Basic Nuclear Engineering 4 (原子核工学基礎第四)
(6) Diagnostic use of Radiation and Protection from Radiation Effects

Department of Transdisciplinary Science and Engineering

Institute of Integrated Research
Laboratory for Zero-Carbon Energy

Yoshihisa Matsumoto

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Radiation Diagnostics

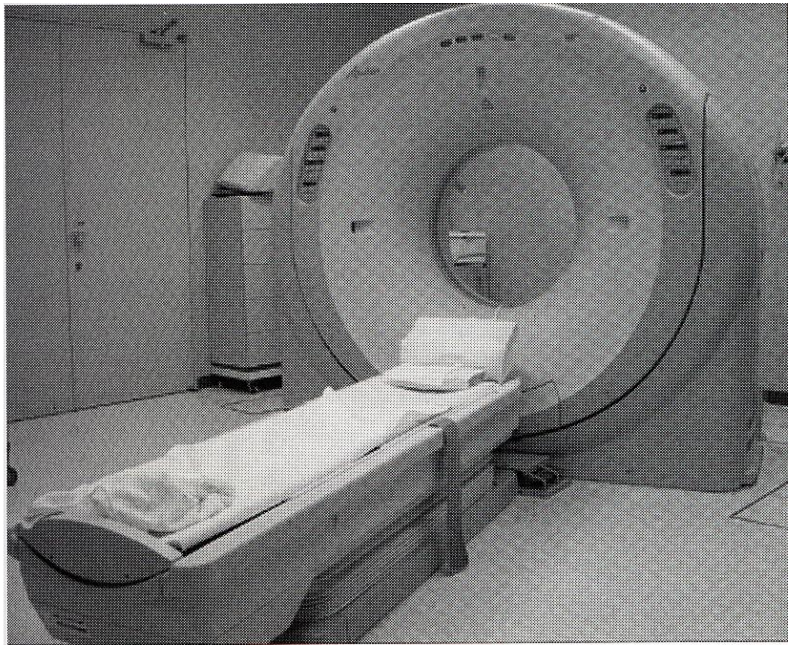
◆CT (Computed Tomography)

◆PET (Positron Emission Tomography)

◆Nuclear Medicine (核医学)

CT (Computed Tomography)

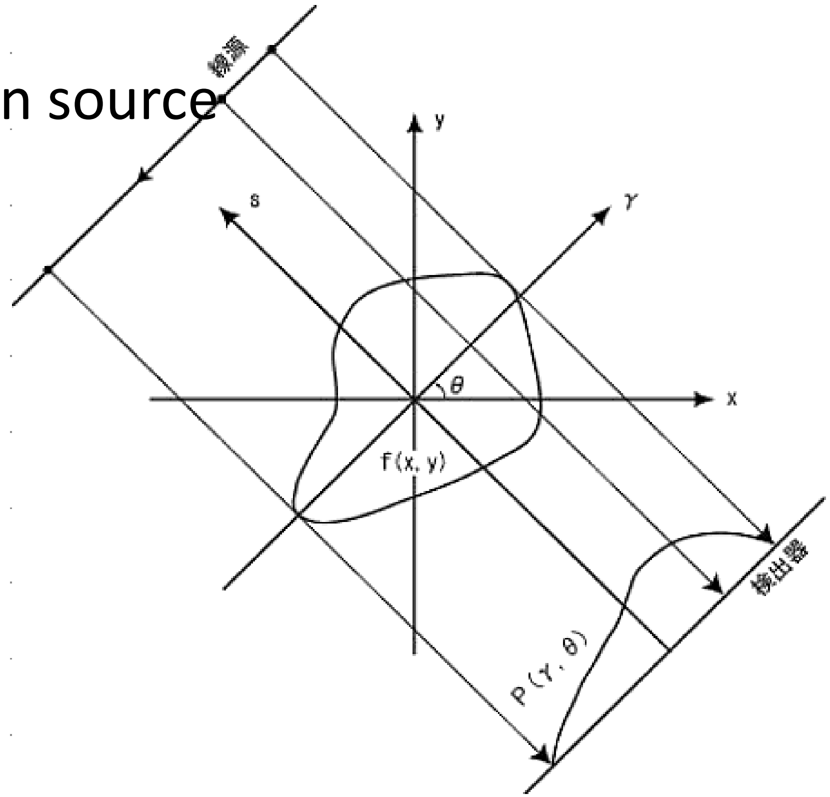
1963 Alan Cormack(UK) Theoretical basis of CT
1972 Godfrey Hounsfield(South Africa→USA)
Build CT apparatus
1979 Nobel prize



CT apparatus

(「放射線医科学」)

Basic Principle of CT



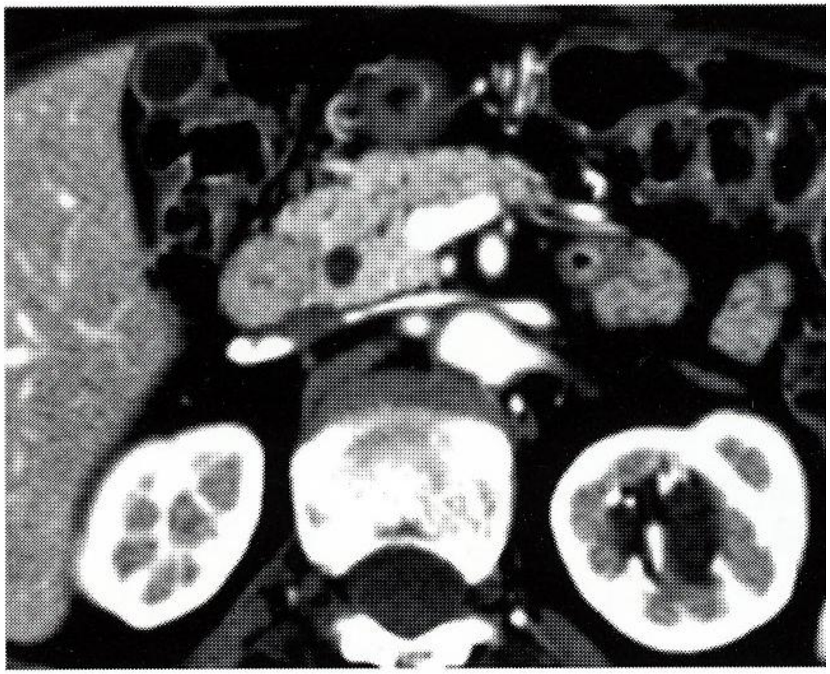
$$p(r,\theta)=\int f(r\cos\theta - s\sin\theta, r\sin\theta + s\cos\theta)ds \qquad (1)$$

f(x,y): X−ray absorbance coefficient at coordinate (x,y)

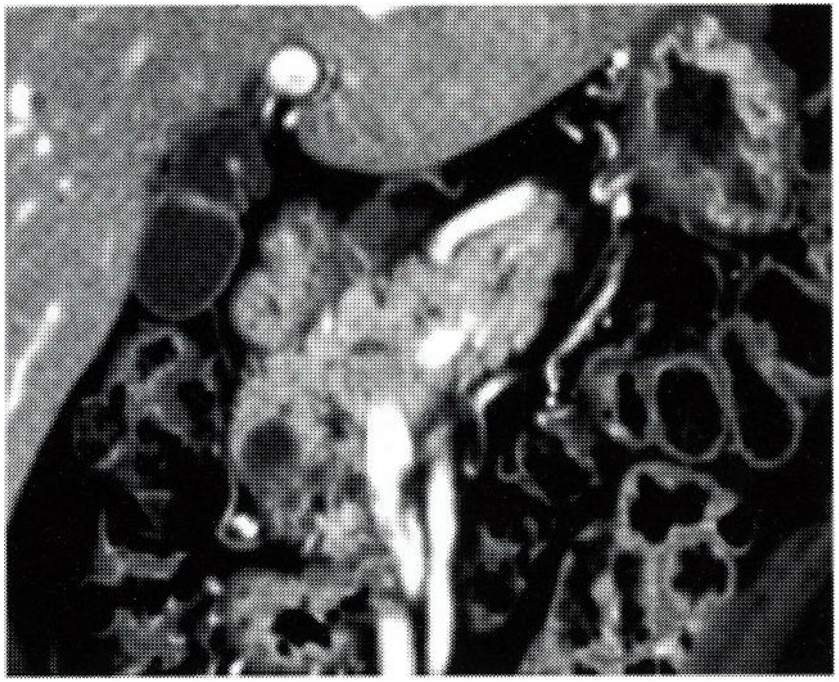
f(x,y)→p(r, θ) : Radon transformation (projection)

p(r, θ)→f(x,y) : Inverse Radon transformation (back projection)

Examples of CT (1)



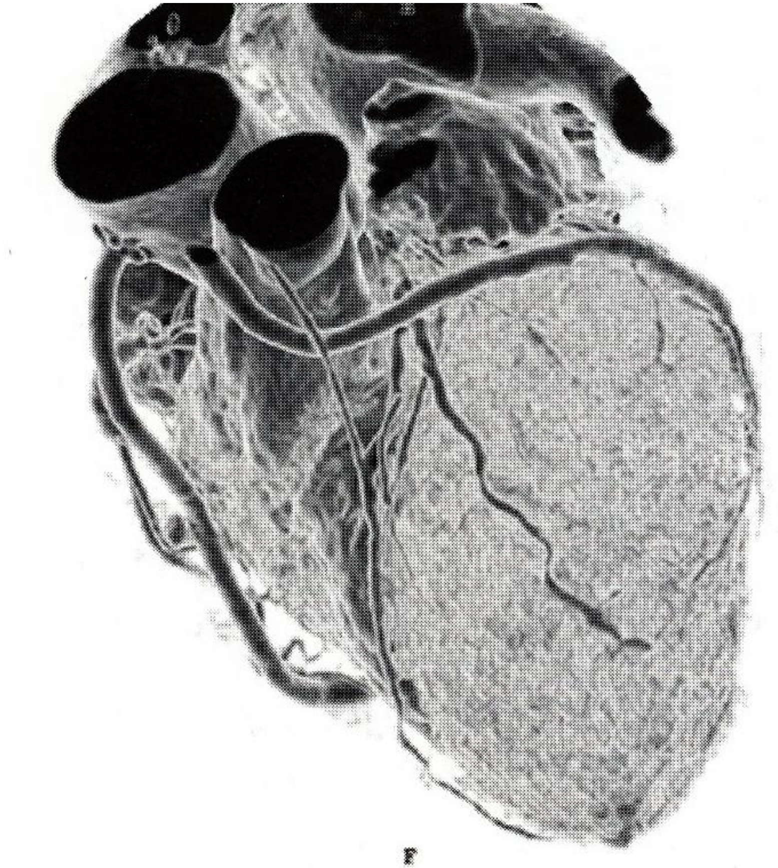
Cross section of pancreas
(膵臓)



3D-reconstituted image
(MRP image)

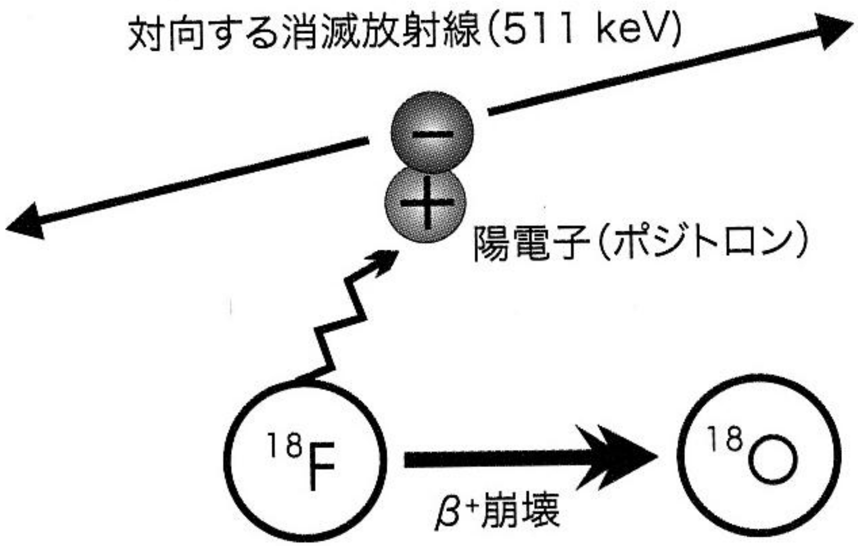
MRP: multi-planar
reconstruction

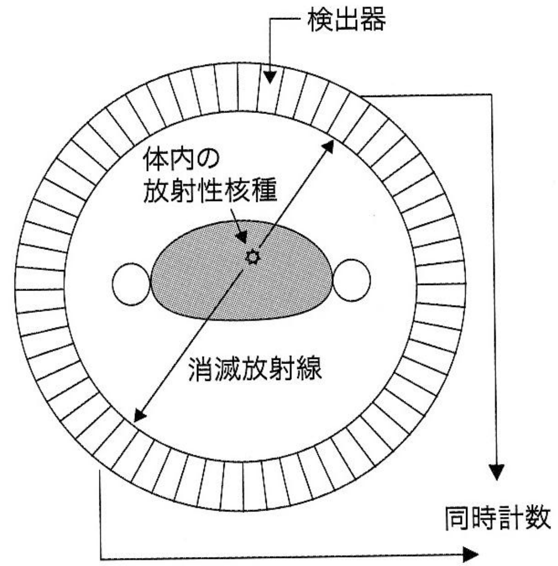
Examples of CT (2)



Coronary artery and heart
冠動脈と心臓

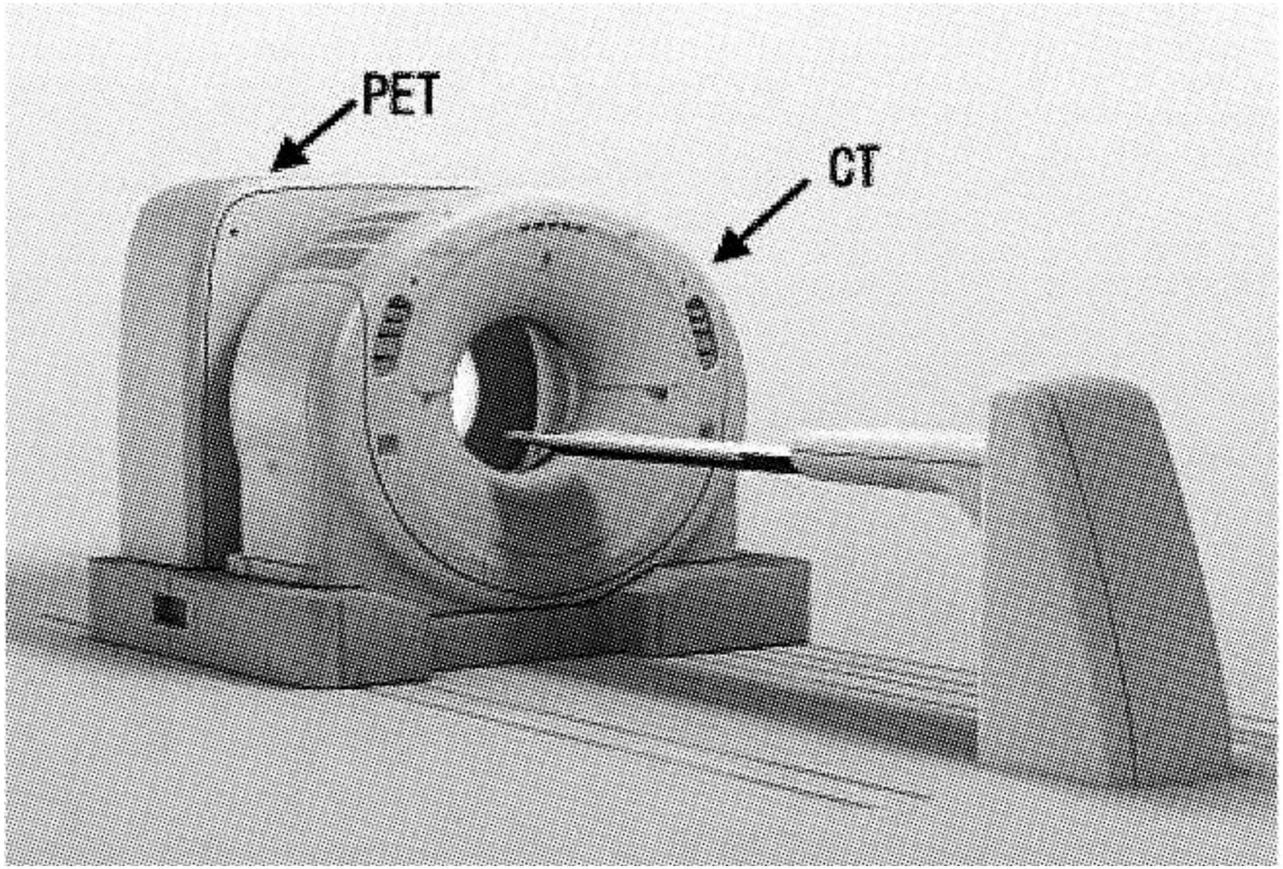
PET (Positron Emission Tomography)





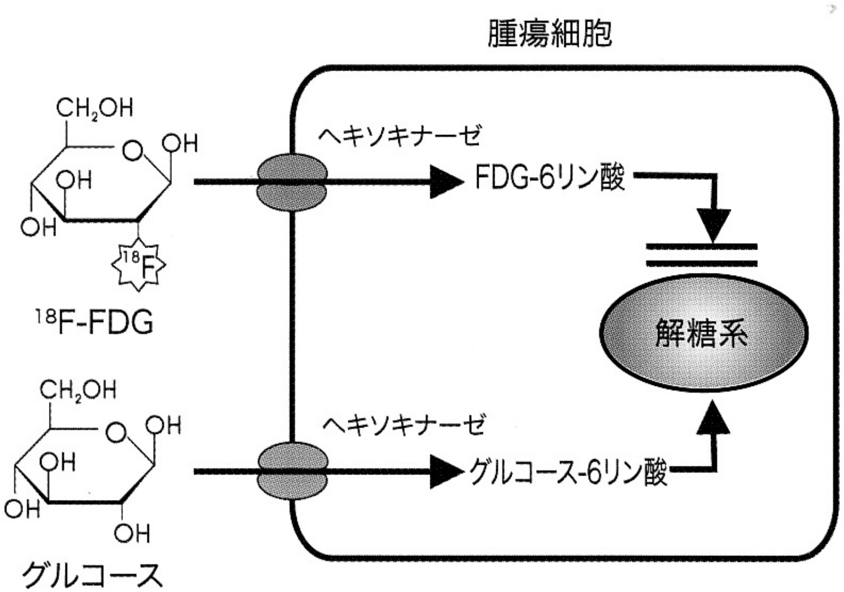
Detect annihilation radiation (511keV) associated with β^+ decay. Two photons of 511keV are emitted toward opposite direction. Therefore, the radioactivity is considered to exist between two detectors which detected two photons simultaneously.

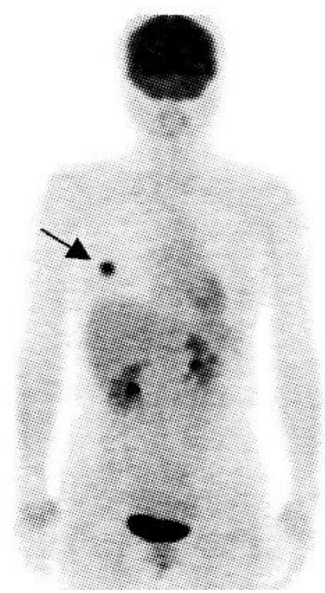
PET apparatus



In this apparatus, CT scanner and PET scanner is aligned on the same base. The combination of “functional image” by PET and “morphological image” by CT enables diagnosis of high accuracy.

^{18}F-FDG (fluorodeoxy-glucose) PET

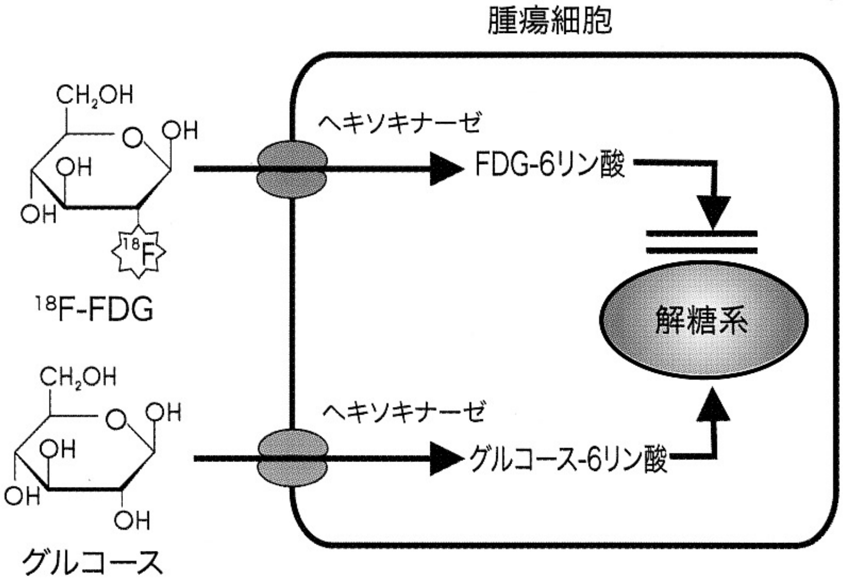


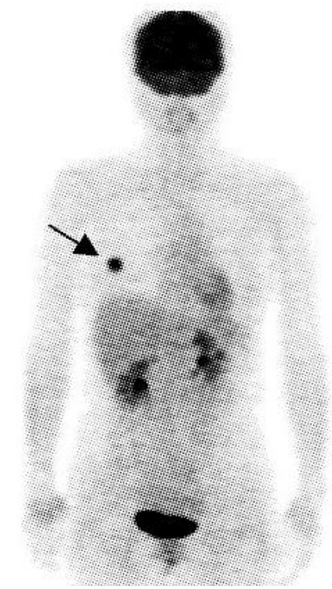


PET image of breast cancer. Arrow shows breast cancer. Note also accumulation in brain, kidneys and bladder.

FDG is incorporated into cells by glucose transporter and then phosphorylated by hexokinase. While glucose undergoes metabolism by glycolysis system, FDG does not go to metabolic pathway and accumulates in cells. Cancer cells show strong accumulation of FDG, because of highly active glycolysis. However, FDG also accumulates strongly to brain, in which glycolysis is active, and also in kidneys and bladder, which are on the way for urinal excretion.

^{18}F-FDG (fluorodeoxy-glucose) PET





FDGはグルコーストランスポーターにより、細胞内に取り込まれ、
ヘキソキナーゼにより、リン酸化される。
グルコースは解糖系により代謝されるが、FDGは代謝されず、
体内に蓄積する。がんはグルコース代謝が盛んであるため、
強い集積を示す。他に、正常組織の中でグルコース代謝が盛んな
脳、排泄経路である腎臓、膀胱などにも集積が認められる。
右は乳がんのPET画像。

Representative PET reagent

Nuclide	Half life	Compound and purpose of use
^{18}F	110m	FDG (Imaging tumor) NaF (Bone metabolism)
^{11}C	20m	Choline (Tumor)
^{13}N	10m	Ammonia NH_3 (Myocardial blood flow)
^{15}O	2m	Water H_2O (Myocardial blood flow)

代表的なPET薬剤

核種	半減期	化合物と用途
^{18}F	110分	FDG(悪性腫瘍描出) NaF(骨代謝)
^{11}C	20分	コリン(腫瘍)
^{13}N	10分	アンモニア(心臓の血流評価)
^{15}O	2分	水(心筋の血流評価)

Nuclear Medicine

Nuclide	Half life	γ-ray energy
^{99m}Tc	6h	141keV
^{201}Tl	73h	70～80keV
^{67}Ga	78h	93, 185, 300keV
^{123}I	13h	159keV
^{131}I	8d	364keV

How to generate nuclides

Nuclides used in nuclear medicine, like ^{99m}Tc, have very short half-life times. It is not suitable for generation in factory and transportation to hospitals. Therefore, it is generated in the hospital using mini accelerator or shipped in the form of parental nuclides, e.g., ^{99}Mo for ^{99m}Tc.

$$^{99}\mathrm{Mo} \xrightarrow[66\mathrm{h}]{\beta} {}^{99m}\mathrm{Tc} \xrightarrow[6\mathrm{h}]{\gamma} {}^{99}\mathrm{Tc} \xrightarrow[2.1\mathrm{x}10^{5}\mathrm{y}]{\beta} {}^{99}\mathrm{Ru}$$

^{99}Mo is generated in nuclear reactor from ^{98}Mo. After sufficient time, the ratio of ^{99m}Tc to ^{99}Mo become constant ((transient) radiation equilibrium). At that time, ^{99m}Tc is separated from ^{99}Mo. ^{99}Mo is called a generator or “cow”. Procedure to isolate ^{99m}Tc from ^{99}Mo is called “milking”.

核医学

主な核種

核種	半減期	γ線エネルギー
^{99m}Tc	６時間	141keV
^{201}Tl	７３時間	70～80keV
^{67}Ga	７８時間	93, 185, 300keV
^{123}I	１３時間	159keV
^{131}I	８日	364keV

Radiation Detection in Nuclear Medicine

γ -ray線

↓Collimeter

↓NaI Scintillator

Scintillation light

↓Photo electron multiplier

Electric signal

Scintigraphy : Photograph with planer detector attached to body surface

SPECT (single photon emission computed tomography) :
Photograph with detector rotating around body

核医学における検出法

γ 線
↓コリメータ
↓NaIシンチレータ
蛍光
↓光電子増倍管
電気信号

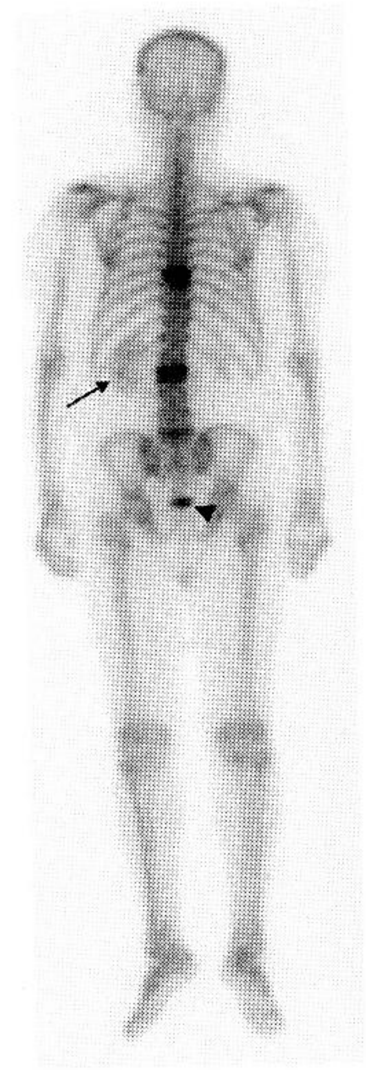
シンチグラフィー：パネル状のカメラを体表に接して撮影
SPECT (single photon emission computed tomography)：
　カメラを体の周囲で回転させて撮影

Examples of Nuclear Medicine (1)

◆Bone scintigraphy (骨シンチグラフィー)

^{99m}Tc–MDP (methyl enediphosphonate) show accumulation in bone with hydroxyapatite, a major inorganic constituent of bone. The extent of accumulation reflects blood flow and bone metabolism. Useful in the detection of metastasis of malignant tumor.

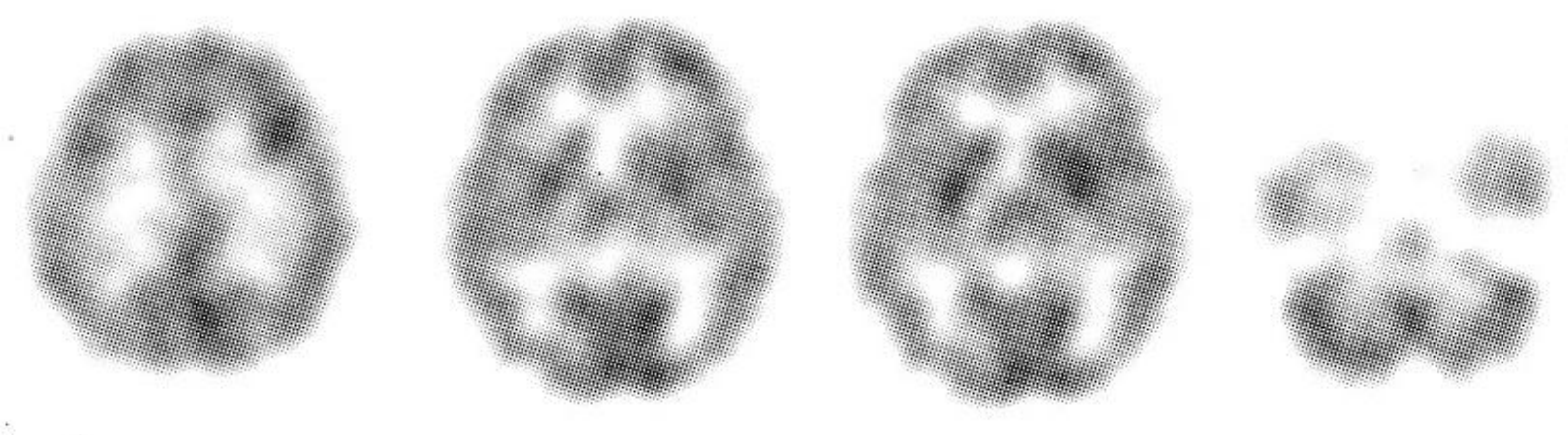
^{99m}Tc–MDP (methyl enediphosphonate)は、骨の無機質の主要成分であるヒドロキシアパタイトに集積し、その程度は血流量と骨代謝に依存して決まる。悪性腫瘍の転移の検索に有用。



Examples of Nuclear Medicine (2)

◆Cerebral Blood Flow Scintigraphy

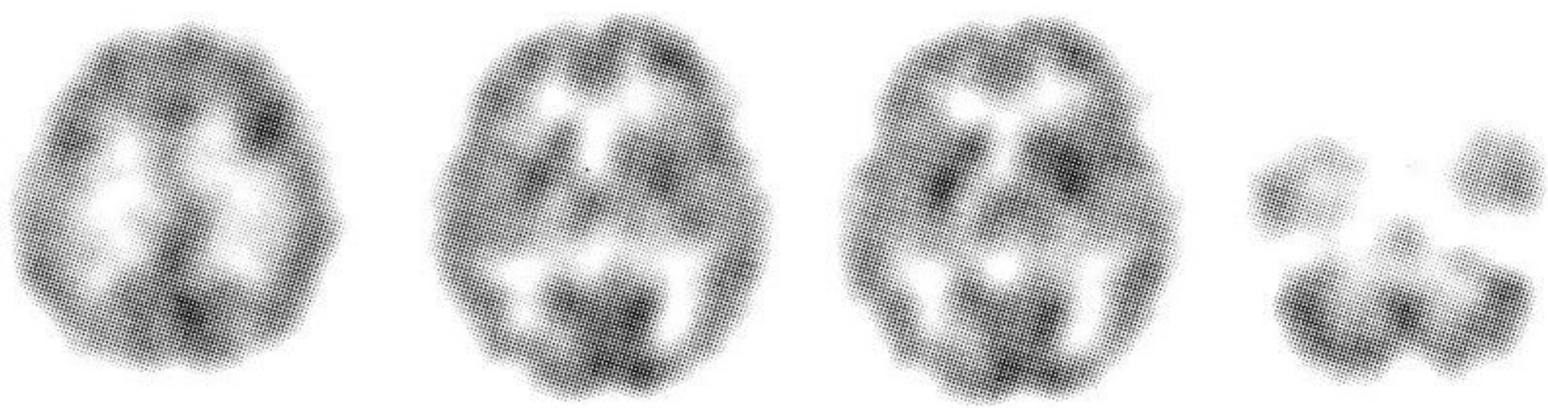
Using lipid soluble molecule, such as ^{99m}Tc-ECD (ethyl cysteinate dimmer)、 ^{99m}Tc-HMPAO (hexamethylpropylene amine oxime),which can pass blood-brain barrier and be incorporated to brain parenchyma, measure the cerebral blood flow (CBF) rate per brain tissue weight.



主な核医学検査(3)

◆脳血流シンチグラフィー

^{99m}Tc-ECD (ethyl cysteinate dimmer)、^{99m}Tc-HMPAO (hexamethylpropylene amine oxime)などの脳血流関門を越えて脳実質内に取り込まれる脂溶性物質を利用して、脳組織重量あたりの毎分血流量CBF(cerebral blood flow)を測定することができる。灰白質の血流量は白質より多い。



Examples of Nuclear Medicine (3)

◆Myocardial Scintigraphy

①Myocardial blood flow: ^{201}Tl reflects myocardial blood flow as it shows similar biological properties to K^{+} and incorporated into cardiomyocytes. The accumulation of ^{201}Tl is decreased in ischemic heart disease. Sensitivity is improved by exercise load. ^{99m}Tc-MIBI (methoxyisobutyl isonitrile) or ^{99m}Tc-tetrophosmine are also used for the same purpose.

②Myocardial fatty acid metabolism: Cardiomyocytes usually use fatty acids as the energy source but use anaerobic glucose metabolism in ischemia or myocardial dysfunction. Thus, the decreased fatty acid metabolism can be used as an indicator for ischemia and myocardial dysfunction can be diagnosed. ^{123}I-BMIP is often used as it is incorporated to cardiomyocytes and stays for a long period.

主な核医学検査(4)

◆心臓シンチグラフィー

①心筋血流 ： ^{201}TlはK+と似た生物学的性質を示し、Na+−K+ ATPaseにより心筋細胞に取り込まれ、心筋の血流を反映する。虚血性心疾患では集積が低下する。特に、運動負荷を与えることにより検出感度が向上する。 ^{99m}Tc−MIBI (methoxyisobutyl isonitrile) や^{99m}Tc−テトロホスミンなどが用いられる場合もある。

②心筋脂肪酸代謝：心筋はエネルギー源として脂肪酸を利用しているが、虚血や心筋障害時には嫌気性糖代謝が行われる。脂肪酸代謝の低下を指標として、虚血や心筋障害を捉える。脂肪酸と同様に心筋に取り込まれ、長く留まる^{123}I−BMIPPなどが用いられる。

Radiation Protection

International Organizations (1)

◆Scholarly committees

Committees that summarize and analyze data and suggest risk estimates (not feel compelled to make a recommendation)

i) UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation)

ii) BEIR committee (Biological Effects of Ionizing Radiation) in USA

International Organizations (2)

◆Pragmatic committees

Committees that formulate the concepts for use in radiation protection and recommend maximum permissible levels

i) ICRP (International Commission on Radiological Protection)
ii) IAEA (International Atomic Energy Agency)
iii) ICRU (International Commission on Radiation Units and Measurements)
iv) NCRP (National Council on Radiation Protection and Measurements) in USA

ICRP

International Commission on Radiological Protection
国際放射線防護委員会
Headquarter： Canada, Ottawa
・Initially established as IXRPC (International X-ray and Radium Protection Committee, 国際X線およびラジウム防護委員会).　Renamed in 1950.
・Consisting of five committees. Members are scientific experts from all over the world in radiation physics, chemistry and biology.
・Publish recommendations. The recommendations have no legally binding power but incorporated to acts and regulations of various countries including Japan.

UNSCEAR

United Nations Scientific Committee on Effects of Atomic Radiation
原子放射線の影響に関する国連科学委員会
Headquarter: Austria, Wien

Consist of scientific experts. Collect and analyze scientific data related to radiation effects. The data and databases are important bases for ICRP or other international organizations.

Aim of Radiological Protection (1)

◆ICRP

The primary aim of radiological protection is to provide an appropriate standard of protection for man without unduly limiting the beneficial actions giving rise to radiation exposure.

This aim cannot be achieved on the basis of scientific concepts alone. All those concerned with radiological protection have to make value judgments about the relative importance of different kinds of risk and about the balancing of risks and benefits.

In this, they are no different from those working in other fields concerned with the control of hazards.

Aim of Radiological Protection

◆NCRP

(1) To prevent clinically significant radiation-induced deterministic effects by adhering to dose limits that are below the apparent or practical threshold

(2) To limit the risk of stochastic effects (cancer and hereditary effects) to a reasonable level in relation to societal needs, values, and benefits gained.

Three Principles of Radiological Protection (1)

1) Justification

A practice involving exposure to radiation or intervention to reduce radiation exposure should produce sufficient benefit to the exposed individual or to society to offset the radiation detriment it causes.

2) Optimization

"As low as reasonably achievable"

Economic and social factors being taken into account

3) Dose Limit

防護の三原則

1）正当化：放射線被ばくの量が変わるような行為・介入による利益が不利益を上回らなければならない

× 誰にも利益がない被ばく

× 被ばく低減のためにかえって健康を損なう

２）防護の最適化：ALARA

As low as reasonably achievable

経済的及び社会的な考慮を行った上で合理的に達成可能な限り低く維持する

３）線量限度

Evolution of the ALARA principle wording

to **reduce** exposures	**to the lowest**	**possible** level		(ICRP, 1950)
to **keep** exposures	**as low as**	**practicable**		(ICRP 1, 1958)
to keep exposures	as low as	**readily achievable**	**economic and social considerations** being taken into account	(ICRP 9, 1965)
to keep exposures	as low as	**reasonably achievable**	economic and social considerations being taken into account	(ICRP 22, 1973)

(From: J. Lochard, ISOE International ALARA Symposium, 2008, Modified)

As Low As Reasonably Achievable (ALARA)

「防護の最適化」とは？

「できるだけ」とは？　～ICRP勧告の変遷

「可能な限り低く維持する」(1950)

「実際的に可能な限り低く維持する」(1958)

「容易に達成可能な限り低く維持する」(1965)

「経済的及び社会的な考慮を行った上で合理的に達成可能な限り低く維持する」(1973)

As Low As Reasonably Achievable
(ALARA)

Exposure Situations (1)

Planned Exposure Situation

Arises from the planned operation of a source or from a planned activity that results in an exposure from a source. Dose limits and dose constraints are applied.

Emergency Exposure Situation

Arises as a result of an accident, a malicious act, or any other unexpected event, and requires prompt action in order to avoid or reduce adverse consequences. Reference levels are applied.

Exposure Situations (2)

Existing Exposure Situation

Exposure which already exists when a decision on the need for control needs to be taken. Examples of an existing exposure situation are exposure to natural background radiation and exposure to residual radioactive material from a nuclear or radiological emergency after the emergency exposure situation has been declared ended. Reference levels are applied.

被ばくの状況

計画被ばく

線源の計画的な導入と操業に伴う被ばく。原発の新設など。被ばく線量を予測可能。線量拘束値と線量限度が適用。

緊急時被ばく

事故やテロなど予測しない状況から生じ、緊急の対策を要する被ばく。原発事故直後の状況など。参考レベルが適用。

現存被ばく

策定の段階で既に存在する被ばく。ただし、制御可能なもの(たとえば、食品中のカリウム40などは除外)。原発事故の緊急事態を脱した後の回復、復興期など。その他、屋内、作業場のラドン濃度が高い場合など。参考レベルが適用。

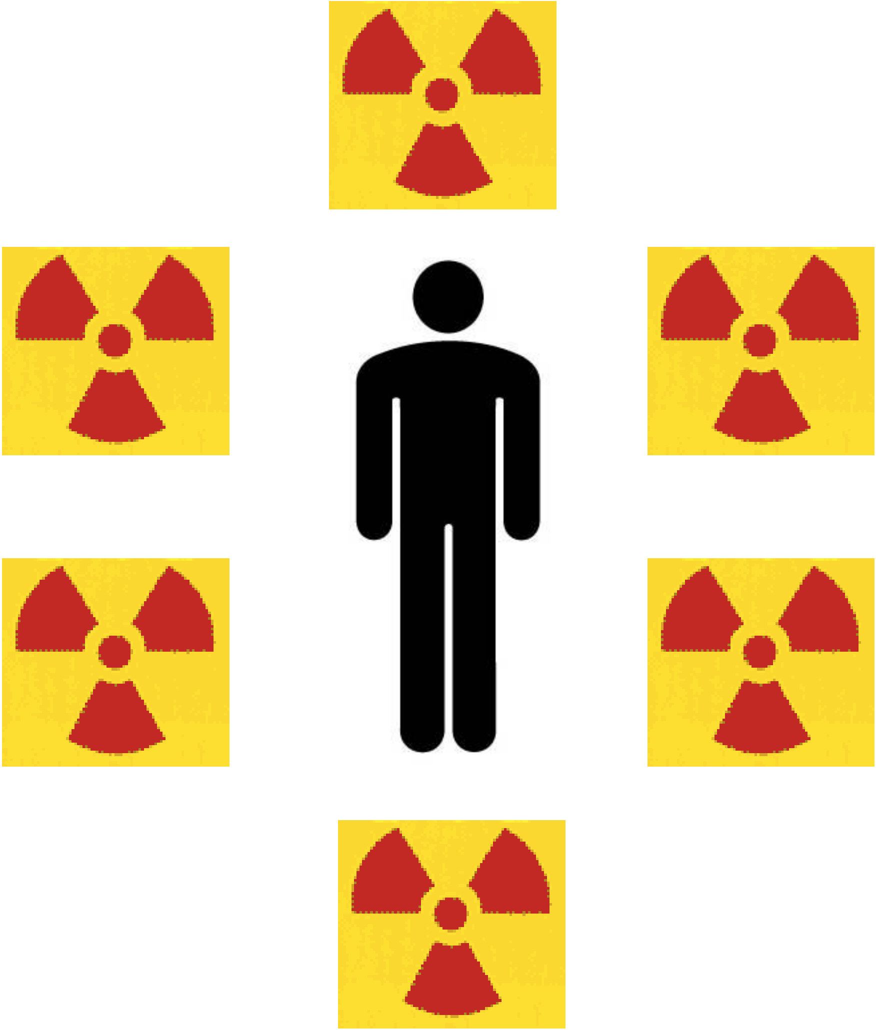
Dose Limit and Dose Constraint

Dose Limit

Upper limit of exposure from all regulated sources, in planned exposure situations

Dose Constraint, Reference Level

Upper limit of exposure from a source, in all exposure situations



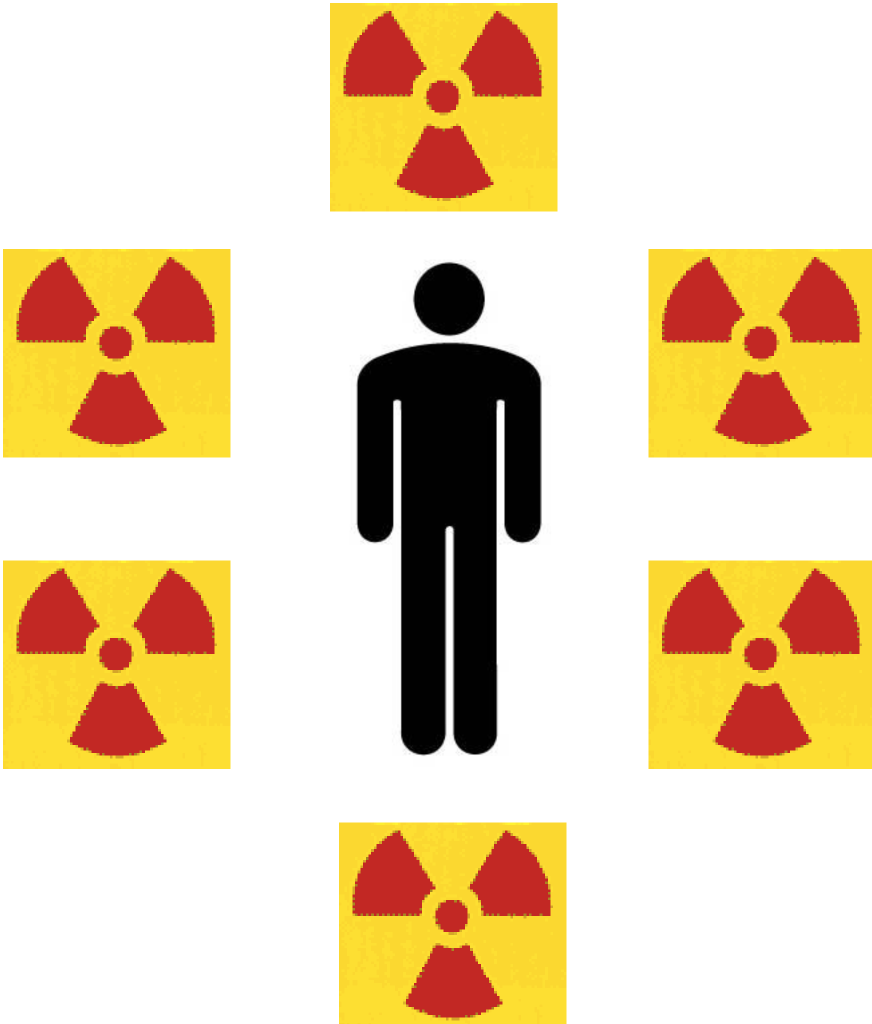
線量限度と線量拘束値

線量限度

計画被ばく状況において個人が受けることが予測される線量の上限値。

線量拘束値、参考レベル

ある線源から個人が受けることが予測される線量の上限値。



Dose Limit, Dose Constraint and Reference Level

Dose Limit and Dose Constraints

Applied to planned exposure situations. It must be assured that the predicted dose for all the people is below them. Otherwise, the plan is not permitted.

Reference Level

Applied to controllable exposure in emergency or existing exposure situations. The situation or plan which allows the exposure above this is considered inappropriate, needing amendments.

線量限度・線量拘束値と参考レベル

線量限度・線量拘束値

計画被ばく状況に対して適用。計画から予測される線量が全ての人に対してこれ以下を担保することが求められる。

参考レベル(Reference Level)

緊急被ばく状況あるいは現存被ばく状況において、制御可能なものについて適用。これを上回る被ばくの発生を許す計画は不適切であると判断される。

Dose Range for Reference Levels and Dose Constraints

Band of constraint or reference level	Characteristics
Greater than 20 to 100 mSv	Individuals exposed by **sources that are not controllable**, or where **actions to reduce doses would be disproportionately disruptive**. Exposures are usually controlled by action on the exposure pathways.
Greater than 1 to 20 mSv	Individuals will usually receive **benefit from the exposure situation but not necessarily from the exposure itself.** Exposures may be controlled at source or, alternatively, by action in the exposure pathways.
1 mSv or less	Individuals are exposed to a source that gives them **little or no individual benefit but benefits to society in general.** Exposures are usually controlled by action taken directly on the source for which radiological protection requirements can be planned in advance.

(From: J. Lochard, ISOE International ALARA Symposium, 2008)

線量限度、線量拘束値、参考レベルの範囲

20-100mSv：被ばくを低減させるためにとられる対策が混乱を起こすような場合に適用。事故後の緊急事態時など。

1-20mSv：被ばく状況において何らかの便益がある場合(被ばくを低減しなければならないことにより便益が損なわれる場合)に適用。職業被ばく、異常に高い自然放射線、事故後の復旧段階など。

1mSv以下：被ばくする個人にとってはほとんどまたは全く便益はないが、社会一般にとって便益がある場合に適用。原発の新設など。

Notes for Dose Constraints and Reference Level

It must be understood that dose constraints and reference level are NOT representing the boundary of “safe” and “danger” or leap in the effect on human health.

(ICRP Pub.2007, 228)

There is not discontinuity of effect at between 1mSv and 20mSv, for example.

参考レベル、線量拘束値についての注意書き

「拘束値や参考レベルに選択された値は、考慮されている被ばく事情によるであろう。線量拘束値とリスク拘束値も参考レベルも、”安全”と”危険“の境界を表したり、あるいは個人の健康リスクに関連した段階的変化を反映するものではないことを理解しなければならない」

（ICRP Pub.2007, 228)

1mSvと20mSvの間でリスクに不連続性があるということではない。

Dose Limit (1)

Occupational Exposure

- Effective dose： 100mSv/5y, and 50mSv/y
- Equivalent dose in eye lens：
  150mSv/y → to be changed to 100mSv/5y, and 50mSv/y
- Equivalent dose in skin： 500mSv/y
- Effective dose for pregnancy-competent female: 5mSv/3m
- Abdominal surface of pregnant female:
  2mSv from the date of reporting pregnancy to delivery
- Internal exposure of pregnant female:
  1mSv from the date of reporting pregnancy to delivery

Public exposure

- Effective dose： 1mSv/y
- Equivalent dose in eye lens： 15mSv/y
- Equivalent dose in skin： 50mSv/y

線量限度(1)

職業被ばく

・実効線量限度：100mSv/5年、かつ50mSv/年
・眼の水晶体における等価線量限度：150mSv/年
　→今後100mSv/5年、かつ50mSv/年に引き下げ
・皮膚における等価線量限度：500mSv/年

・妊娠可能な女子の実効線量限度：5mSv/3月
・妊娠中の女子の腹部表面：妊娠申告から出産まで2mSv
・妊娠中の女子の内部被ばく：同1mSv

公衆被ばく

・実効線量限度：1mSv/年
・眼の水晶体における等価線量限度：15mSv/年
・皮膚における等価線量限度：50mSv/年

Dose Limit (2)

Effective dose limit for emergency operation： 100mSv

↓

In Fukushima Accident: 250mSv (H23.3.15)

Cf.

Threshold of male transient infertility： 150mSv

→Recoverable

Threshold for malformation： 100mSv

(8d to 8w after fertilization)

→Prevented if pregnancy-competent female are excluded from workers

Cancer： estimated to increase 1.25% (if we assume LNT)

→Risk-benefit consideration, block expansion of disaster.

線量限度(2)

緊急作業に当たる場合の線量限度：100mSv

↓

福島第一原発事故の緊急事態に限り、

250mSvに(H23.3.15)

参考：

男性の一時的不妊のしきい値：150mSv

→回復可能

奇形のしきい値：100mSv（受精後8日～8週)

→妊娠可能女性を従事させなければ防げる

がん：1.25%増加（仮定）

→災害拡大阻止とのバランス

Radiation Controlled Area

(1) Effective dose for external radiation may exceed 1.3 mSv/3 months.

(2) Concentration of radioisotope in air, averaged over 3 months, may exceed 1/10 of concentration limit in air*.

*Specified for each nuclide.

(3) Density of radioisotope on the surface of radioactively contaminated material may exceed 1/10 of surface density limit#.

#α-ray emitting nuclides 4Bq/cm^2

Other nuclides 40Bq/cm^2

管理区域

(1) 外部放射線に係る線量が実効線量で1.3mSv/3月を超える

(2) 空気中の放射性同位元素の濃度*が3月間の平均で空気中濃度限度の1/10を超える

*核種ごとに定められている

(3) 放射性同位元素によって汚染される物の表面の放射性同位元素の密度が表面密度限度#の1/10を超える

#α線放出核種　　$4Bq/cm^2$

それ以外の核種　$40Bq/cm^2$