \cdot \sin\psi$
  - $z_1 = z_0 + L \cdot \cos\theta$

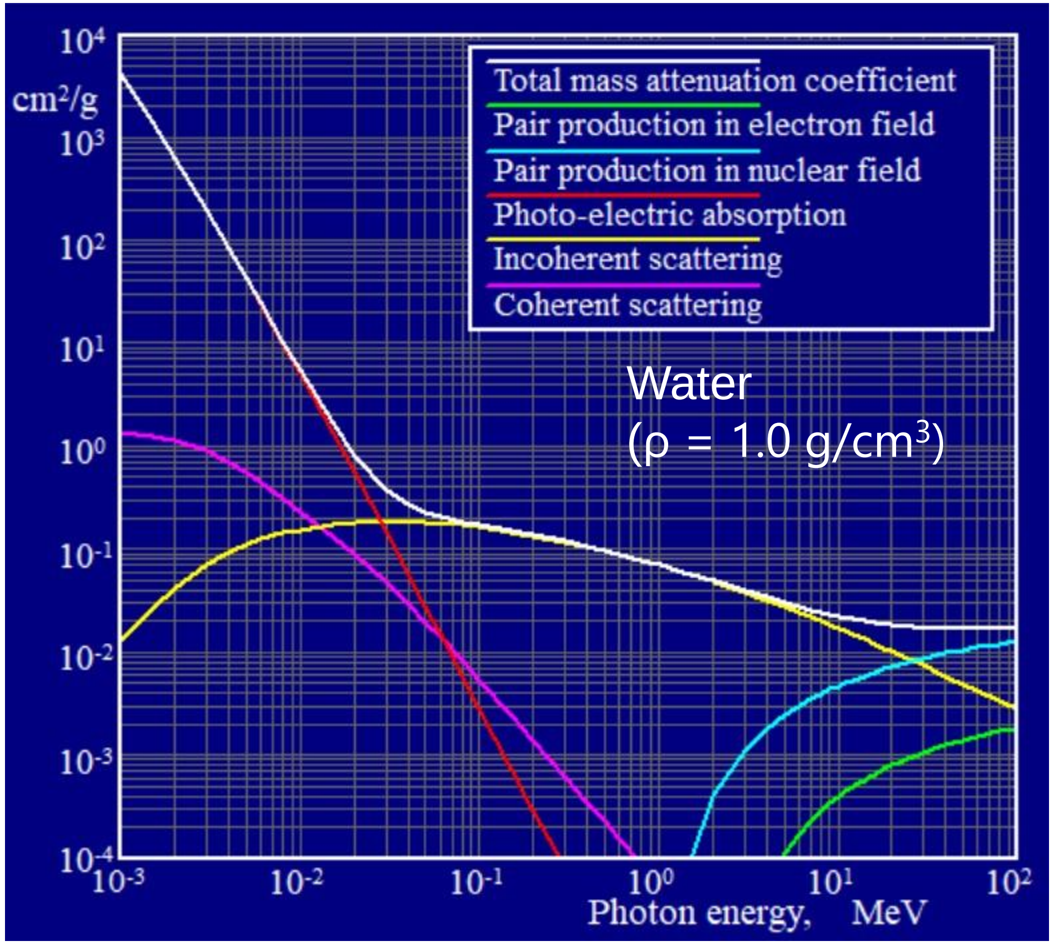


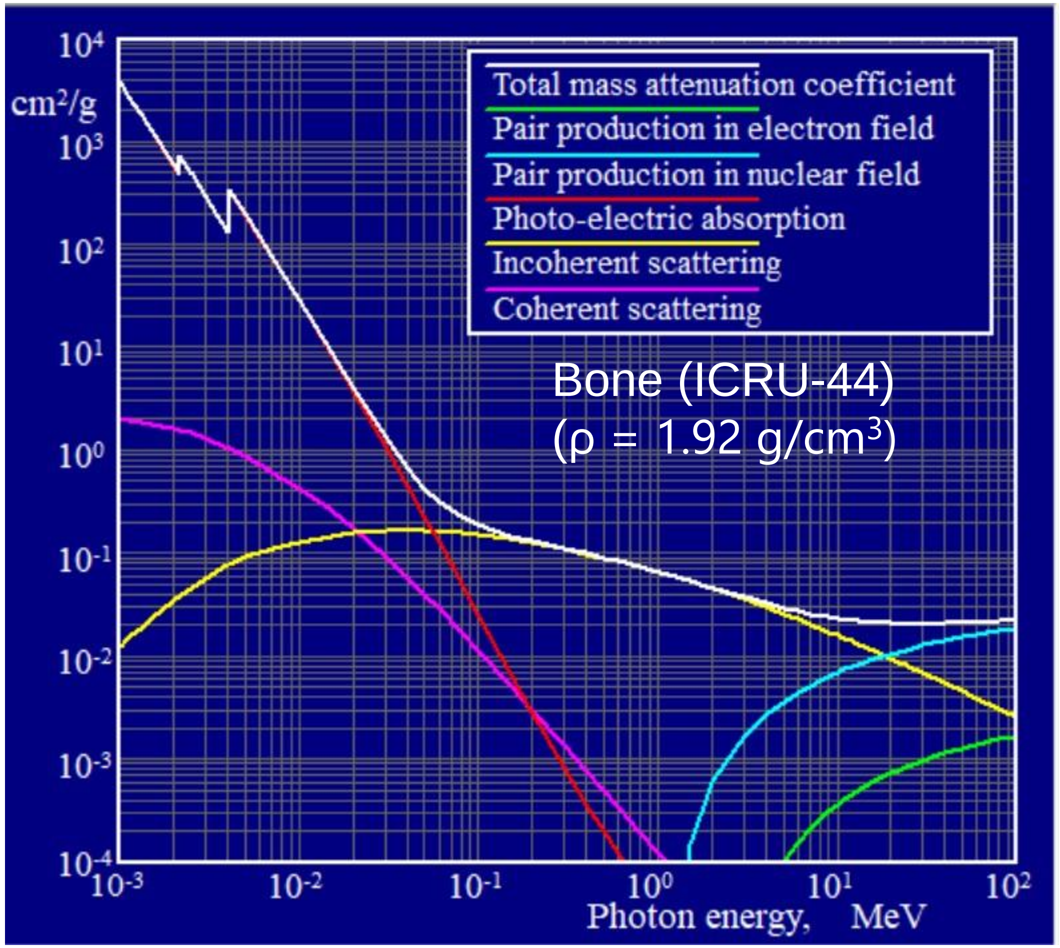
Flowchart (from incidence to exit of one photon)



Mass attenuation coefficient

$$\mu(E_0) = \tau(E_0) + \sigma_{coh}(E_0) + \sigma_{incoh}(E_0) + \pi(E_0)$$





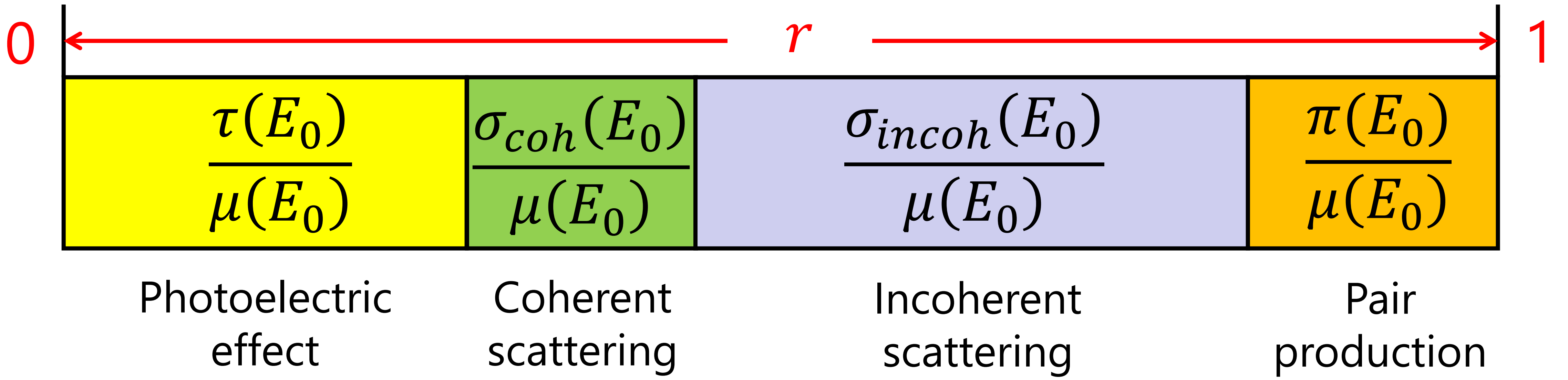
Obtained from Phics V7
https://www.vector.co.jp/soft/winnt/edu/se526094.html

Determination of interaction type

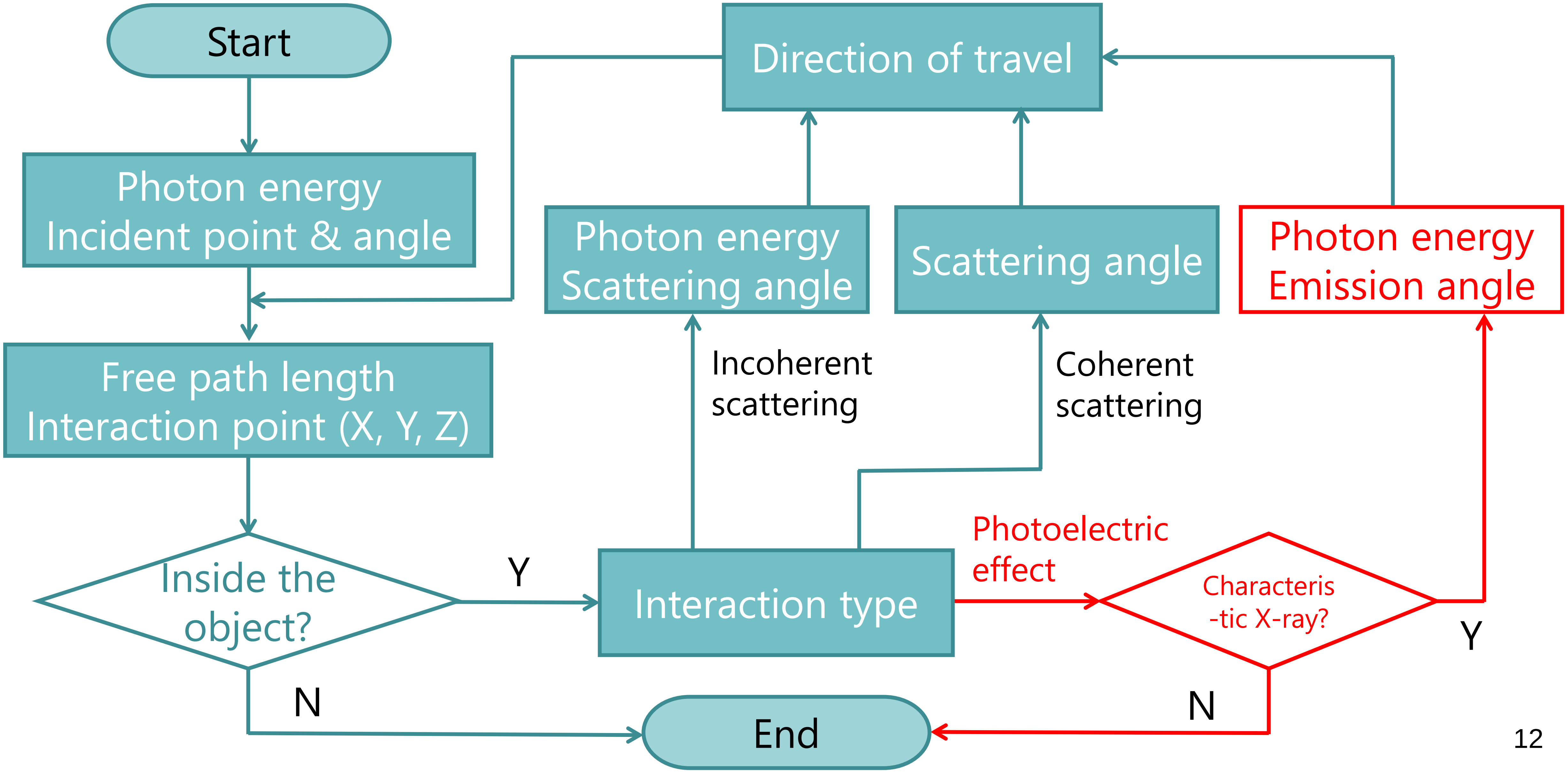
- Total cross section of interaction μ between photon of energy E_0 and material:

$$\mu(E_0) = \tau(E_0) + \sigma_{coh}(E_0) + \sigma_{incoh}(E_0) + \pi(E_0)$$

- Generate random number r in the interval [0,1]

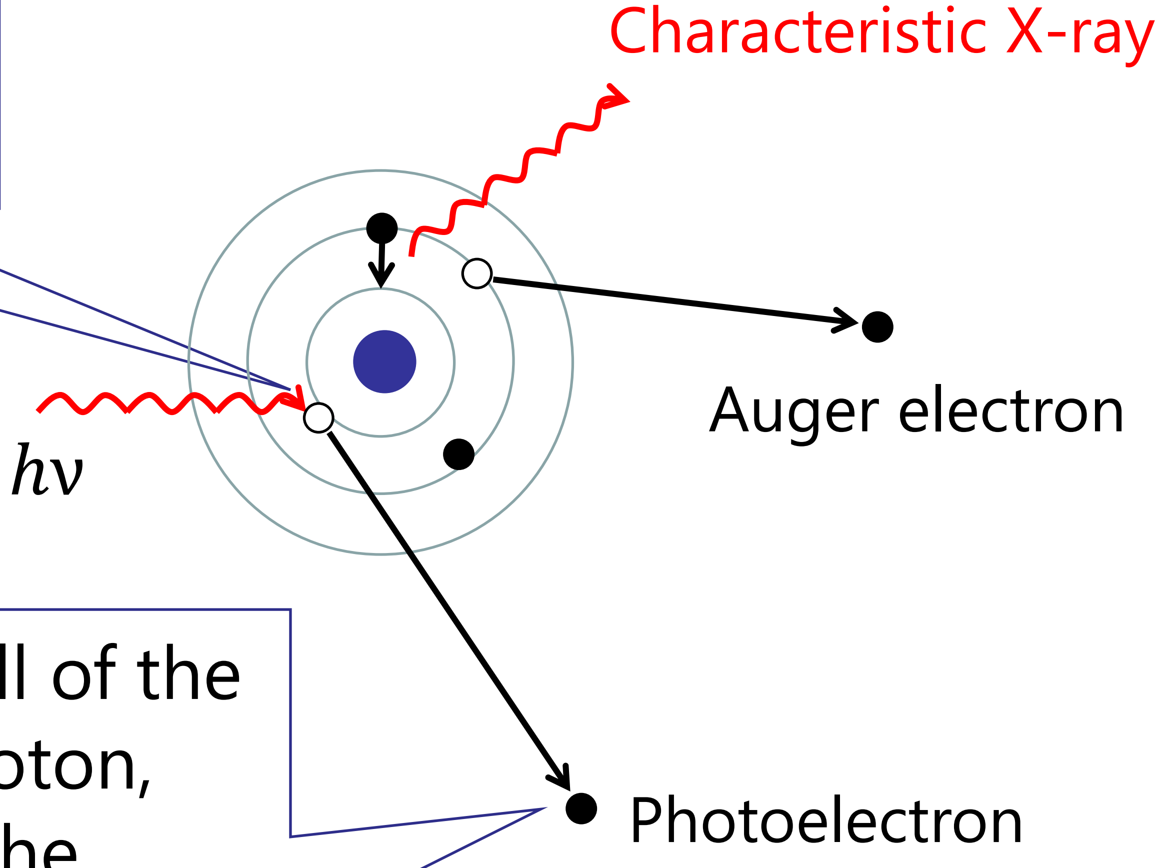


Flowchart (from incidence to exit of one photon)



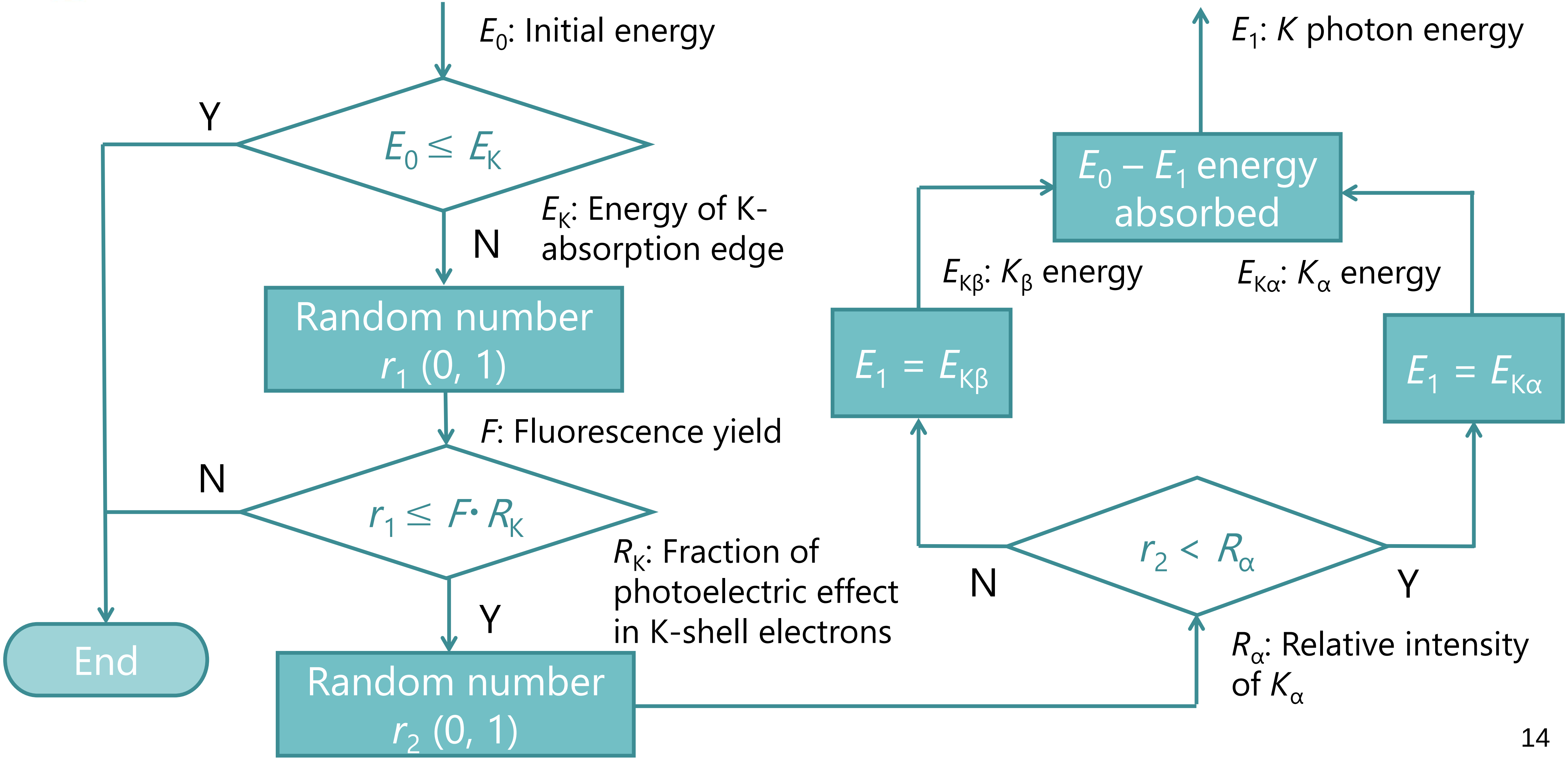
Photoelectric effect

A photon disappears and an electron is ejected from an atom.

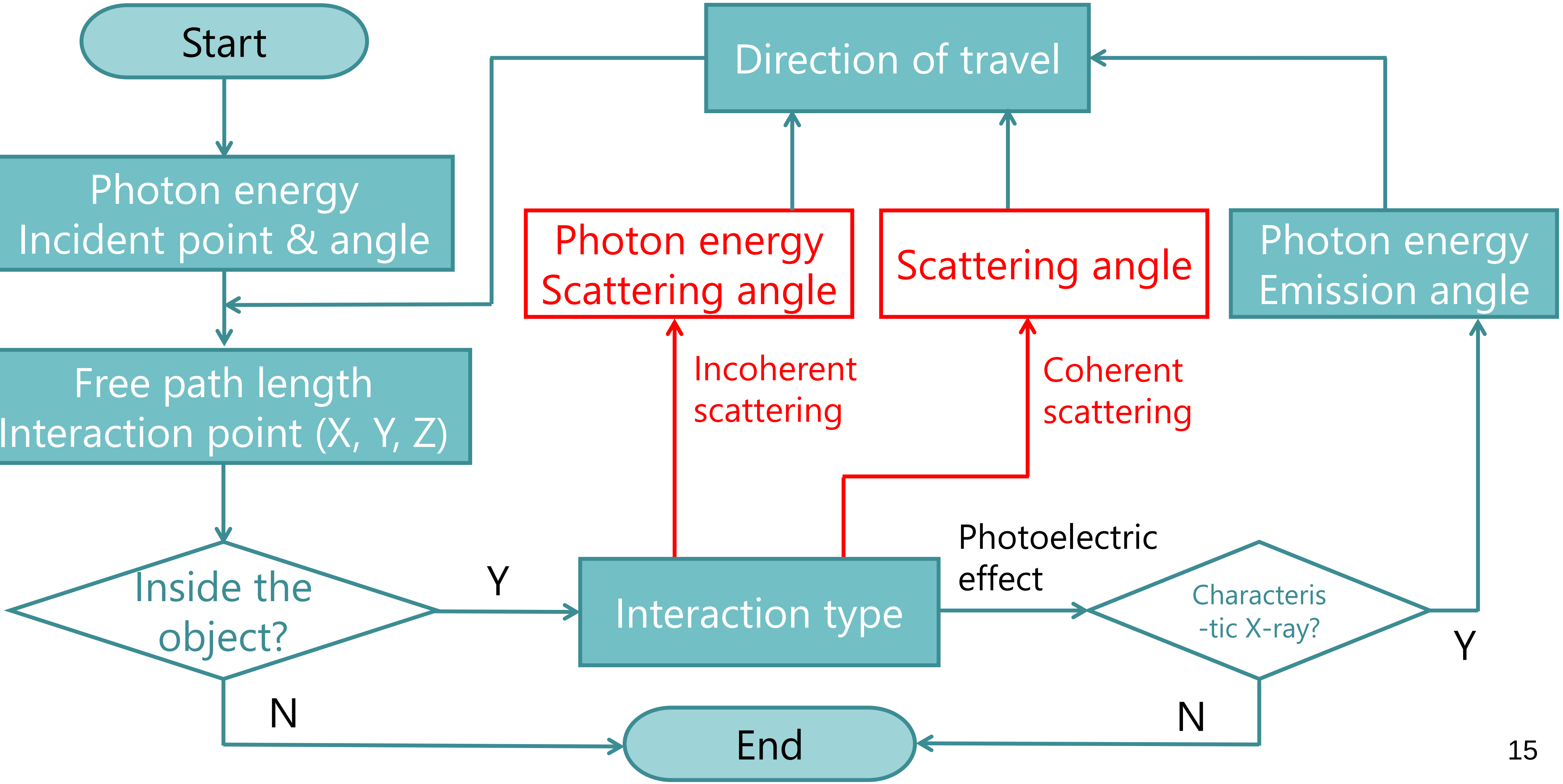


The electron carries away all of the energy of the absorbed photon, minus the energy binding the electron to the atom.

Process of photoelectric effect



Flowchart (from incidence to exit of one photon)



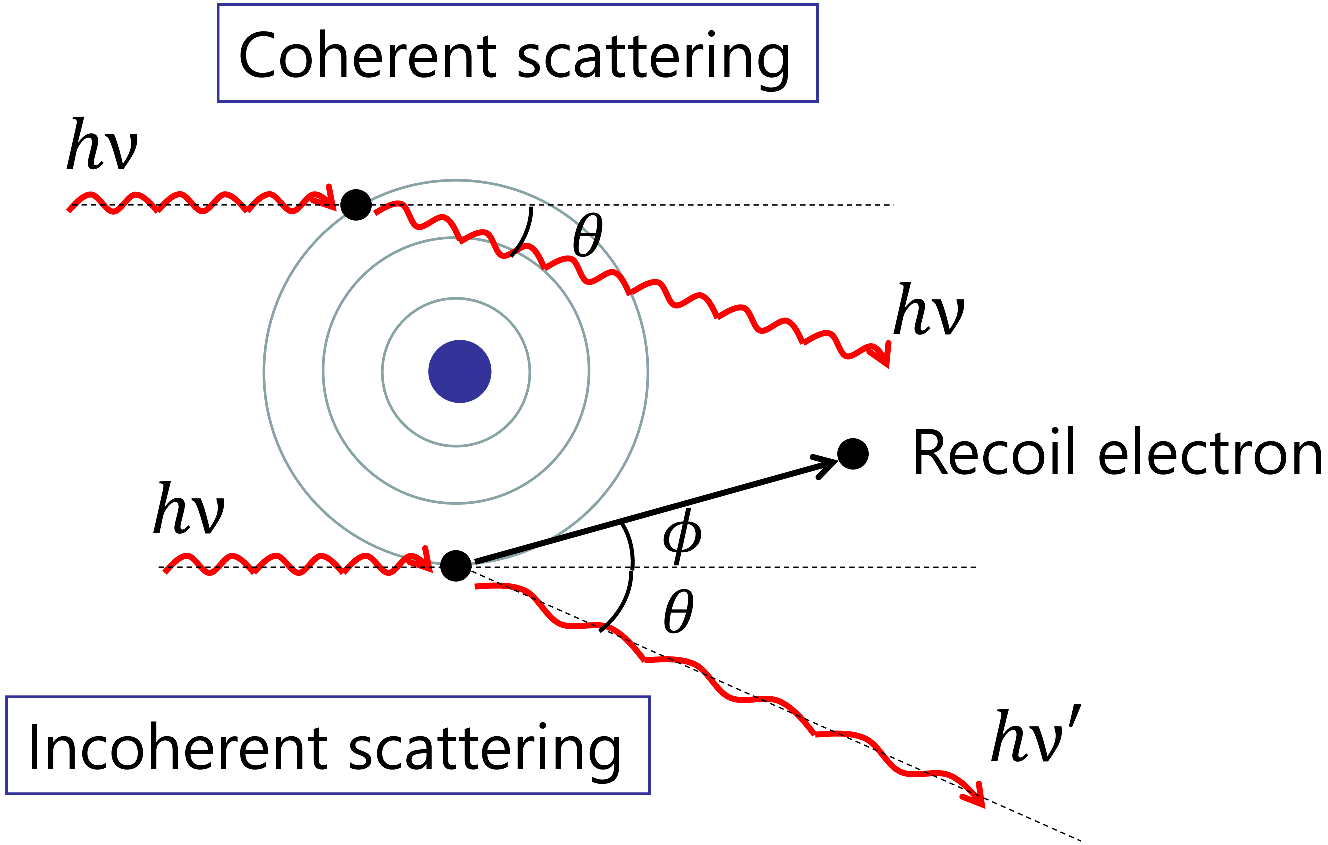
Coherent and incoherent scattering

Coherent scattering

- A photon is scattered by a bound atomic electron.
- The atom is neither ionized nor excited.

Incoherent scattering

- A photon collides with an electron, loses some of its energy.
- It is deflected from its original direction of travel.



Process of coherent scattering

Random number r_1 [0, Φ_{max}]

$$r_1 = \int_0^x F^2(\xi)\xi d\xi$$

x: Momentum transfer $= \dfrac{\sin(\theta/2)}{\lambda}$

$$\lambda = \frac{12.4}{h\nu}$$

$$x = \sin(\theta/2)/(12.4/E_0)$$
$$\cos\theta = 1 - \sin^2(\theta/2)$$

Random number r_2 [0, 2]

$r_2 \leq 1+\cos^2\theta$

N

Y

θ determined

Differential cross section for coherent scattering

$$\frac{d\sigma_{coh}}{d\theta} = \frac{d\sigma_{TM}}{d\theta} \cdot \boxed{F_m^2(x)} \quad \phi_{\max}$$

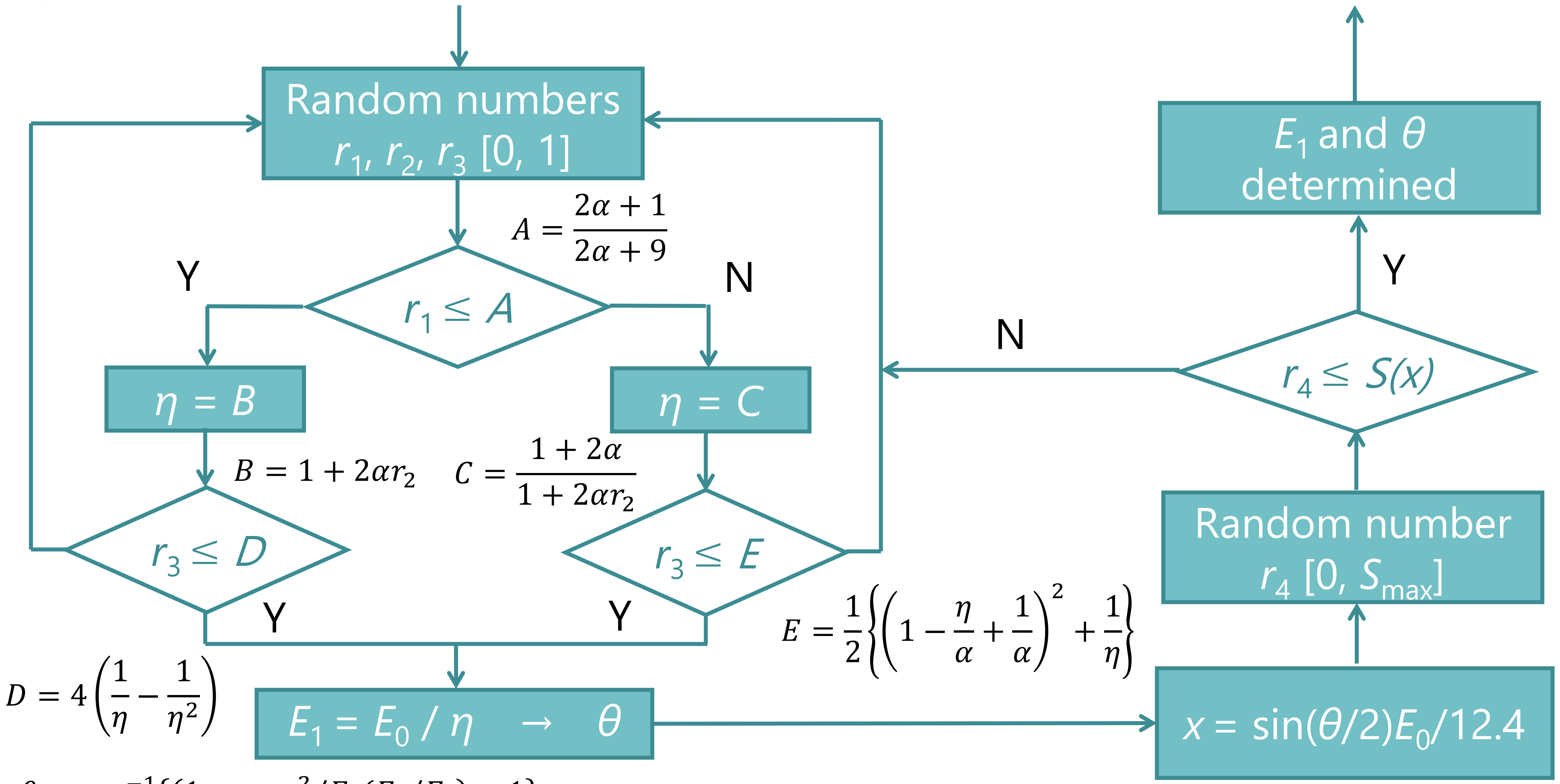
$$\frac{d\sigma_{TM}}{d\theta} = \frac{1}{2} r_0^2 (1 + \cos^2\theta) \cdot 2\pi \sin\theta$$

(Thomson differential cross section)

r_0: Classical electron radius

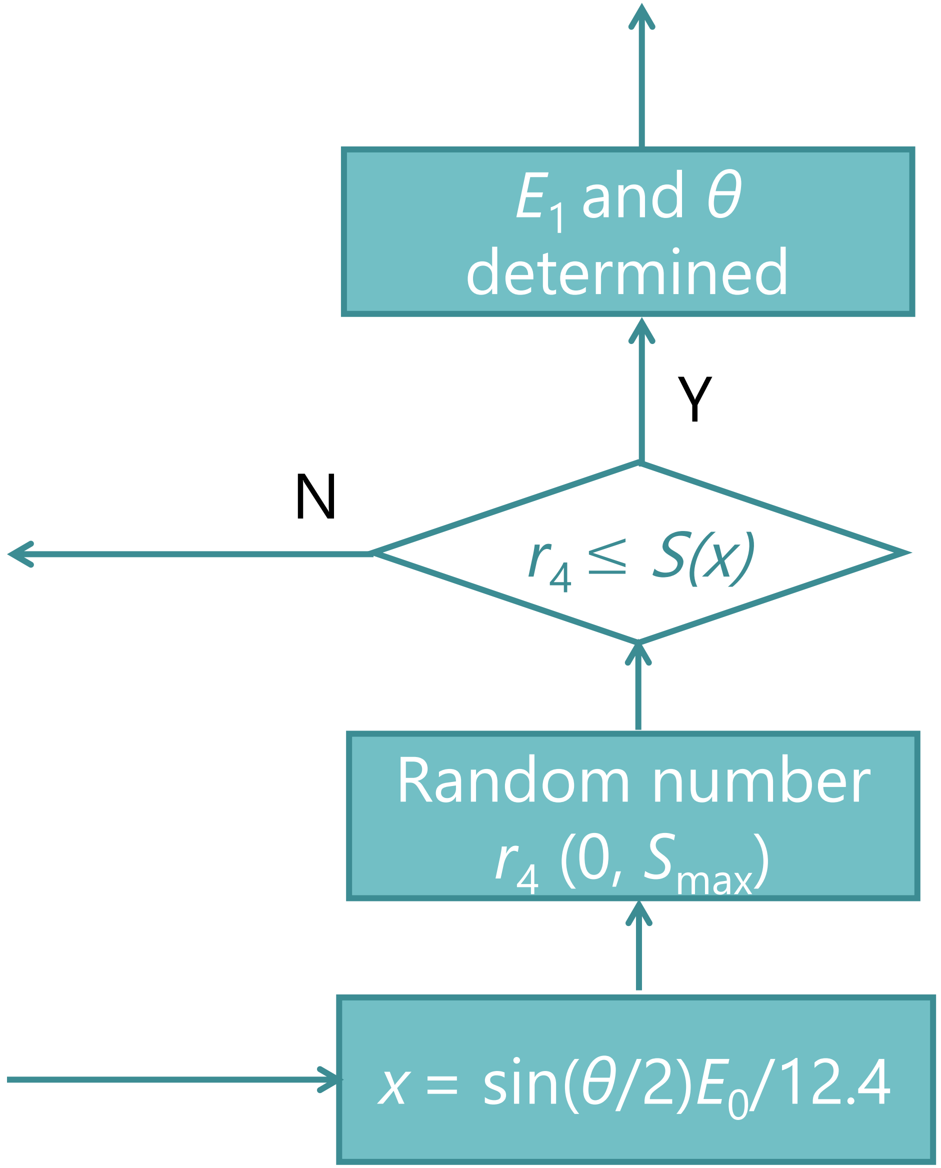
$F_m(x)$: Atomic form factor for material m

Process of incoherent scattering



$$\theta = \cos^{-1}\{(1 - m_0c^2/E_0(E_0/E_1) - 1\}$$

Process of incoherent scattering (cont'd)



<u>Differential cross section for incoherent scattering</u>

$$\frac{d\sigma_{incoh}}{d\theta} = \frac{d\sigma_{KN}}{d\theta} \cdot S_m(x)$$

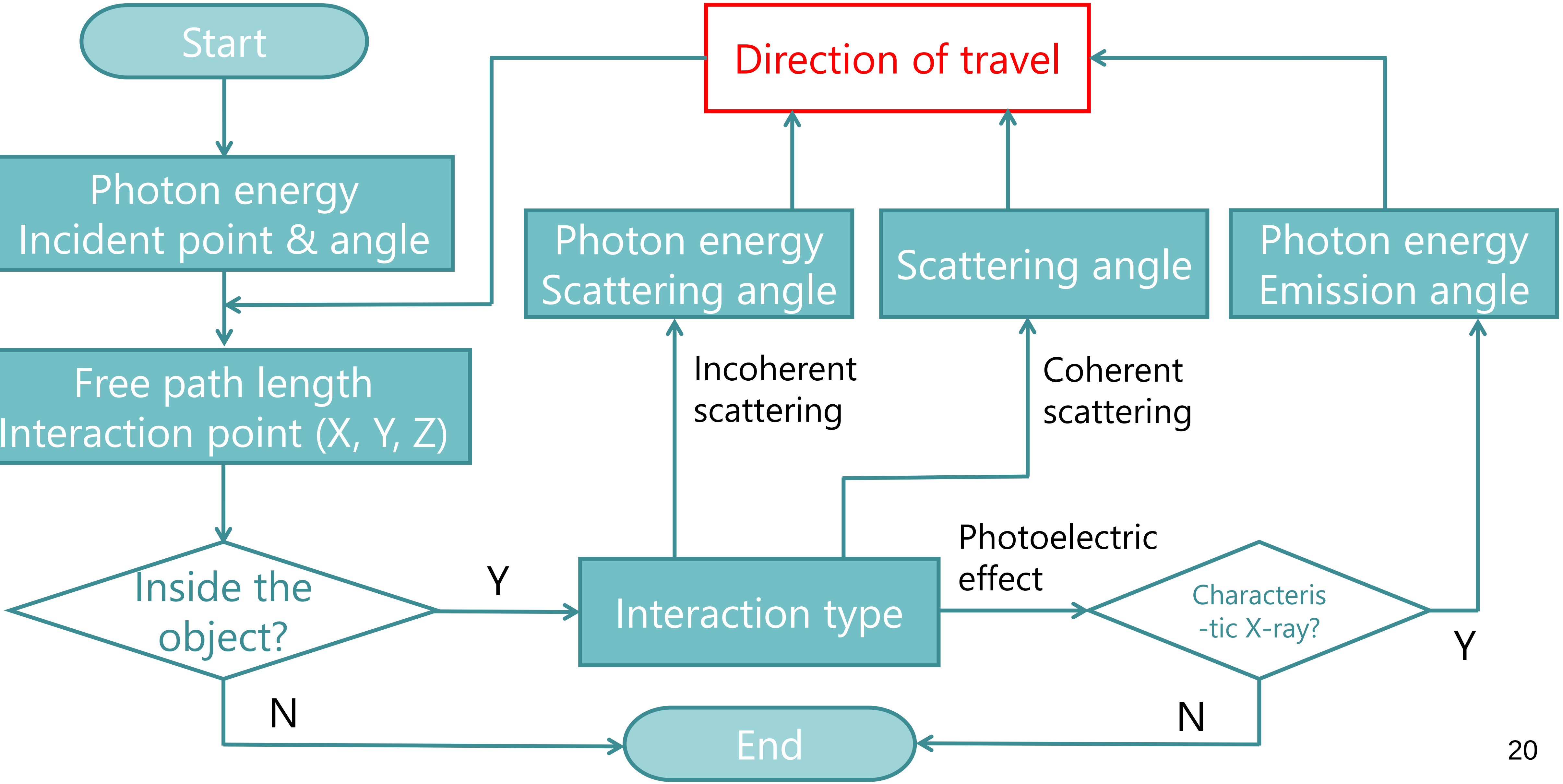
$$\frac{d\sigma_{KN}}{d\theta} = \frac{1}{2} r_0^2 \cdot \left(\frac{E_0}{E_1}\right)^2 \left(\frac{E_0}{E_1} + \frac{E_1}{E_0} - \sin^2\theta\right)$$

(Klein-Nishina differential cross section)

r_0: Classical electron radius

$S_m(x)$: Incoherent scattering function for material m

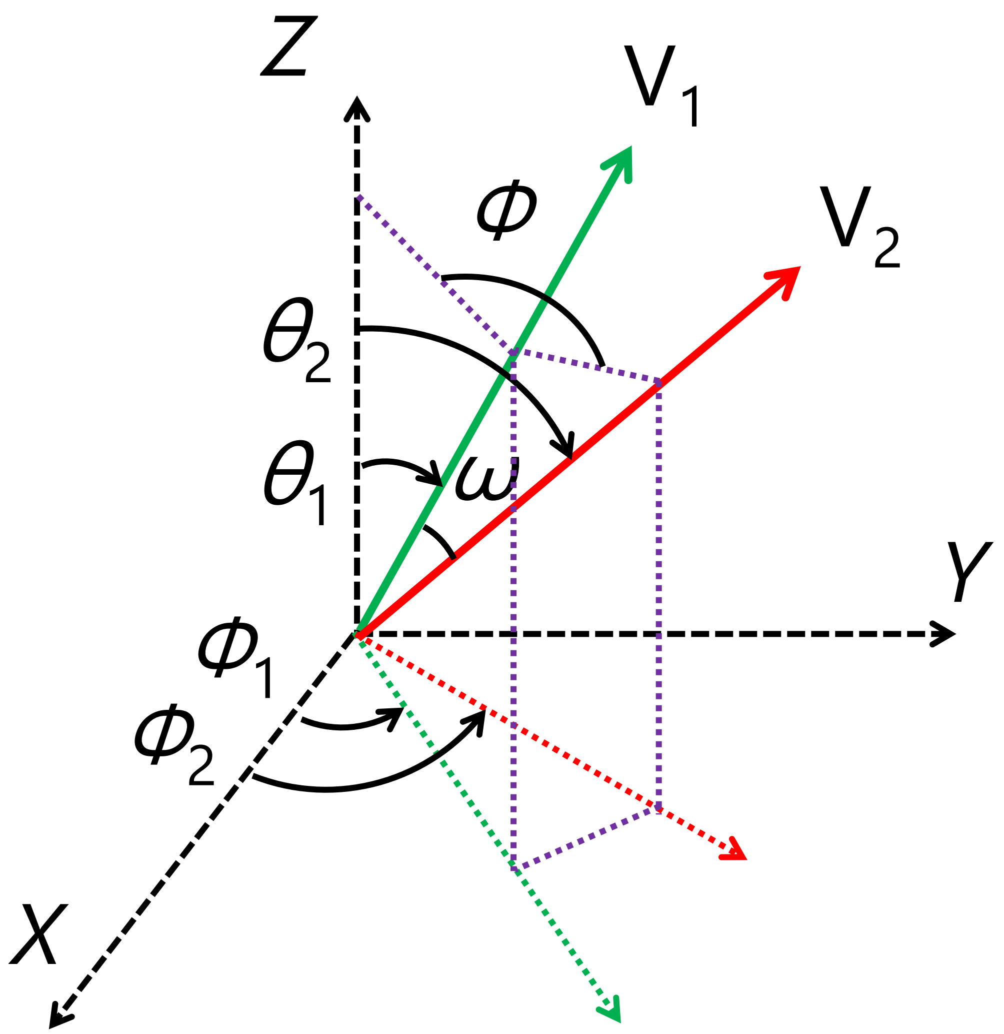
Flowchart (from incidence to exit of one photon)



Photon travel angle after scattering

- Photon before scattering V_1
  (θ_1, Φ_1)
  - Scattering angle ω
  - Scattering azimuth Φ

- Photon after scattering V_2
  (θ_2, Φ_2)



Photon travel angle after scattering

- Photon before scattering $V_1\ (\theta_1, \Phi_1)$

$$\cos\theta_2 = \cos\theta_1 \cdot \cos\omega + \sin\theta_1 \cdot \sin\omega \cdot \cos\phi$$

$$\sin\theta_2 = \sqrt{1 - \cos^2\theta_2}$$

$$\sin\phi_2 = \sin\phi_1 \cdot \cos(\phi_2 - \phi_1) + \cos\phi_1 \cdot \sin(\phi_2 - \phi_1)$$

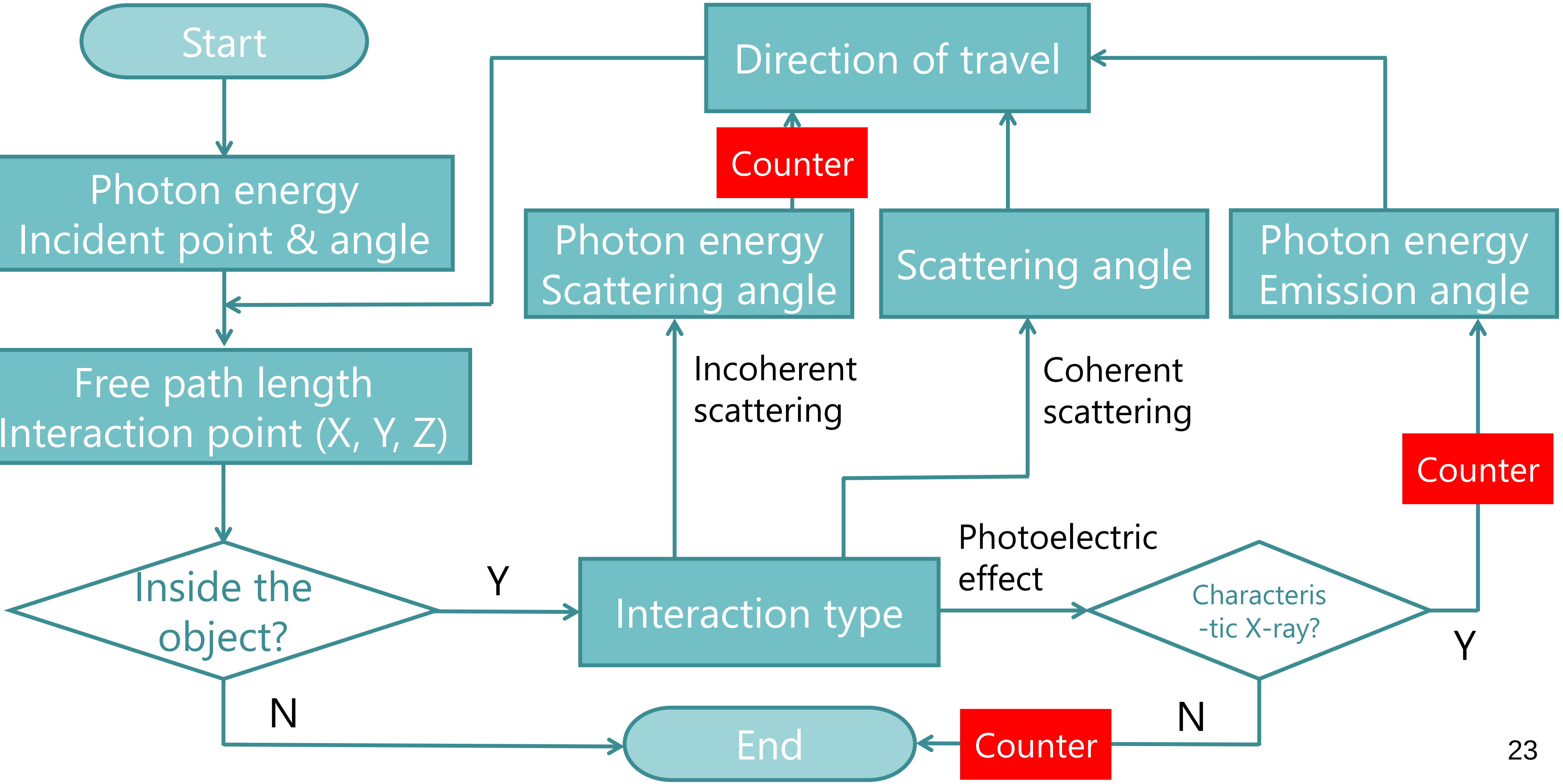
$$\cos\phi_2 = \cos\phi_1 \cdot \cos(\phi_2 - \phi_1) - \sin\phi_1 \cdot \sin(\phi_2 - \phi_1)$$

$$\sin(\phi_2 - \phi_1) = \sin\phi \cdot \sin\omega \,/\, \sin\theta_2$$

$$\cos(\phi_2 - \phi_1) = (\cos\omega - \cos\theta_1 \cdot \cos\theta_2)/\sin\theta_1 \cdot \sin\theta_2$$

- Photon after scattering $V_2\ (\theta_2, \Phi_2)$

Flowchart (from incidence to exit of one photon)



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MC software for performing dose calculations

CT-Expo (CT)

- http://www.sascrad.com/information/downloads/

WAZA-ARIv2 (CT)

- http://waza-ari.nirs.go.jp/waza_ari_v2_1/

VirtualDoseCT (CT)

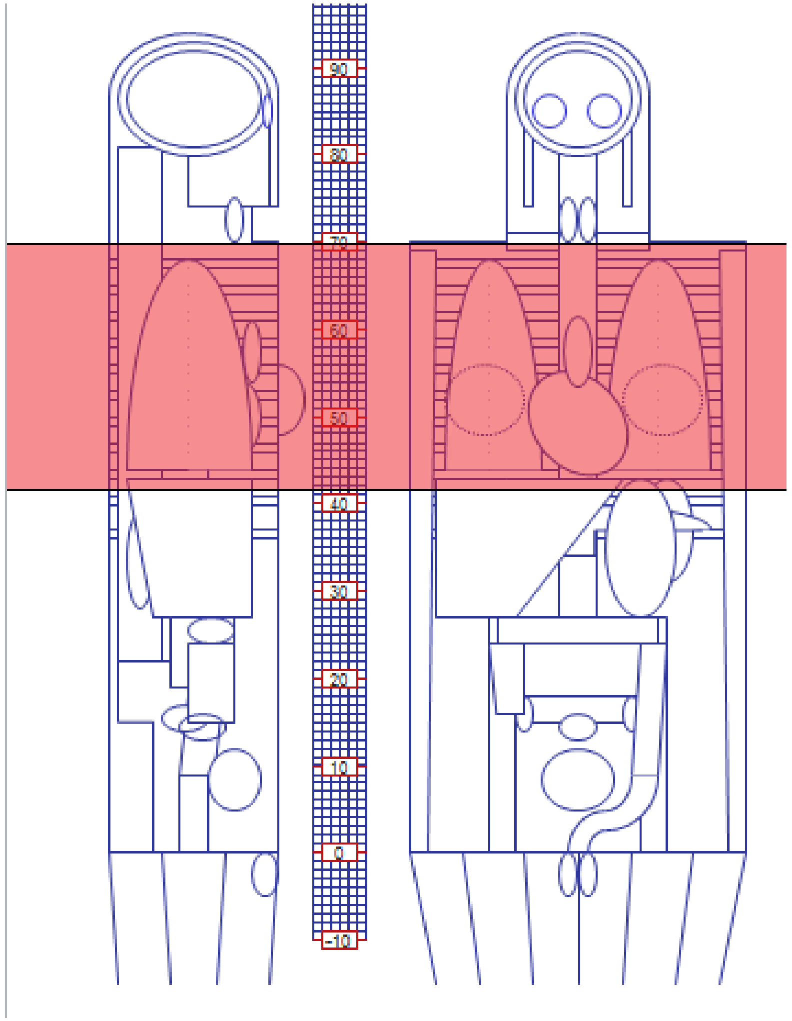
- http://www.virtualphantoms.com/our-products/virtualdose/

VirtualDoseIR (IR)

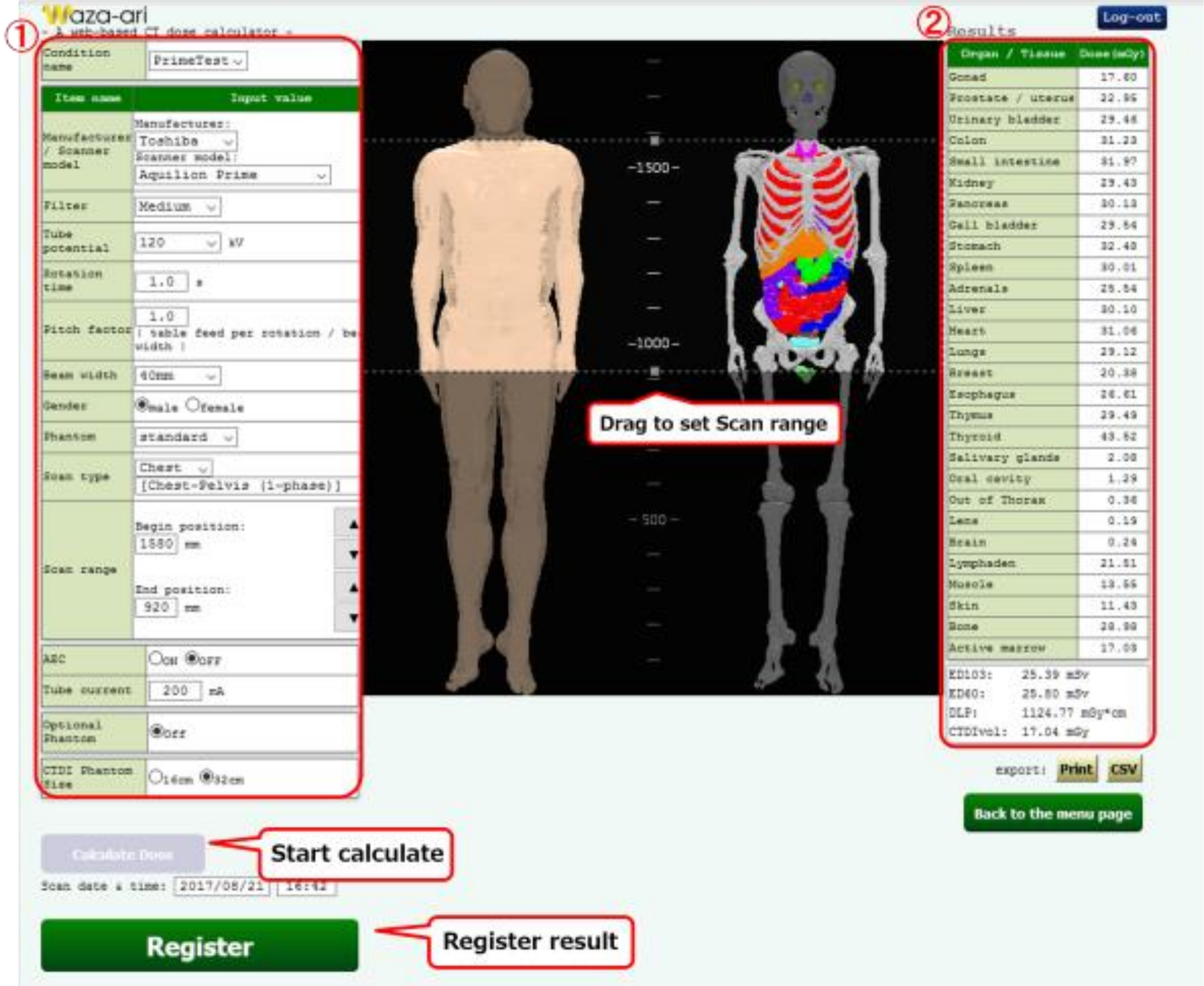
- http://www.virtualphantoms.com/our-products/virtualdoseir/

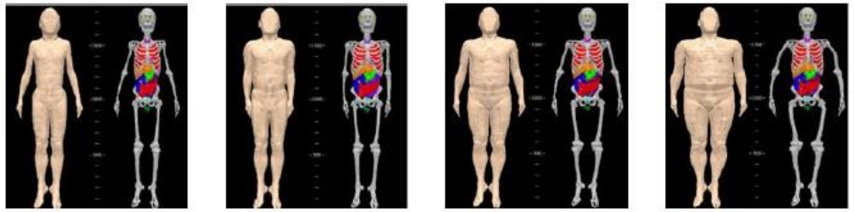
OLINDA (NM)

- https://www.doseinfo-radar.com/OLINDA.html



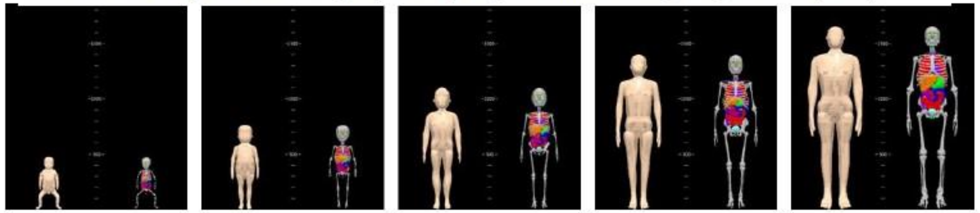
Dose calculation software (Waza-ari v2)





Adult Male (from left to right): thin (-2σ), standard, fat (+2σ), obese (+5σ)

Adult Female (from left to right): thin (-2σ), standard, fat (+2σ), obese (+5σ)

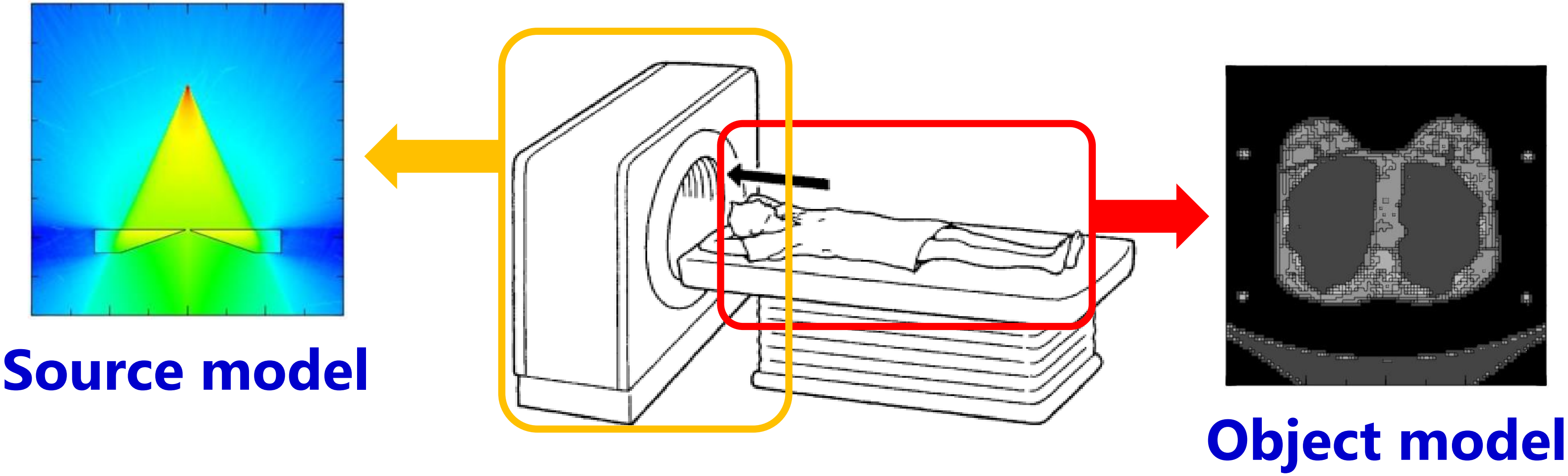


Boy (from left to right): 0-yr-old, 1-yr-old, 5-yr-old, 10-yr-old, 15-yr-old

Girl (from left to right): 0-yr-old, 1-yr-old, 5-yr-old, 10-yr-old, 15-yr-old

https://waza-ari.nirs.qst.go.jp/

Dose evaluation by MC simulation



- Freely constructs a **<u>source model</u>** and an **<u>object model</u>**
- Provides **<u>more detailed dose information</u>** not available with dose calculation software

MC simulation code

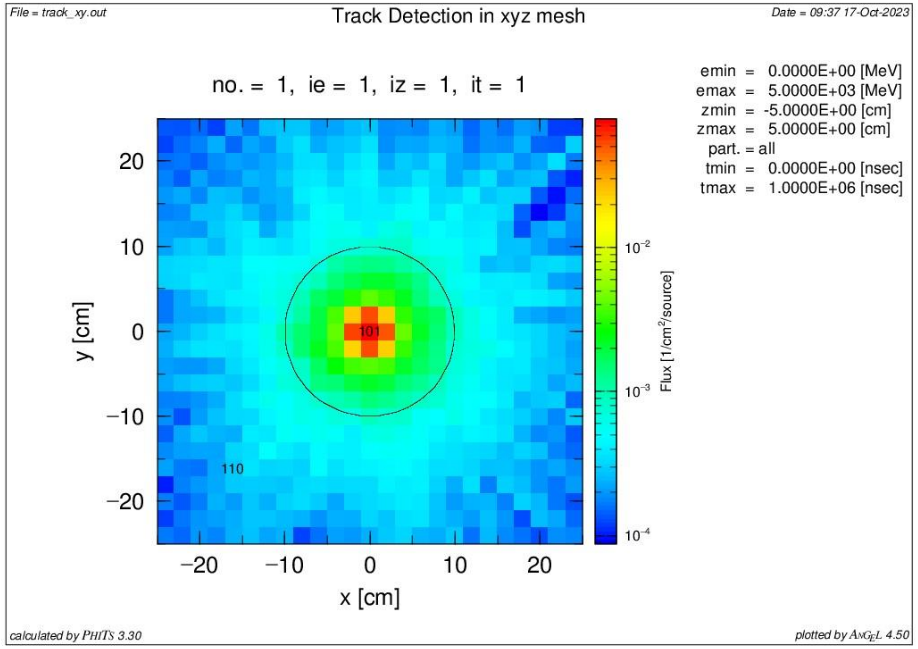
```
[ T i t l e ]
input file for lecture about tally

[ P a r a m e t e r s ]
 icntl    =           0     # (D=0) 3:ECH 5:NOR 6:SRC 7,8:GSH 11:DSH 12:DUMP
 maxcas   =          50     # (D=10) number of particles per one batch
 maxbch   =           2     # (D=10) number of batches

[ S o u r c e ]
   s-type =   1             # mono-energetic axial source
       z0 =  -10.           # minimum position of z-axis [cm]
       z1 =  -10.           # maximum position of z-axis [cm]
       r0 =   2.5           # radius [cm]
      dir =   1.0           # z-direction of beam [cosine]
       e0 =   250.          # energy of beam [MeV/u]
     proj =  12C            # kind of incident nucleus

[ M a t e r i a l ]
mat[1]    H 2  O 1

[ Mat Name Color ]
    mat   name      color
     1    Water     pastelblue

[ S u r f a c e ]
  10  so     500.
  11  cz      10.
  12  pz       0.
  13  pz      50.

[ C e l l ]
 100    -1       10
 101     1 -1.   -11  12  -13
 110     0       -10  #101

[ T - T r a c k ]
    title = Track Detection in xyz mesh
     mesh =  xyz            # mesh type is xyz scoring mesh
   x-type =    2            # x-mesh is linear given by xmin, xmax and nx
       nx =   25            # number of x-mesh points
     xmin =  -25.           # minimum value of x-mesh points
     xmax =   25.           # maximum value of x-mesh points
   y-type =    2            # y-mesh is linear given by ymin, ymax and ny
       ny =   25            # number of y-mesh points
```

Input file

```
bat[      34] ncas =          1700. : date = 2023-10-17 : time = 09h 37m 06s
bat[      35] ncas =          1750. : date = 2023-10-17 : time = 09h 37m 07s
bat[      36] ncas =          1800. : date = 2023-10-17 : time = 09h 37m 08s
bat[      37] ncas =          1850. : date = 2023-10-17 : time = 09h 37m 08s
bat[      38] ncas =          1900. : date = 2023-10-17 : time = 09h 37m 09s
bat[      39] ncas =          1950. : date = 2023-10-17 : time = 09h 37m 10s
bat[      40] ncas =          2000. : date = 2023-10-17 : time = 09h 37m 11s
bat[      41] ncas =          2050. : date = 2023-10-17 : time = 09h 37m 11s
bat[      42] ncas =          2100. : date = 2023-10-17 : time = 09h 37m 12s
bat[      43] ncas =          2150. : date = 2023-10-17 : time = 09h 37m 13s
bat[      44] ncas =          2200. : date = 2023-10-17 : time = 09h 37m 14s
bat[      45] ncas =          2250. : date = 2023-10-17 : time = 09h 37m 14s
bat[      46] ncas =          2300. : date = 2023-10-17 : time = 09h 37m 15s
bat[      47] ncas =          2350. : date = 2023-10-17 : time = 09h 37m 16s
bat[      48] ncas =          2400. : date = 2023-10-17 : time = 09h 37m 16s
bat[      49] ncas =          2450. : date = 2023-10-17 : time = 09h 37m 17s
bat[      50] ncas =          2500. : date = 2023-10-17 : time = 09h 37m 17s
bat[      51] ncas =          2550. : date = 2023-10-17 : time = 09h 37m 18s
bat[      52] ncas =          2600. : date = 2023-10-17 : time = 09h 37m 19s
bat[      53] ncas =          2650. : date = 2023-10-17 : time = 09h 37m 20s
bat[      54] ncas =          2700. : date = 2023-10-17 : time = 09h 37m 21s
bat[      55] ncas =          2750. : date = 2023-10-17 : time = 09h 37m 21s
bat[      56] ncas =          2800. : date = 2023-10-17 : time = 09h 37m 22s
bat[      57] ncas =          2850. : date = 2023-10-17 : time = 09h 37m 23s
bat[      58] ncas =          2900. : date = 2023-10-17 : time = 09h 37m 23s
bat[      59] ncas =          2950. : date = 2023-10-17 : time = 09h 37m 24s
bat[      60] ncas =          3000. : date = 2023-10-17 : time = 09h 37m 24s
bat[      61] ncas =          3050. : date = 2023-10-17 : time = 09h 37m 25s
bat[      62] ncas =          3100. : date = 2023-10-17 : time = 09h 37m 26s
bat[      63] ncas =          3150. : date = 2023-10-17 : time = 09h 37m 26s
```

Calculation

Tally results in xyz mesh



Recommendation for ending routine gonadal shielding[1)]

National Council on Radiation Protection and Measurements
7910 Woodmont Avenue / Suite 400 / Bethesda, MD 20814-3095
http://ncrponline.org

NCRP Recommendations for Ending Routine Gonadal Shielding During Abdominal and Pelvic Radiography

NCRP Statement No. 13, January 12, 2021

Executive Summary

The purpose of radiological protection, including recommendations for shielding, is to reduce the likelihood of possible harm. For medical exposures, the goal is to keep exposures as low as reasonably achievable while simultaneously ensuring that the needed information is obtained. Gonadal shielding (GS) was introduced and widely recommended in the 1950s with the intent of minimizing the potential for heritable genetic effects from medical exposures. Scientific evidence has led the National Council on Radiation Protection and Measurements (NCRP) to reconsider the recommendation for GS. Several factors contribute to NCRP's new recommendation.

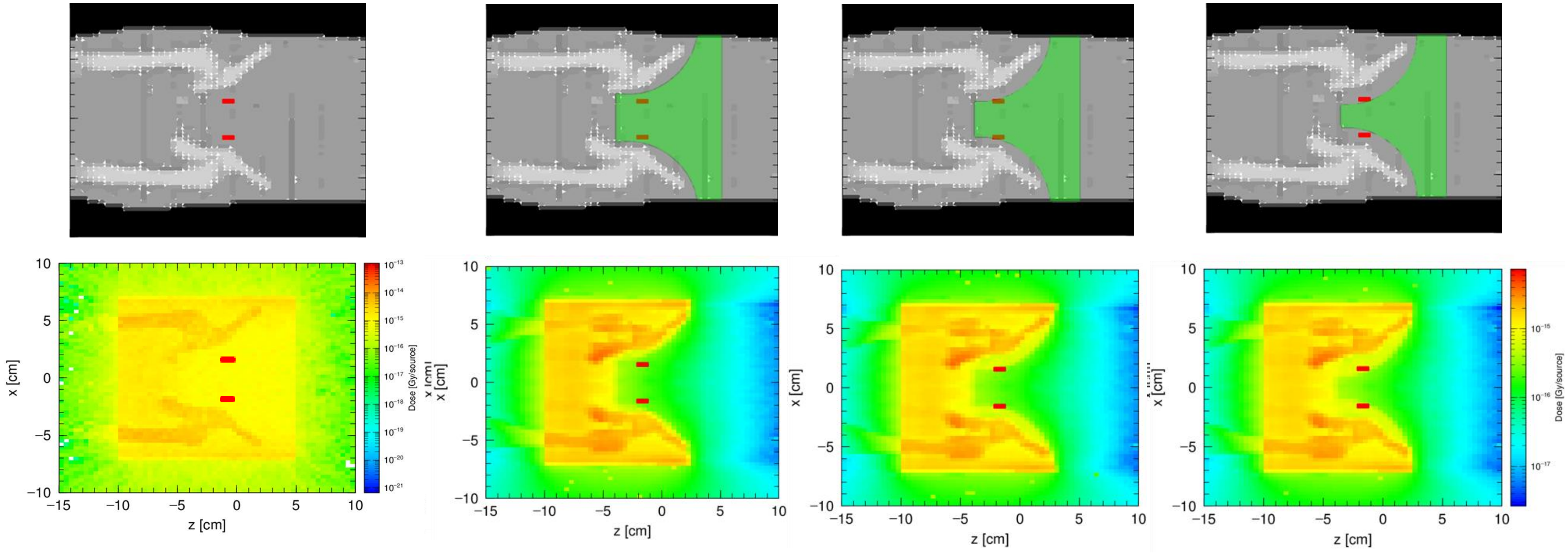
1) NCRP Statement No. 13 (2021)

Absorbed doses in ovaries during pediatric hip radiography

1-year-old pediatric phantom (704, CIRS)

Result of absorbed doses (by MC simulation)

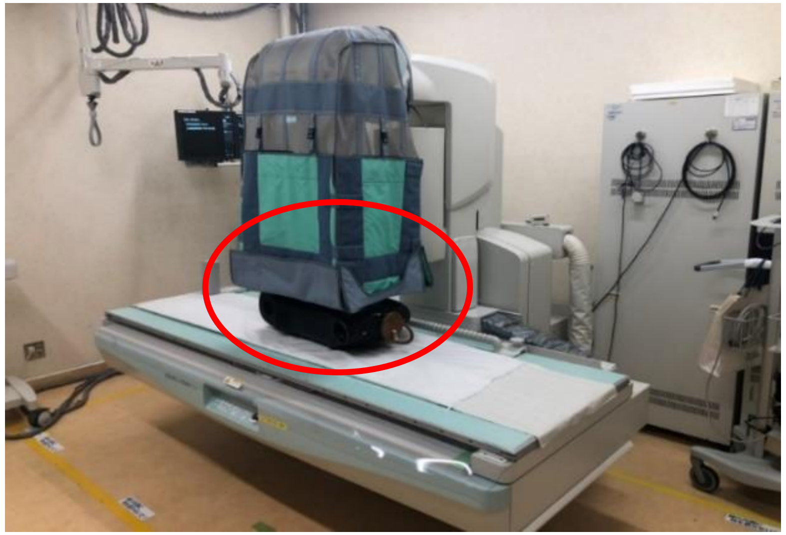
No shield | Shield (large) | Shield (medium) | Shield (small)



Dose reduction rate	80.0-80.1%	72.4-73.1%	53.6-55.3%

Clinical use of radioprotective curtains

folding

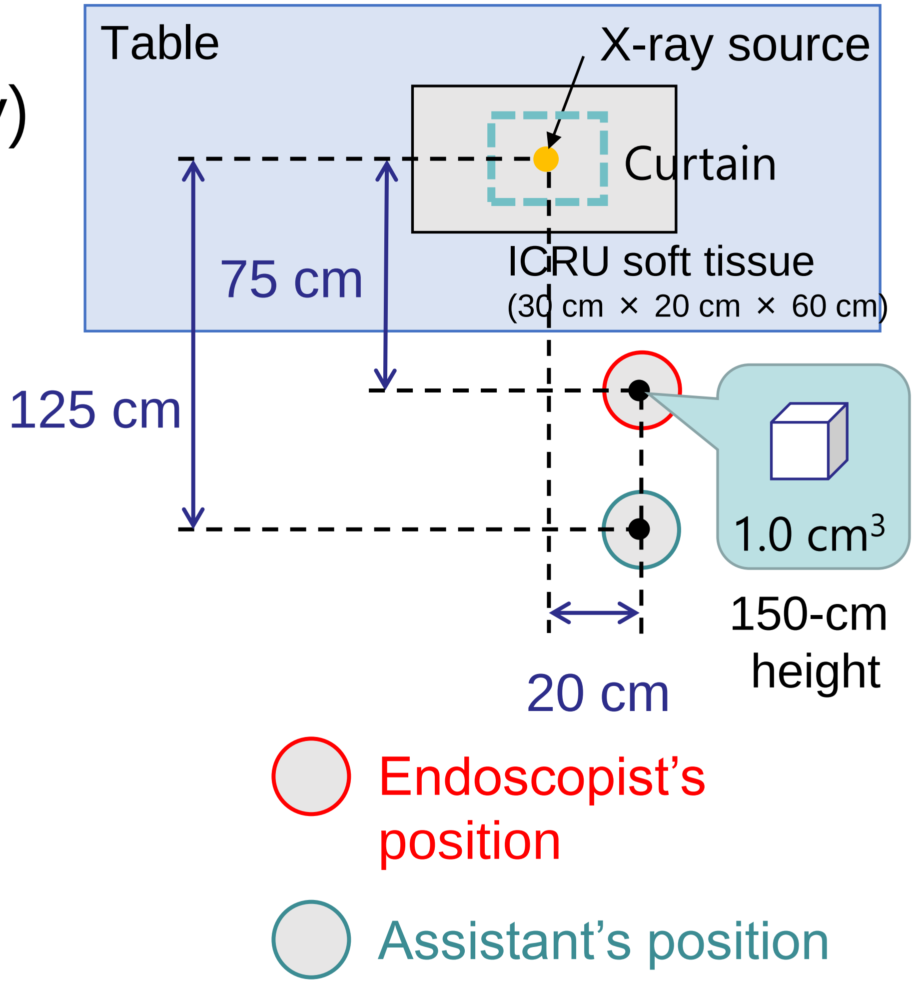


Protective curtains are sometimes folded

Folded curtains may not provide adequate protection

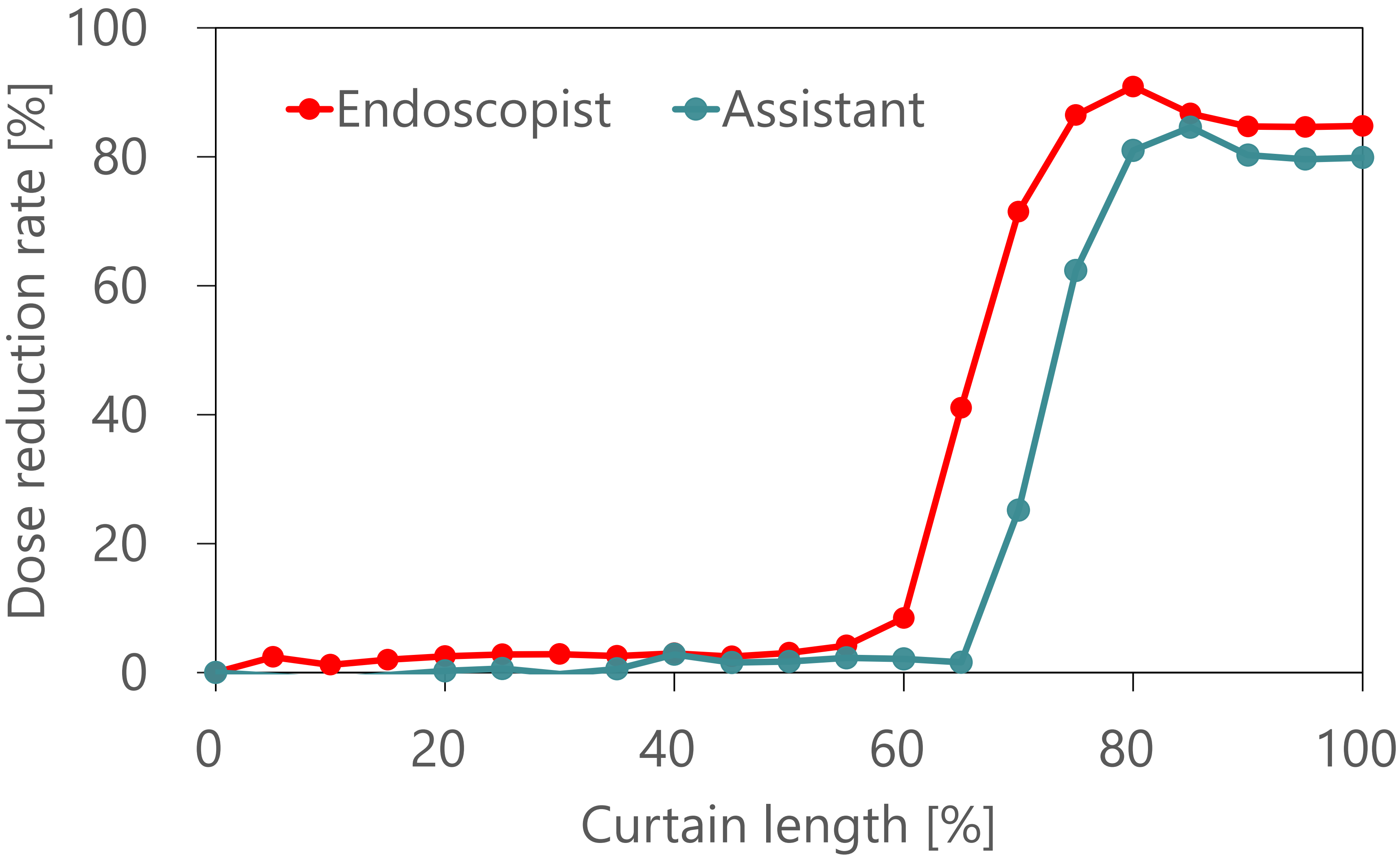
Effect of radioprotective curtain length

- **Simulation code**
  PHITS (Japan Atomic Energy Agency)
- **Curtain length**
  0-100% (5% increments)
- **Relative standard error**
  <1%
- **Photon cutoff energy**
  1 keV



Matsubara K, et al. Phys Eng Sci Med (in press)

Dose reduction rates by simulation

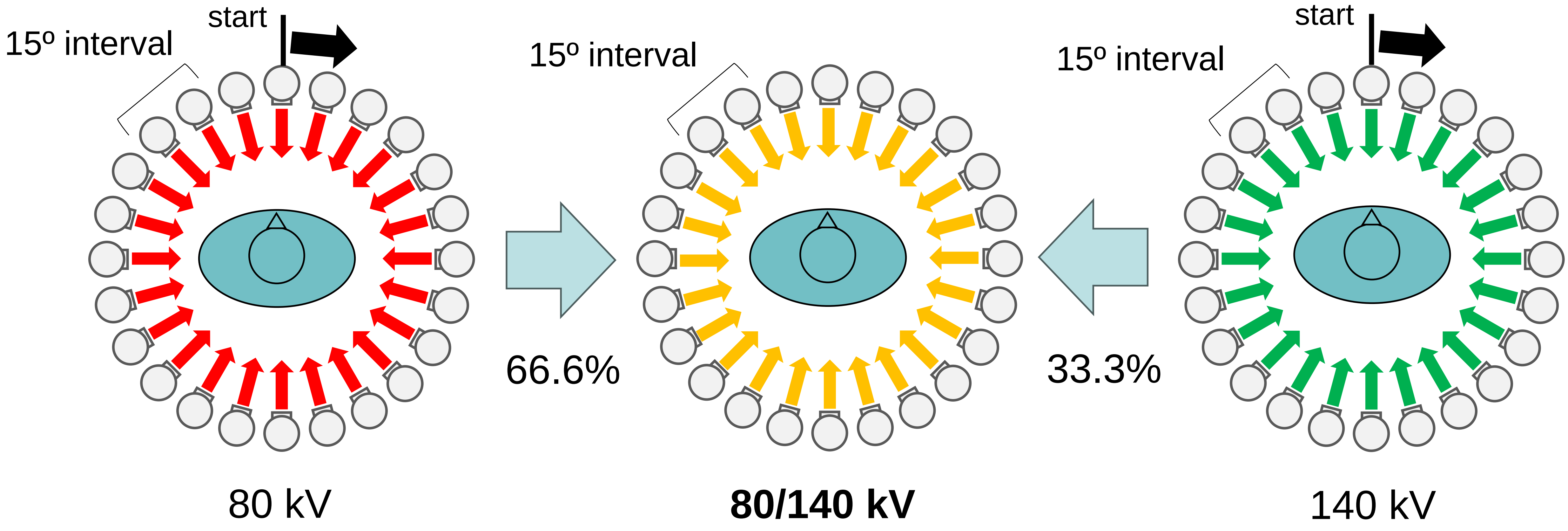


Matsubara K, et al. Phys Eng Sci Med (in press)

MC simulations for fast kV switching dual-energy CT

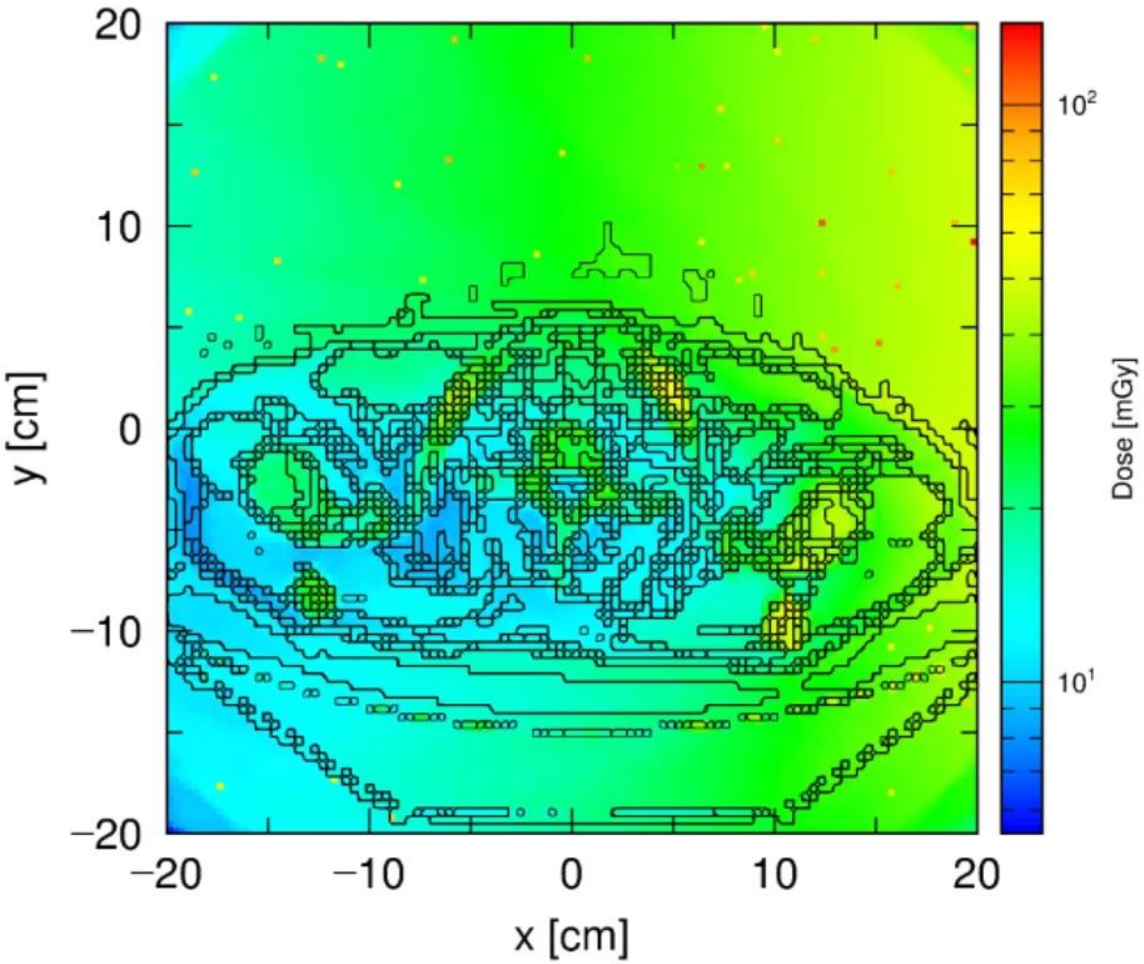
- Modeled CT device

  Revolution CT Apex (GE Healthcare)

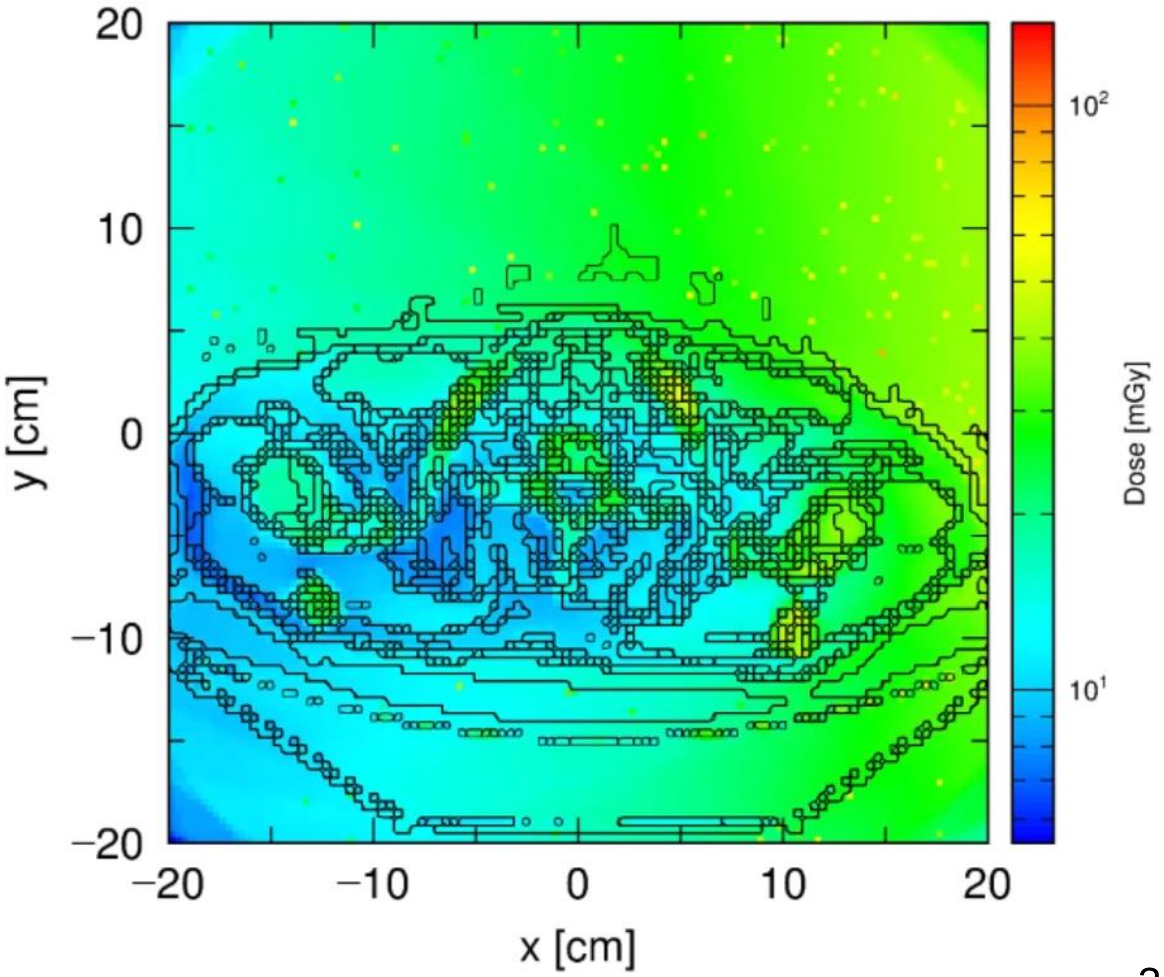


Dose calculation results (Fast kV switching dual energy CT)

◆Single energy CT　120 kV
（$CTDI_{vol}$ = 11.1 mGy）



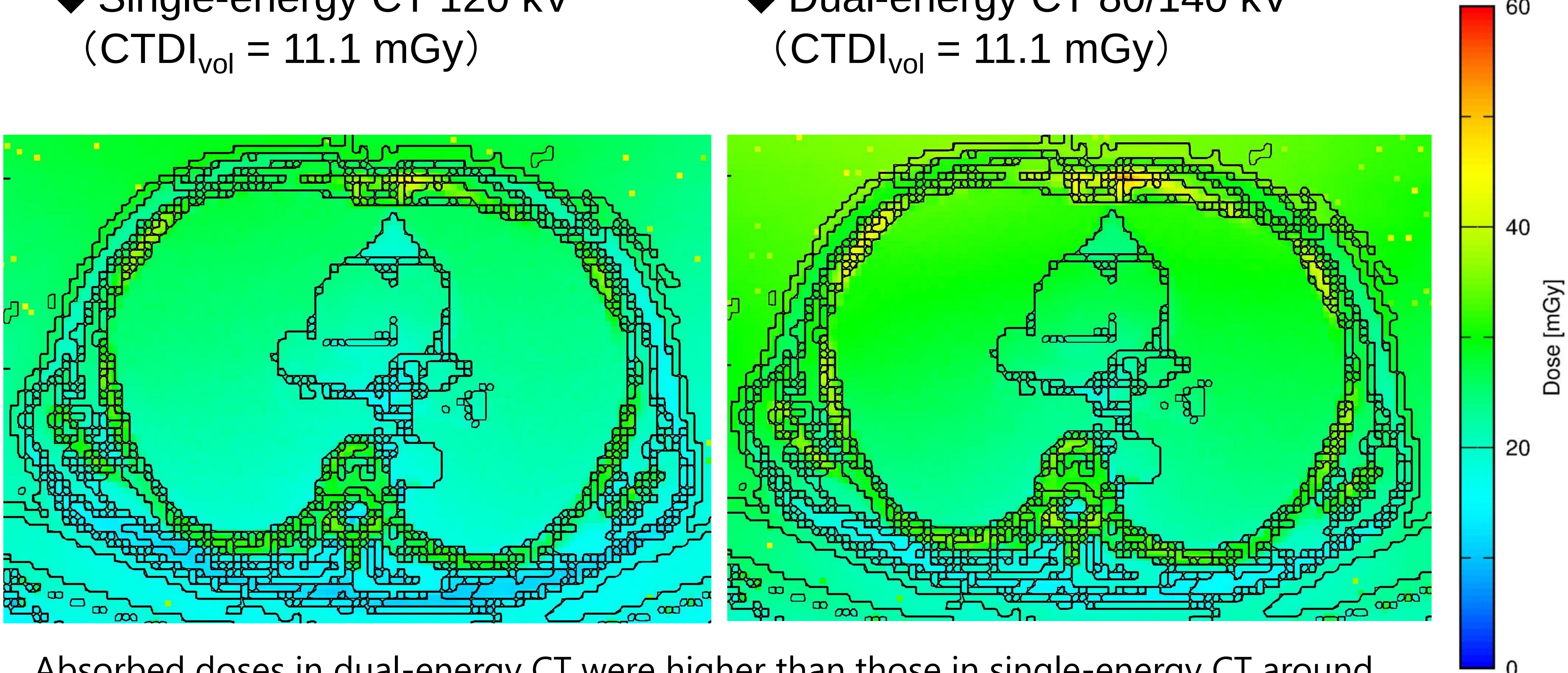
◆Dual energy CT　80/140 kV
（$CTDI_{vol}$ = 11.1 mGy）



Dose calculation results (Fast kV switching dual-energy CT)

◆ Single-energy CT 120 kV
（$CTDI_{vol}$ = 11.1 mGy）

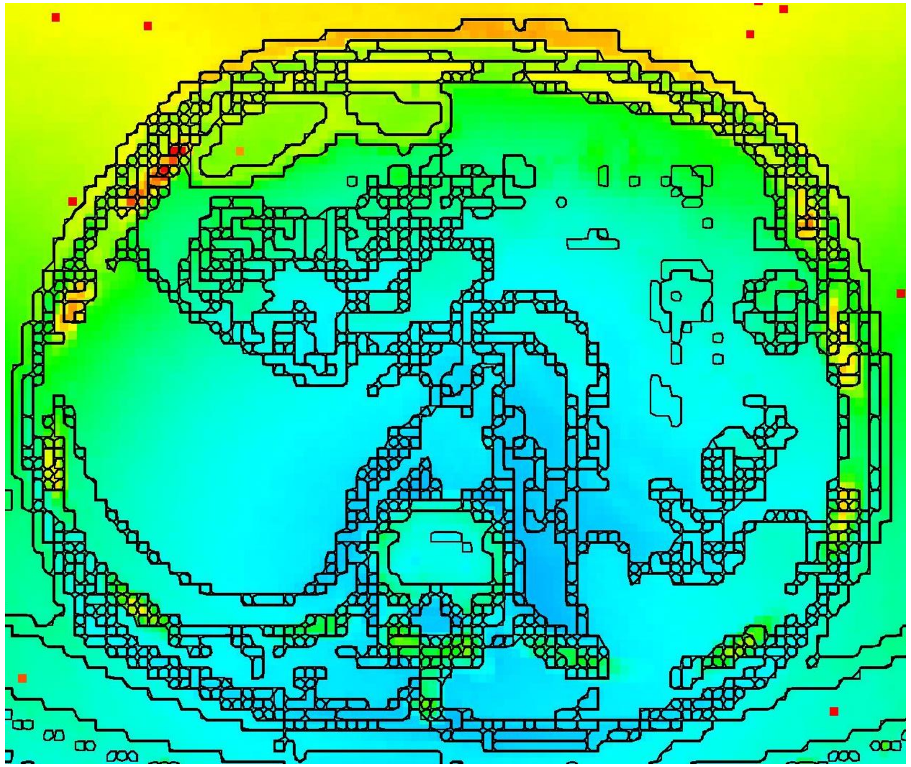
◆ Dual-energy CT 80/140 kV
（$CTDI_{vol}$ = 11.1 mGy）



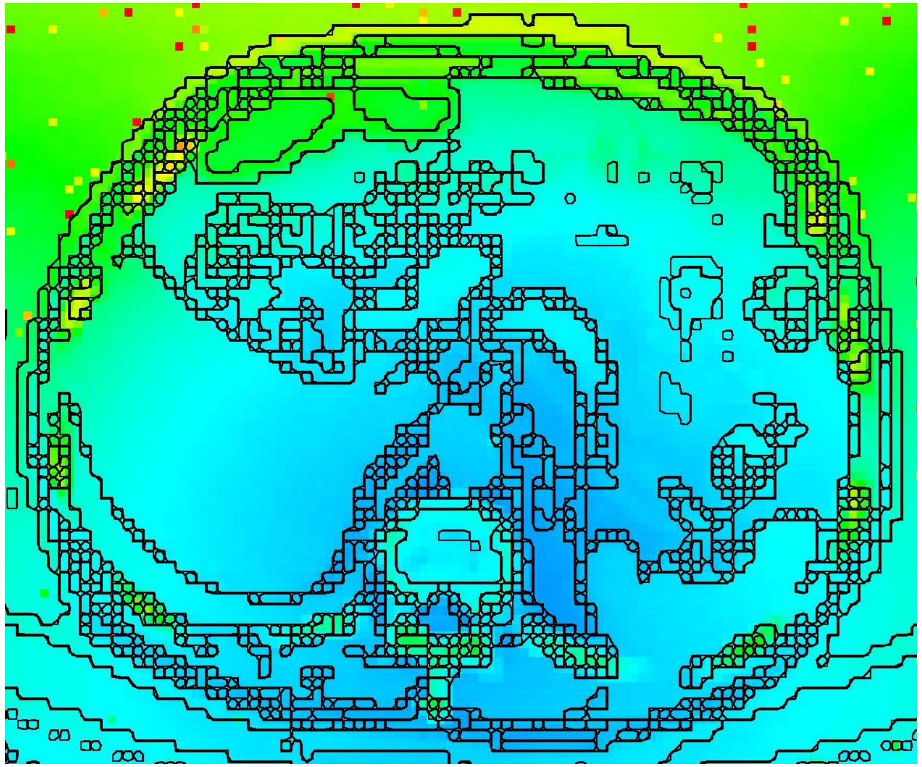
Absorbed doses in dual-energy CT were higher than those in single-energy CT around the mediastinum and the thoracic cage under the same $CTDI_{vol}$

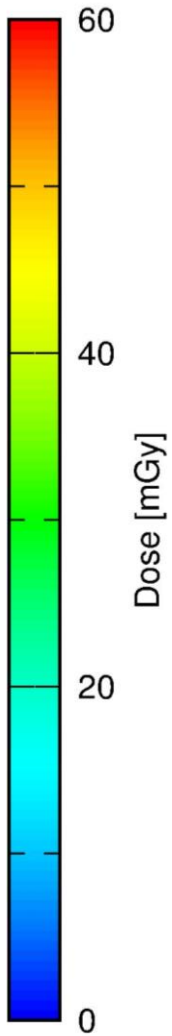
Dose calculation results (Fast kV switching dual-energy CT)

◆ Single-energy CT 120 kV
(CTDI$_{vol}$ = 11.1 mGy)



◆ Dual-energy CT 80/140 kV
(CTDI$_{vol}$ = 11.1 mGy)



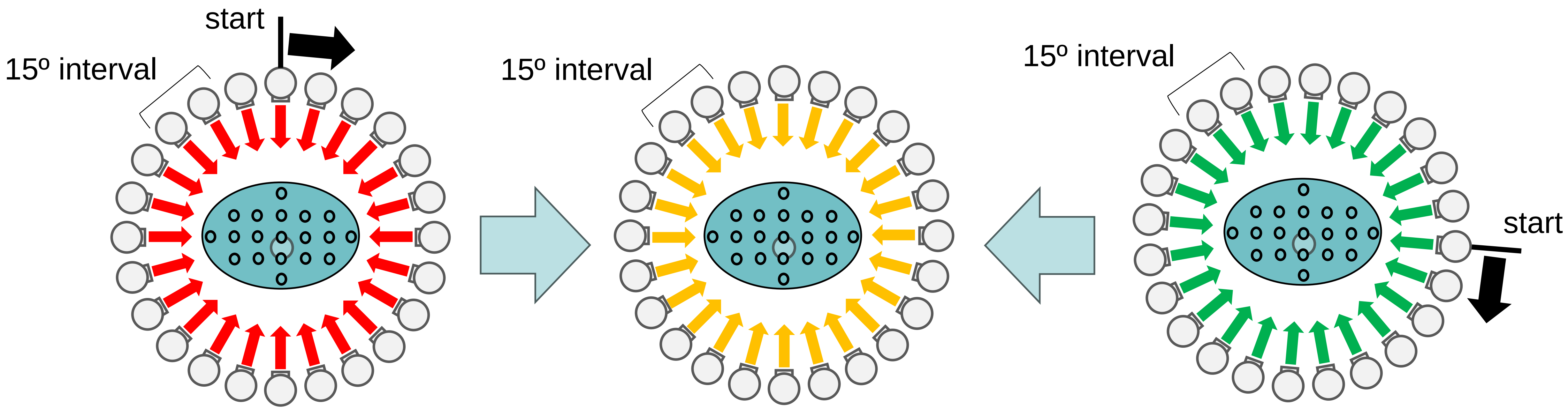


Absorbed doses in single-energy CT were higher than those in dual-energy CT especially at the anterior surface region under the same CTDI$_{vol}$

MC simulations for dual-source dual-energy CT

- Modeled CT device

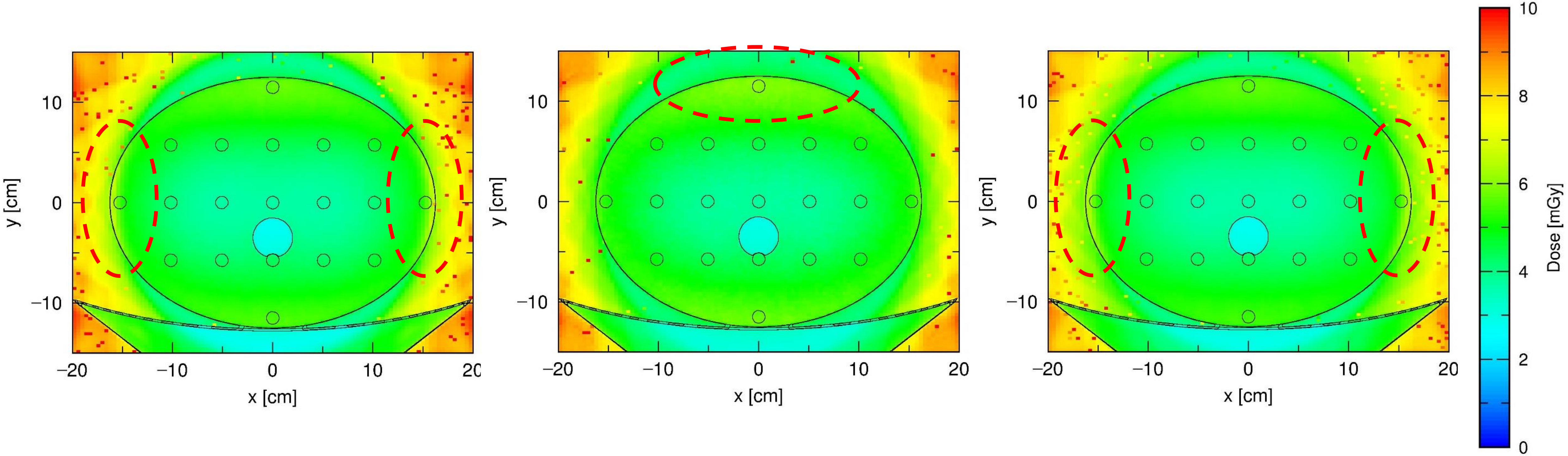
  SOMATOM Force (Siemens Healthineers)



80 kV / 300 eff. mAs	**80/Sn150 kV**	Sn150 kV / 150 eff. mAs
100 kV / 183 eff. mAs	**100/Sn150 kV**	Sn150 kV / 92 eff. mAs

Dose calculation results (Dual-source dual-energy CT)

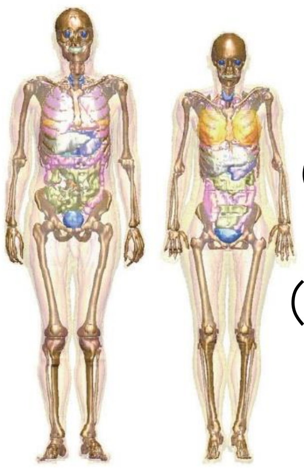
- Single-energy CT 120 kV（$CTDI_{vol}$ = 10.0 mGy）
- Dual energy CT 80/Sn150 kV（$CTDI_{vol}$ = 10.0 mGy）
- Dual energy CT 100/Sn150 kV（$CTDI_{vol}$ = 10.0 mGy）



- Absorbed doses for 80/Sn150 kV were slightly higher than those for 120 and 100/Sn150 kV at the anterior surface region under the same $CTDI_{vol}$
- However, they were slightly lower than for 120 and 100/Sn150 kV at the lateral surface regions

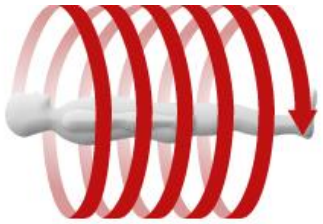
Uncertainties with MC organ dose estimations in CT[1]

Computational phantoms & Patient matching



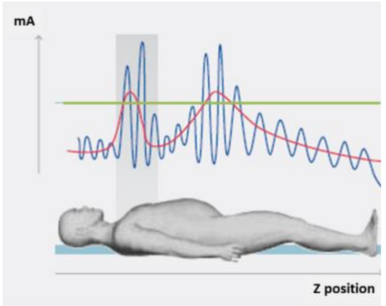
3–66%
（Anatomical structure）
10–15%
（Geometry differences）

Organ start/end location



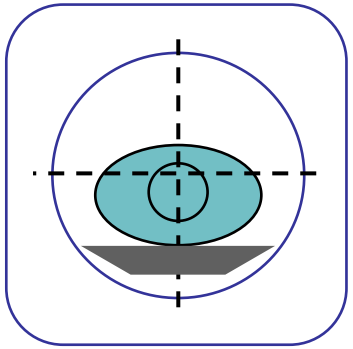
＜10%
（Most organs）
10–33%
（Small surface organs）

TCM simplification



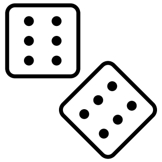
20%
(Depending on the method used to model the dose field under TCM)

Patient positioning



–50%
(Depending upon the actual patient centering)

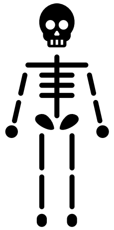
Monte Carlo simulation



5～10%
(differences in the physical models used by different codes)

Slow calculation

Organs partially irradiated



Depends on the extent of partial organ irradiation

1) Created based on AAPM Report 246 (2019) Table 4

Novel methodology for fast and accurate dose assessment

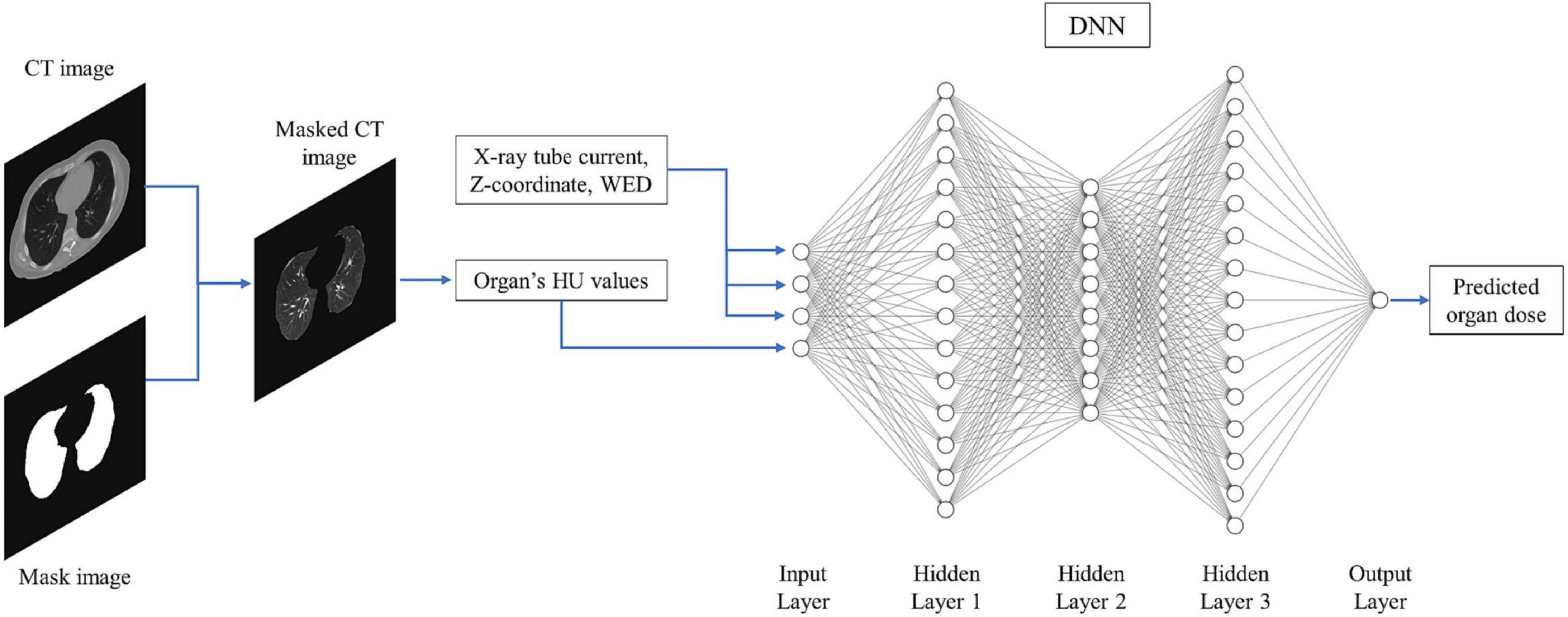
- Speeding up MC calculations
  - Acceleration of calculation by parallel computing
  - Output/read of voxel data in binary format

- Dose distribution prediction using neural network model[1,2)]
  - The collected CT images and the Monte Carlo–produced dose maps were processed and used for the training of the deep neural network (DNN) model
  - Dose maps were produced from CT images using the trained DNN model

1) Tzanis E and Damilakis J. Eur Radiol (2022)
2) Tzanis E, et al. Phys Med (2024)

Workflow and architecture of the DNN

- The training data for the DNN model were retrieved from 119 diagnostic CT examinations and the respective dose maps.



Tzanis E, et al. Phys Med (2024)

Organ doses estimated with DNN model and MC simulations

- To evaluate the dose prediction DNN, data from 67 diagnostic CT examinations and the respective dose images, were used.

	DNN (mGy)	MC (mGy)
Lungs	12.0 ± 4.1	12.7 ± 5.1
Liver	18.1 ± 4.6	18.1 ± 4.5
Spleen	18.3 ± 4.5	18.7 ± 4.2
Stomach	17.7 ± 4.4	17.7 ± 4.1
Kidneys	18.6 ± 4.3	18.4 ± 4.0

The developed machine learning-based methodology resulted in a 99 % reduction of the processing time.

Tzanis E, et al. Phys Med (2024)

Future perspective with the use of MC simulation

Dose calculation software

+

MC
simulation

Accurate dose assessment for individual patients

Risk assessment for individual patients

Determining acceptable image quality levels

Optimization of image quality and dose for individual patients

TMPS and JSRT

MOU was concluded
(Kanazawa, 2015)

Business meeting
TMPS & JSRT
(Bangkok, 2016)

MOU has been renewed
(Nan, 2023)