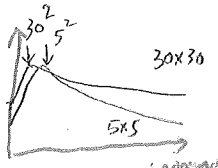
Photon:

when FS ↑
- skin dose ↑.
- d_m ↓ ⇒ more to surface
- PDD ↑



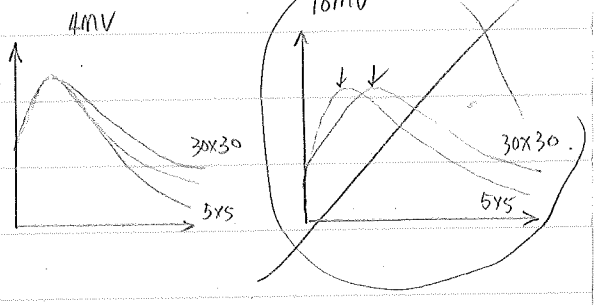
- PDD

PDD ↑ with FS, E ↑

d_{max} not change with FS for low E

d_{max} ↓ with FS ↑ for high E

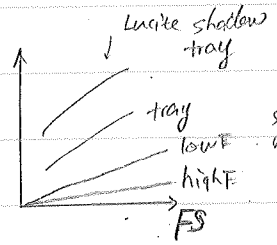
d_{max} independent of SSD for the same FS.

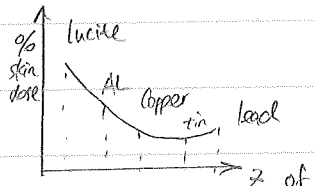


Skin dose

Co	4MV	10MV	18MV
18	14	12	17
70.5	57	30	28
90	74	46	39.5
98	84	55	47

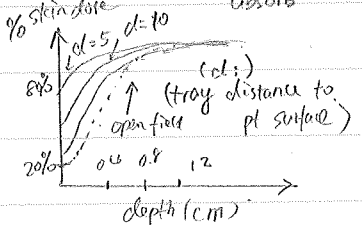
- Surface dose { E. FS. block/tray/compensator/beam spoiler. oblique





- photon (30~40%) electron (80%-90%)
- increase with photon FS ; Oblique angle. low E. absorber in path.
- decreas with physical wedge in path (filteration effect) (7-12% reduction (compared with open field)

EDW surface dose 2% higher than open field.



- skin dose ↓ when SSD ↑, especially for large FS.

- Penumbra.

physical: 20% ~ 80% IDL @ dmax { geometric. side scatter

$P_{geo} = \frac{S\cdot(SSD+d-SCD)}{SCD}$

P_{geo} ↑ with S ↑. SSD ↑. d ↑

↓ with SCD ↑. ⇐ SRS circular cone.

independent of filtering filter

⇐ P ↑ with { S ↑ / SSD ↑ / d ↑ } geo. / FS ↑ / E ↑ (scatter e⁻ have longer scatter range)

For e⁻ beam Penum ↓ with E ↑ ⟷

4-6MV. Penum is sharpest

	penumbra	side scatter
Orthovolt	sharp (S small)	significant
^{60}Co	wide (S large)	some side scatter
4MV	moderate	slightly less
10MV	moderate	little, but larger range side scatter

- output factor ↑ with FS.

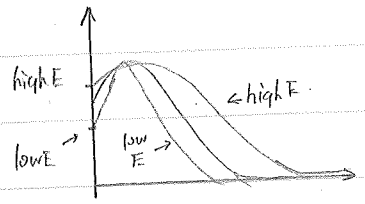
- dose due to scattering is greater for { low E / deeper depth

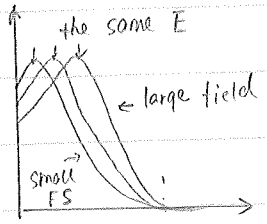
Inhomogeneity correction is more for { low E / more thickness of IM. (lung = bone)

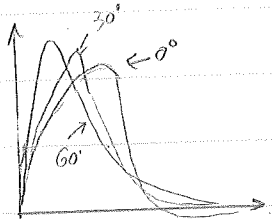
if FS > min lat scatter equv.
change F.S. ⇒ the same PDD.
↑↑ but different output.
% skin dose not changed.

Electron:

- PDD.







R_{80}. R_{90} ↓ with FS ↓
(more significant for high E because of Lateral scatter equilibrium)

surface dose Ds ↑ with FS ↓

Rp remains the same (bremsstrahlung same)

output ↓ flatness ↓

Oblique field:
dmax ↓ Ddmax ↑
PDD shift upstream.
(penetration ↓)
Rp ↑

- $E_z = E_0(1 - \frac{z}{R_p})$ if Rp not given, $R_p = \frac{1}{2} \cdot E_0$

- with SSD ↑ 90% IDL extended more
penumbra ↑ ⇒ can be restored by skin collimator
output ↓ but doesn't follow IVS
PDD, E not changed.

$$\begin{cases} E_0 = 3.2\, R_{90} \\ E_0 = 2.8\, R_{80} \\ E_0 = 2.33\, R_{50} \Rightarrow R_{50} = 1.029\, I_{50} - 0.06 \\ E_0 = 2\, R_p \end{cases}$$

cm ↓ cm ↓

$(R_{50} > I_{10})$

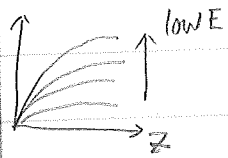
- x-ray contamination

6mev	0.5%
9mev	1%
12mev	1-2%
16mev	4%
20mev	5%

- Virtual soure

$$\sqrt{\frac{I_0}{I_g}} = \frac{f + d_m + g}{f + d_m}$$

- back scatter



- Inhomogeneity (1-1.65 for bone, 0.25 for lung)

$d_{eff} = d - z(1 - CET)$

- penumbra ↑ with SSD, surface to cone distance ↑
with E ↓
with depth d ↑.

- mini field size for Lat. Scatter equiv

$\phi = R_p = \frac{mev}{2}$

or $r > 0.88\sqrt{(E_p)_0}$

TG-40 / NRC

- overall uncertainty for external beam: ±5% dosimetric uncertainty
  ± 5mm geometric (spatial) uncertainty
  for intracavitary plaque brachy: ±15% in delivery of prescribed dose.

- Electron energy specification:
  R_{50} used in TG51
  depth of PDD (2mm @ therapeutic depth) in TG-40.
  should be checked twice a week!

- Daily QA tolerance: 3%-5% report to physicist 5% suspend patient tx.

- wedge interlock check ~~weekly~~ monthly

- Flatness constancy: { photon 2% / electron 3% } symmetry constancy: { photon 3% / electron 3% } rad vs light field ⇒ 1% or 2mm

- 10% brachy seeds or at least 2 ribbons need to be surveyed ⇒ { >3% investigate / >5% report to vendor }

- HDR shielding survey: quarterly after source change, initially and every 5 years (also check head leakage < 0.25mR/hr @ 1m.

- leakage test (wipe) (5nCi)
  (every 6 months for sealed/brachy sources in use)

- Ion chamber / local standard field Instrument
  - leakage; collecting potential ⇒ Each use.
    (0.1%)
  - Redundancy check ⇒ Each
    (2%)
  - Linearity ⇒ 2y
    (0.5%)
  - ADCL ⇒ 2y
  - venting ⇒ 2y
  - Stem effect ⇒ I
    (0.5%)
  - Recombination ⇒ I

Well ion chamber
- leakage ⇒ Each use.
- redundancy check ⇒ each
  (2%)
- linearity ⇒ 2y
  (1%)
- ADCL ⇒ I.S.
- venting
- collection efficiency (1%)
- Geometric / length dependency
- energy dependency
- precision (2%)
- Source well depending

} I

everything 2% 2mm except
- geometry (e^-, γ) 3% ⇐
- mass e^- 3%
- MU chamber Linearity 1%
- daily output 3%

sealed source inventory.
Quarterly for in-use source
semi-annual for stored source

TG-40/NRC

• barometer calibration	3m	1mm/Hg
Thermometer calib	Init	0.1 deg/c.
Linear rule	Init	0.3%

• patient can be released if

radiopharm { measured $\dot{D}$ @ 1m < 5mrem/hr
activity remains in pt < 30 uCi (?)

brachy { measured $\dot{D}$ @ 1m < 5mrem/hr
all temp sources removed

• TG-40 No weekly QA except ^{60}Co → check source position (3mm)

Machine

- cooling system
  - stand:
    - Klystron, Klystron solenoid
    - circulator, rf driver
    - rf load, pulse transform
  - gantry
    - accelerate guide
    - bending maget
    - accelerate solenoid ⇒ 螺线管
    - primary coll /
    - target.
    - energy slit

- vaccume system.
  - klystron
  - electron gun
  - accelerate guide — not (wave guide) ↑ gas filled!
  - bending magent

- e^- emitted from cathode in electron gun in Linac. (Not Anode)

- Thyratron fires ⇒ electron / RF (microwave generator) will be pulsed.

- Dual scattering foils in E beam ⇒ improve flatness for E > 15MeV
  - first high Z foil → scatter e^-
  - second low Z foil → function like field flattening filter
    - ↳ high Z in the middle thicker portion

  For low E e^- beam, only the first foil is enough. So dual scattering foils are not always in beam in electron mode.

- which of following can be replaced without re-scan/calibrate all beams?
  Klystron → only E change → PDD may change.
  RF

Radiobiology:

$$RBE = \frac{\text{dose of 250kV}}{\text{dose of radition of interest}}$$

RBE ↑ with LET ↑. (α, β, heavy charged particles)

↳ high LET (>30 kev/um)

low LET < 2 kev/um.

⇒ clinical e^- beam : 0.2~0.3 kev/um

$$ORE = \frac{\text{dose without } O_2}{\text{dose with } O_2}$$

- X, γ-ray : 2-3.5
- neutron : 1.5
- α : 1

- ORE the smaller, the better
- RBE the bigger, the better

4R
- repopulation
- repair
- reoxygenation
- reassortment

$$S = e^{-(\alpha D + \beta D^2)}$$

$$BED = nd\left(1 + \frac{d}{\alpha/\beta}\right)$$

Rule of thumb

- β particle range: ⇒ to shield β^- source
  - use low Z material
  - high Z ⇒ bremstrulung

  Avg E = 1/3 Emax (β^-)

  Avg E = 0.44 Emax (β^+)

  range in air = Emax (MeV) · (3.66 cm/MeV)

  range in medium R (g/cm²) = Emax/2 (MeV)

  d(cm) · ρ(g/cm³) = Emax/2

  ⇒ d(cm) · 1 g/cm³ = 1MeV/2 ⇒ d = 0.5cm in water

  ^{90}Sr ⇒ 0.5MeV β^- ⇒ 0.5 × 3.66 = 1.83m range in air

  ^{90}Y ⇒ 2.4 MeV β^- ⇒ 2.4 × 366 = 8.78m range in air

- Dose to contralateral breast:
  - Lat field: scattering
  - med field: wedge (dyn wedge ⇒ ↓ dose)

  5% total, each field 2.5%

  5000 cGy ⇒ 250 cGy to contralat

- Dose rate in brachy

  Pt A $\dot{D}$ ≃ 50~60 cGy/hr Pt B $\dot{D}$ ≐ 1/3 Pt A dose rate

  ^{125}I prostate $\dot{D}$ ≃ 5~10 cGy/hr

  ^{103}Pd ... ≃ 20~30 cGy/hr.

  LDR 0 ~ 2Gy/hr

  mDR 0 ~ 12Gy/hr

  HDR > 12Gy/hr

  Vascular brachy (IVBT): 15-20 Gy

  $\dot{D}$ = 5Gy/min

  2mm prescription point

- Inhomogeneity correction:

	Lung	bone
^{60}Co	4%/cm	-3.5%
4mV	3%/cm	-3%
6 mv	2.5%/cm	-2.5%
10 mV	2%/cm	-2%
25 mV	1%/cm	

TMR change (attenuation per cm)

6mV	3.5%/cm
10mV	2.5%/cm
18mV	2%/cm

% attenuation	^{60}Co : 4%/cm
6MV :	3.5%/cm
10MV :	2.5%/cm
18MV :	2%/cm

PDD change per cm will be greater than this

- Important PDD TMR values

	d=10	d=15-16	d=20-21	Tip:
6MV	PDD(d=10) = 67%	PDD% = 50%		When estimate dose change due to patient thickness change.
	TMR(10×10, d=10) = 0.78			
16MV	PDD(d=10) = 77%		PDD(d=20~21) = 50%	① For SAD ⇒ use TMR estimate
	TMR(10×10, d=10) = 0.875			② For PDD ⇒ use PDD (more correct)

- Dose outside field:

6MV 10cm depth. 10×10 cm^2.

2cm	5cm	10cm	20cm	30cm
5%	1-2%	1%	0.2-0.5%	0.1%

↓ ^{60}Co in Khan's book

⇔

TG-36 Table III. Pregnant with Hodgkins disease

6MV 38Gy to tumor / 40Gy Ant plus 13Gy post.

	Top of fetus 15.6cm	mid fetus 28.5	pubic 41.5
dose (cGy)	42	14	6
%	1%	0.4%	0.15%

↓ ↓

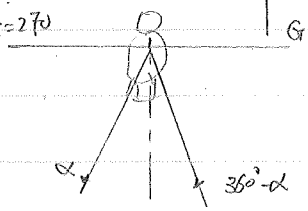
20 ~ 80 cGy according to Raphex.

- photon interaction E

E (meV)	PE (τ)	Compton (σ)	pair (κ)
0.01	95	5	0
0.026	50	50	0
0.150	0	100	0
24	0	50	50

- CSI beam match

	Prone			Supine		
	RL	LL	PA	RL	LL	PA
Y_1	Y_{16}	Y_{16}		Y_{16}	Y_{16}	
Y_2			Y_{25}			Y_{25}
G	90°	270°	0°	270	90	180°
Coll	$\theta = \tan^{-1}(\frac{Y_{25}}{100})$	360°-θ	0°	0	360°-θ	0
Couch	360°-α	$\alpha = \tan^{-1}(\frac{Y_{16}}{100})$	0°	α	360°-α	0

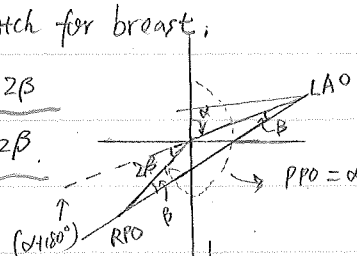


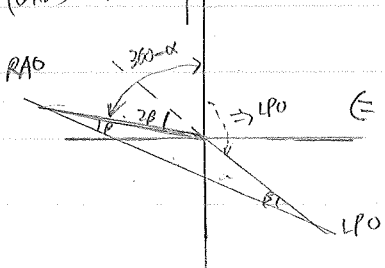
- Tan/Lat field match for breast:

$RPO = LAO^{(\alpha)} + 180^\circ - 2\beta$

$LPO = RAO - 180^\circ + 2\beta$

$\beta = \tan^{-1}(\frac{FS/2}{100})$





$LPO + [(360-\alpha) - 2\beta] = 180^\circ$

$LPO + 360^\circ - \alpha - 2\beta = 180^\circ$

$LPO = \alpha + 2\beta - 180^\circ$

↓

RAO

- pressure change with h:

$$P = P_0 \cdot e^{-\frac{0.0342}{T}\cdot\Delta h} = P_0 \cdot e^{-\frac{0.0342}{273.2+T}\cdot\Delta h}$$

- SRS measurement resolution

{ Linac ⇒ 2mm for profile ; 3mm for output/TMR.
Gammaknife ⇒ 1mm

- machine time error (τ)

$D_1 = \dot{D}(T+\tau) \Rightarrow \dot{D} = \frac{D_1}{(T+\tau)} = \frac{D_n}{T+n\tau} \Rightarrow \tau = \frac{(D_n - D_1)\cdot T}{nD_1 - D_n}$

$D_n = \dot{D}(T+n\cdot\tau)$

To satisfy $\{\Delta D\% = (D_1 - \dot{D}T)/\dot{D}T\} < x\%$

$$\dot{D}\tau/\dot{D}T < x\%$$

$$\tau/T < x\%.$$

$$\Rightarrow \boxed{T > \frac{\tau}{x\%}} \qquad D > \frac{\tau}{x\%}\cdot\dot{D}$$

- IVRT (intra-vascular) film → dose distribution

calibration ⇒ β^- source { extrapolation ion chamber
in water (solid water) $r = 2mm$, $\theta = \frac{\pi}{2}$.

γ source ⇒ re-entrant chamber
free-air ion chamber

Target volume: 2 ~ 5 cm length
0.5 ~ 2mm in thickness

β^- source → higher specific activity ⇒ ^{32}P, $^{90}Sr/^{90}Y$ (activity 30 ~ 40 mCi)
higher dose rate ⇒ 2.3 min Tx time
longer $t_{1/2}$.

γ source → more uniform dose ⇒ ^{192}Ir, (1-4 Ci) ⇒ 20 min Tx time
better radial dose distribution

- Compton scatter:

$$h\nu' = h\nu_0 \cdot \frac{1}{1+\alpha(1-\cos\theta)}$$

$$E_e = h\nu_0 \cdot \frac{\alpha(1-\cos\theta)}{1+\alpha(1-\cos\theta)}$$

$$\alpha = \frac{h\nu_0}{0.511}$$

if $h\nu_0 = 6MV$. E_{emax} when $\theta = 180°$; $h\nu'_{min} = 0.255\ MeV$.

$$E_{emax} = h\nu_0 \cdot \frac{\alpha\times 2}{1+2\alpha} = 5.755\ MeV$$

$$\#\text{ of ion-pairs} = \frac{5.755\ MeV}{33.97\ eV/ion} = \cdots$$

- POF (parallel opposed Field) Khan Page 212.

to achieve ±5% uniformity		to achieve ±10%	
4~6mV	thickness ≤ 15cm	4~6mv	thickness ≤ 20-22cm
10mV	≤ 20cm	10mV	≤ 25-27
^{60}Co	≤ 15cm	^{60}Co	≤ 17cm

- POF TX. If dose from each field change by x%, the total dose change by x%
  not (2× x%)

- POF dmax dose. (Ddm/Dmp)
  anything ↑ PDD will ↓ the dmax dose relative to dmp (better homo):
  - beam E. ↑
  - SSD ↑
  - FS ↑
  - thickness of patient ↓
  - SSD better than SAD

- Higher E in POF tx.:
  - ↓ dm dose
  - ↓ skin dose.
  - ↓ dose in buildup region
  - ↓ dose in lung-tissue interface ⇐ loss of lateral e^- equilibrium
  - improve homogeneity

- Inhomogeneity correction
  - more for low E (because of more attenuation)
  - more for lung
  - for high E, less correction, but may underdose lung tissue interface

- Integral Dose

  = kg × cGy = J

  as E↑ integral dose ↓

  less beam ↓

- Estimate TX dose changes:

  ① patient relative position change

  use IVS correction:

  Ex: ODI read 98cm instead of 100cm (SSD)

$$\begin{cases} D = (MU \cdot Output)_w \cdot PDD(f=98, d) \cdot \left(\frac{SCD}{98+d_m}\right)^2 = (MU\,output) \cdot PDD(f=100, d) \left(\frac{SCD}{98+d_m}\right)^2 \cdot F \\ D_0 = (MU \cdot output)_w \cdot PDD(f=100, d) \cdot \left(\frac{SCD}{100+d_m}\right)^2 \end{cases} \Rightarrow \frac{D}{D_0} = \left(\frac{100+d_m}{98+d_m}\right)^2 \cdot \left(\frac{98+d_m}{100+d_m}\right)^2 \left(\frac{100+d}{98+d}\right)^2$$

$$= \left(\frac{100+d}{98+d}\right)^2 \overset{d=10}{\approx} 1.037$$

  Ex: Patient iso should be 100, but setup @ 98cm. (SAD)
  (for example, laser shifted)

$$D_0 = (MU.output) \cdot TMR(d=X, r_{dx}) \cdot \left(\frac{100}{100}\right)^2$$

$$D = (MU.output) \cdot TMR(d=X, r'_{dx}) \cdot \left(\frac{100}{98}\right)^2 \Rightarrow \frac{D}{D_0} = \frac{TMR(d=X, r'_{dx})}{TMR(d=X, r_{dx})} \cdot \left(\frac{100}{98}\right)^2$$

$$= 1.041$$

  ② patient thickness change.

photon beam d_m:

- the point where kerma = dose.
- equal to the max range of secondary electrons
- the point of electronic equilibrium.

TG-51

photon:

[1]. PID% scan @ SSD=100cm. ⇒ %dd(10)x from PDD shifted upstream 0.6r
>10mv. Pb 1mm @ 50±5 cm %dd(10)$_{Pb}$ → calculate %dd(10)x
↓ also shift upstream
} ⇒ K_Q = ?

[2] $M = M_{raw} \cdot P_{TP} \cdot P_{ion} \cdot P_{elec} \cdot P_{pol}$

d_{ref} { SAD=100 d=10 ⇒ or SSD=100 d=10

$P_{TP} = \frac{273.2+T}{295.2} \cdot \frac{760}{P} \left(\frac{101.33}{P}\right)$ $P_{ion} = \frac{(1-\frac{V^H}{V^L})}{(\frac{M^H}{M^L}-\frac{V^H}{V^L})}$ $P_{pol} = \frac{|M^+_{raw}-M^-_{raw}|}{2M_{raw}}$

[3] $D_{ref} = M \cdot N^{Co^{60}}_{Dw} \cdot K_Q$

[4] $D_{cal} = D_{ref} / PDD(d=10)$ if SSD=100, dm → 1cGy/mU.

$D_{cal} = D_{ref} / TMR(d=10, 10\times10)$ if SAD=100, dm → 1cGy/mU

⇓ if calib at d=10cm, calculate as d=dm ⇒ overdose $1/TMR(d=10)$
if calib at d=dm, calculate as d=10 ⇒ underdose.

Electron:

[1] PID scan @ SSD=100cm ⇒ I_{50} on upstream shifted PID (0.5r)

$R_{50} = 1.029 \cdot I_{50} - 0.06$ (cm). ⇒ calculate $K'_{R50} = 0.9905 + 0.071 e^{-R_{50}/3.67}$

[2] $d_{ref} = 0.6 \times R_{50} - 0.1$ (cm). chamber model ⇒ K_{eqal} = ?

[3] SSD=100 d=d_{ref}. 15×15 cone.

$M = M_{raw} \cdot P_{TP} \cdot P_{ion} \cdot P_{elec} \cdot P_{pol}$

[4] shift chamber by 0.5 r_{cav}.

$P^Q_{gr} = \frac{M_{raw}(d_{ref}+0.5r_{cav})}{M_{raw}(d_{ref})}$

[5] $D_{ref} = M \cdot P^Q_{gr} \cdot K'_{R50} \cdot K_{eqal} \cdot N^{Co^{60}}_{Dw}$ (K_{R50})

P.P.I chamber

⇑

$D_{ref} = M \cdot K'_{R50} \cdot K_{eqal} \cdot N^{Co^{60}}_{Dw}$ (K_{eqal} from cross-calib)

[6] $D_{cal} = D_{ref} / PDD(d=d_{ref})$ ⇒ SSD=100, d=dm, 1cGy/mU

Dose Limits:

		Shielding
A. Occupational		
1. TEDE	50mSv/yr	0.1mSv/wk
2. DE for tissue & organs		
lens of eye	150mSv/yr	
All others	500mSv/yr.	
3. Guidance: cumulative.	10mSv x age.	
B. public.		
1. TEDE continuous	1mSv/yr	0.02mSv/wk
		<0.02mSv any one hour.
infrequent.	5mSv/yr	
2. Dose equiv to		
lens, skin, extremities	50mSv/yr,	lens 15mSv/yr
C. Educational & training		
1 TEDE	1mSv/yr	
2. Dose equiv to lens/skin/extremities.	50mSv/yr	
D. Embryo-fetus		
1. TEDE	5mSv/yr	
2. Dose limit in a month:	0.5mSv/month	

Radiation Signs:

Cause Rad Area	5 mRem in a hr @ 30cm	⇒ Gamma knife.	0.05mSv
High Rad Area	100 mRem in a hr @ 30cm.	⇒ HDR, ^{60}Co	1mSv
Very High Rad Area	500 rads in a hr @ 1m.		5Sv
Airborne Rad	Air concentration exceeding DAC		
Radioactive material	use or storage of 10 times the quantity in Appendix C.	⇒ HDR. ^{60}Co, γ-knife, hot lab	

Transportation labels:

Transport Index (TI): dimensionless number (round up to the next tenth)

= [max radiation (mSv/hr) @ 1m from ext surface] × 100

= max radiation (mRem/hr) @ 1m from ext surface

	TI	max rad level at any point on ext. surface		Label
< 0.05 mrem ⇒	0	≤ 0.5 mrem/hr	0.005 mSv/hr	white
< 1 mrem ∈	0 ~ 1	≤ 50 mrem/hr	0.5 mSv/hr	yellow-I
< 10 mrem ∈	2 ~ 10	≤ 200 mrem/hr	2 mSv/hr	yellow-II
	> 10	≤ 1000 mrem/hr	10 mSv/hr	yellow-III

covert to 1m by IVS $\left(\frac{1}{100}\right)^2$

⇓

compared with 2mRem/hr

- The container must be D.O.T. approved.
- TI must be measured, written on label.
- The activity & radionuclide must be stated on label