基調講演
「放射線の人体影響」

Keynote Speech

"The Effects of Radiation on the Human Body"

【土肥】

それでは，続きまして，ローゼンブラット先生です。簡単にご紹介したいと思います。ウルグアイ国立大学医学部をご卒業，現在，原子力科学・応用局ヒューマンヘルス部応用放射線生物学・放射線治療セクションヘッドでございます。本日は「放射線の人体影響」ということでお話いただきますので，我々にも近いお話しだと思います。それではよろしくお願いします。

Dr. Hiroo Dohy

Our next speech will be by Dr. Eduardo Rosenblatt. Dr. Rosenblatt graduated from Medical School of Uruguay National University; he is currently Head of the Applied Radiation Biology and Radiotherapy Section of the Division of Human Health, IAEA. Today, Dr. Rosenblatt will be speaking on the subject of "the Effects of Radiation on the Human Body," a subject which of course has particular significance for us. Dr. Rosenblatt!

エドワード・ローゼンブラット
国際原子力機関（IAEA）
原子力科学・応用局ヒューマンヘルス部
応用放射線生物学・放射線治療セクションヘッド

Eduardo ROSENBLATT, MD,
Head of the Applied Radiation Biology and Radiotherapy Section, Department of Nuclear Sciences and Applications, IAEA

こんにちは。エドワード・ローゼンブラットと申します。

私は，IAEAの応用放射線生物学・放射線治療セクションヘッドです。この度は，重要なシンポジウムで講演の機会をいただきまして，土肥会長をはじめとするHICAREの先生方をはじめとする皆様方に，深く感謝申しあげます。放射線の人体影響について，簡単にご説明いたします。

まず，低周波光は，物質を透過しません。可視光線も物質を透過しません。しかし，周波数が高くなると，紫外放射線も人間の皮膚を透過することができ，さらに周波数が高くなると，短波長で，放射線が物質を透過するようになり，人体も透過します。

私たちは，建物や家でラドンガスに，また，大地，宇宙放射線，食品，医療診断，大気圏内核実験，チェルノブイリ事故の放射性降下物などから低レベルの被ばくをしています。

電離放射線は，使い方によって有益にも有害にもなります。IAEAの原子力科学・応用局では，エネルギー，産業活動，診断や治療等の医療への応用，非破壊検査，農業，害虫管理，水文学，動物繁殖における電離放射線の活用等，原子力を平和利用しています。

電離放射線は，人体を細胞内の電離作用によって害します。電離とは，X線等が電子，正に帯電した原子，フリーラジカルと呼ばれる分子等のような荷電粒子を発生させるプロセスです。これらは，非常に反応しやすく，例えば，細胞組織中の分子に

Good afternoon. My name is Eduardo Rosenblatt.

As you just heard, I am Section Head of the Applied Radiation Biology and Radiation therapy Section of the IAEA, and I want to thank President Dohy, and the organizers, the authorities of HICARE, and the authorities of Hiroshima Prefecture, for inviting me to take part and speak to you in this important symposium. I'm going to give a brief introduction to the effects of radiation on the human body.

Low frequency photons do not penetrate matter, and visible light does not penetrate matter. But as we go higher in frequency, even the ultraviolet radiation can penetrate the human skin, and as we go higher and higher in frequency, with the shorter wavelength, the radiation becomes penetrating and it can penetrate matter, and of course, it can penetrate the human body.

We are exposed, normally, to certain low levels of radiation that come mostly from radon gas in the buildings and houses, from terrestrial sources, from cosmic radiation, internal, including some foods, diagnostic procedures, done in medicine, and lower sources, such as atmospheric nuclear testing, the Chernobyl fallout and so on.

But the effects of ionizing radiations can be beneficial and can be harmful, depending on how we use them. And in fact, the beneficial effects of ionizing radiation, we take advantage of for peaceful nuclear applications, such as the production of energy and industry, medical applications for health, such as diagnostic and therapeutic, non-destructive testing, agriculture, pest control, hydrology, and animal production, and I'm mentioning here some of the activities of the Department of Nuclear Sciences and Applications.

Ionizing radiation injures people through the production of ionization in tissue. Ionization is a process in which incidental photons or X-rays or particles produce charged particles, such as electrons or positively charged atoms or molecules, that are called free radicals, and they

化学反応を起こさせるなど，他の分子に化学変化を起こさせます。この化学変化により，細胞機能が阻害され，細胞死に至ることさえあるのです。

細胞の構造上，決定的なダメージは，DNAの損傷です。DNAは，非常に安定した分子で，細胞は，DNAの損傷を修復する作用があります。放射線がDNAを損傷するケースとして，１本鎖DNA切断，２本鎖DNA切断，化学変化又は突然変異を引き起こすという３つのケースがあります。

こうした損傷のいくつかは，修復酵素で修復されます。しかし，例えば，２本鎖DNA切断のように，損傷が非常に深刻な場合は，損傷を修復できません。

DNAは，放射線で損傷を受ける最も重要な分子であり，DNAの損傷によって，遺伝子発現，修正，遺伝子突然変異，染色体異常，ゲノム不安定，そして，極端な場合には細胞死のような様々な影響が出ます。

しかし，ほとんどの放射線によるDNAの損傷は，修復されることを覚えておいてください。

放射線の人体影響は，確率的及び確定的影響に分類されます。確率的影響の重症度は，被ばく線量とは関連性がありません。例えば，低線量又は高線量の放射線被ばくによってがんが発症した場合，いったん発症すれば，その重症度は，そのがんが低線量又は高線量のいずれの被ばくによって引き起こされたかとは関係がない，つまり，確率的影響の場合，重症度は，被ばく線量とは関係がないのです。

一方，影響を受ける可能性は，被ばく線量に比例します。がんの場合のように，確率的影響のしきい値は，存在しないか，不明です。

他方，確定的影響の重症度は，被ばく線量の増加に伴い重症化します。例えば，眼球が被ばくしたとき，被ばく量が増加するほど，進行性放射線白内障が重症化し，期間も長期化します。

放射線白内障は，確定的影響の代表例であり，このタイプの影響には，通常，しきい値があります。しきい値以下の被ばく量では，影響は表れません。

放射線の人体影響は，急性と慢性に分類され，急性被ばくとは，短期間に高線量被ばくしたケースであり，重症化します。非常に高い線量の場合，数時間又は数週間以内に顕著な影響が出ます。放射線被ばく事故での大規模な被ばくは，この種の被ばくの代表例で，ガンマ線，アルファ線，ベータ線，中性子線等，様々なタイプの放射線にさらされます。

are highly reactive, and they produce chemical changes in other molecules, such as, for example, molecules in the cell structure, and these changes can disrupt the cell function, and may even cause cell death.

However, from all the structures in the cell, we can say that the most critical structure damage that is important for us is the damage to the DNA molecule. In general terms, the DNA molecule is a very stable molecule, and the cell has mechanisms to repair the DNA damage. Radiation can damage the DNA molecule in three ways: by causing a single strand break, a double strand break, or chemical changes or mutations. And some of these damages can be repaired by enzymatic repair systems in the cell, but when the damage is very significant, such as, for example, a double strand break; in many occasions the cell is not able to repair this damage.

So DNA is the most important molecule that can be damaged by radiation, and the damage of the DNA molecule results in a cascade or a series of different types of effects, such as gene expression modifications, gene mutations, chromosome aberrations that can be identified under the microscope, genomic instability, and the extreme phenomenon of cell killing.

It is important to keep in mind, though, that most radiation-induced DNA damage is normally repaired by the body.

So, radiation effects can be classified between stochastic and deterministic effects. Stochastic effects are those effects which severity is independent of the absorbed dose. Think, for example, the induction of a cancer as a consequence of radiation exposure. A cancer can be induced by a low dose or by a high dose of radiation, but once a cancer appears, the severity of this cancer does not depend on if it was induced by a low dose or by a high dose. Therefore, the severity of the stochastic effect is independent of the absorbed dose.

However, the probability of having an effect is proportional to the dose absorbed, and there is no threshold or at least there is no known threshold for the production of this kind of stochastic effects, of which cancer is a classic example.

On the other hand, we have the deterministic type of effects. In this type of effects, the severity of this effect will increase with dose. If the lens of the eye, for example, is exposed to radiation, increasing doses of radiation will increase the severity and the time span for the appearance of what is called progressive radiation cataract in the human lens. Therefore, a radiation cataract is a typical example of a deterministic effect, and in this type of effect, there's usually a threshold. There's a certain dose below which the effect will not appear, and the effect will appear above this dose.

Radiation effects on the human body can be classified as acute or chronic. Normally, an acute exposure is an exposure to a high dose of radiation over a short period of time, and this type of exposure, as you can imagine, is very severe. If large enough, it may result in the effects which are observable within a period of hours or weeks. And the massive exposure in radiation accidents is a typical example of this type of exposure. In addition, in these situations, the victims are exposed to various qualities and different types of radiation, such as, for example, gamma rays, alpha radiation, beta radiation,

対照的に，慢性被ばくは，長期間にわたる比較的低線量の被ばくです。細胞にはDNAの低レベルの損傷を修復する力があり，長期間にわたる低線量被ばくによる損傷は，部分的に修復されますので，この種の被ばくには耐性ができます。例えば，放射線従事者の職業被ばくが該当します。

放射線の人体影響は，身体的影響と遺伝的影響に分類でき，身体的影響は，被ばく者の器官及び組織に表れます。身体的影響は，短期的には脱毛，長期的にはがんや器官不全を誘発します。

他方，遺伝的影響は，卵巣やこう丸のような性腺の生殖細胞のDNA損傷により発生し，先天異常となって現れます。

被ばく量の増加に伴い，健康影響も大きくなります。例えば，通常，寿命の期間内に影響があるとまでは言えない100ミリシーベルトの被ばくのような低線量の被ばく，また，特殊な技術で判別可能な染色体異常をもたらす可能性のある250ミリシーベルトの被ばく，さらに，30日以内に死亡する可能性のある10,000ミリシーベルト超の非常に高線量の被ばくがあります。

「放射線障害」は，急性被ばく，つまり，短期間に大量被ばくした人に表れます。放射線症候群には，様々なものがあります。造血系や骨髄に影響を与え，2，3週間以内に死に至るような造血症候群のほかに，胃腸症候群及び中枢神経系症候群，皮膚及び性腺の損傷もあります。

被ばく者のデータ及びがん等の疾病の放射線治療の経験から，臓器によって放射線感受性は，非常に大きく異なります。臓器の放射線感受性は，総被ばく量，線量率に関連します。同じ量の被ばくでも，短期間に被ばくする方が長期間かけて被ばくするよりも人体に有害ですが，これは，放射線で損傷したDNAの修復力と関係があります。もちろん，被ばくした容量の影響も非常に重要です。放射線腫瘍学の経験から，また，器官が被ばくした容量を正確に計算する最新の放射線治療機器により，被ばくした容量が非常に重要であることが分かっています。同じ放射線量を腎臓全体に照射する場合と腎臓の３分の１に照射する場合とでは，後者は，残りの３分の２の機能が回復するため，影響が違ってきます。

neutrons, and others.

On the contrary, a chronic exposure is a relatively small amount of radiation that is received by individuals over a long period of time. And therefore, as we mentioned before, the cells have the capability to repair the low-level damage to the DNA, so lower doses of radiation over a long period of time can be partially repaired, and so the body becomes tolerant to this type of exposure and this is the type of dose received as a consequence of occupational exposure- for example, in radiation workers.

Radiation effect on the human body can be classified as somatic versus genetic. Somatic are those effects that appear in exposed persons' organs or systems in our body. Somatic effects may be divided into prompt, when they happen fast, such as hair loss, or when it happened over a prolonged period of time, such as cataract induction, cancer, and organ failures.

The other is the genetic effects; effects that are produced due to the DNA damage in the gonads' cells, such as ovaries and testicles, and this type of effect can produce effects in the offspring, such as congenital defects or diseases.

We know that there are health effects that increase of course depending on the exposure dose. For example, from the very low, like 100 millisieverts dose, that will induce no detectable effects in normal lifespan, but in people who have received 250 millisieverts, there may be changes in the chromosome system; the chromosome abnormalities that can be identified with particular special techniques, to the highest exposures, such as more than 10,000 millisieverts, that will, or potentially will, produce death within 30 days, sometimes with or without medical care.

“Radiation sickness” is a clinical picture that appears in individuals that have received a massive exposure of radiation over a short period of time; this is the definition of acute exposure. And the radiation sickness syndrome is composed of several syndromes. One is the hematopoietic syndrome that affects the blood-producing system and the bone-marrow, and can induce death in a matter of two or three weeks, or even less. Then, the gastrointestinal syndrome and also central nervous system syndrome. The radiation sickness also will include various levels of damage to the skin, and to the gonads.

The radio-sensitivity of human organs is very variable, and it has been studied not only through the study of exposed individuals, but also through the experience of radiation therapy of cancer and other diseases. We know that the radio-sensitivity of human organs depends on the total dose received, but not only on the dose, but also on the dose-rate, and this is very important to remember. The same dose given in a short period of time is very much more toxic than the same physical dose given through a longer period of time, and this is again related to the potential for repair of the radiation damage to the DNA molecule. Finally, the volume effect is also very important. From the experience in radiation oncology today, and using the modern treatment planning systems, in which we can exactly calculate the volume of organs that receive certain doses of radiation, we know that the volume is critical. It is not the same to give the same physical dose to a whole kidney than to give the same physical dose to one third of the kidney, in which

皮膚は，40グレイまでの放射線分割照射に耐えることができますが，これを超えると，紅斑，乾性落屑，上皮及び真皮が壊れる湿性落屑を発症し，最後には，潰瘍ができ，壊死を起こすという段階になります。まとまった脱毛は，200レム以上の被ばくにより生じます。こうした皮膚損傷は，よく知られています。

甲状腺は，血液中のヨウ素を選択的に吸収する特性があります。甲状腺は，甲状腺ホルモンの生成のためにヨウ素を必要とし，血液中のヨウ素を吸収するため，放射性ヨードに非常に弱いものです。多量の放射性ヨードは，甲状腺の全てあるいは一部分を破壊することがありますが，ヨウ化カリウムの摂取によって，この影響は，軽減できます。

骨髄症候群は，骨髄，脾臓，リンパ組織のような分裂速度の速い細胞を損傷する特徴があります。造血症候群は，赤血球系の損傷による出血及び疲労，白血球系の損傷による細菌感染及び発熱などに表れます。

リンパ組織系は，電離放射線に非常に敏感です。低線量被ばくにより，血液リンパの細胞数は，著しく減少し，伝染病にかかりやすくなります。これは，軽度の放射線病であり，初期症状は，インフルエンザなどです。広島及び長崎のデータによると，徴候が数年から10年程度続き，白血病やリンパ腫にかかるリスクが長期的に増大します。

非常に強い被ばくでは，毛細血管が損傷し，心不全により死亡します。

胃腸粘膜は，非常に敏感で，腸管が被ばくすると，吐き気，嘔吐及び下痢を引き起こします。これは，被ばく量が200レム以上の場合に生じます。

中枢神経系は，放射線被ばく量が比較的高い場合でも耐えることができますが，いったん発病すると，神経細胞など再生しにくい細胞を破壊するため，協調運動障害，混乱，昏睡，けいれん及びショック状態になります。この場合，神経系の放射線障害ではなく，内出血や脳浮腫に起因する合併症で死亡します。

性腺について，生殖器官細胞は，急速に分裂するため，卵巣及び精巣は，200レム程度の低い放射線被ばく量で損傷し，不妊になることがあります。

胎児は，特に妊娠初期20週までは，非常に敏感です。出生前の子宮内での被ばくは，成長遅延の恐れがあり，小頭症，発達中の中枢神経系への影響による知的障害，小児白血病，がんを引き起こすことがあります。

the other thirds will recover and continue the function of this organ.

The skin can tolerate in, fractionated radiotherapy doses, up to 40 gray, but above this dose you will start to see erythema, dry desquamation, moist desquamation with destruction of the epithelium and then the dermis, and finally reaching the state of necrosis and ulceration. Also, the losing of hair, quickly, in clumps, occurs with radiation exposures of about 200 rems or higher. So, the damage of the skin is very well known.

The thyroid gland is a very special organ because the thyroid is able to selectively uptake iodine from the blood. The thyroid gland needs the iodine to produce thyroid hormones, and therefore, the thyroid gland is very susceptible to radioactive iodine, because it absorbs or uptakes this actively from the blood. In sufficient amounts, radioactive iodine can destroy all or part of the thyroid gland and by taking potassium iodide, one can reduce the effects of this exposure.

Bone marrow syndrome is characterized by damage to cells that divide at the most rapid pace, such as, in the case of the bone marrow, but also the spleen and the lymphatic tissue. Symptoms of hemopoietic syndrome will include bleeding, fatigue due to damage to the red blood cell line, bacterial infections and fever, due to the damage to the leukocyte line.

The lymphoid system is one of the most sensitive to ionizing radiation. When a person is exposed to low doses of radiation, the blood lymphocyte cell count will be significantly reduced, leaving the victim more susceptible to infections. This is often referred to as mild radiation sickness, and early symptoms will include the flu. This may go unnoticed unless a blood count is done. Data from Hiroshima and Nagasaki show that the symptoms may persist for many years, up to ten years, and may also have an increased long-term risk of leukemia and lymphoma.

Small blood vessels: intense exposure to very high doses of radiation will do immediate damage to capillaries and probably cause heart failure and death directly.

The gastrointestinal mucosa is also very sensitive. Radiation damage to the intestinal tract will cause nausea, bloody vomiting and diarrhea. This occurs when the victim's exposure is 200 rems or more.

And, the central nervous system: the central nervous system can tolerate relatively high doses of radiation, but when it appears, the damage is characterized by destruction of cells that do not reproduce very often, and these cells are the neurons. Therefore, symptoms usually include loss of coordination, confusion, coma, convulsions, and shock. Death, under these conditions, is not caused by actual radiation damage to the nervous system, but rather from complications caused by internal bleeding and even brain edema- the accumulation of fluid.

Gonads: because reproductive tract cells divide rapidly, these organs, the ovaries and the testes, can be damaged at doses levels as low as 200 rems, and some radiation sickness victims will become sterile.

The embryo and fetus are also very sensitive, in particular, during the first 20 weeks of pregnancy. Prenatal exposure in utero may potentially cause growth retardation, microcephalia, mental retardation due to the effect on the central nervous system which is developing, and childhood leukemia or cancer.

器官の放射線障害は，主に，幹細胞の再生不能や被ばくした器官の細胞の再生力が衰えることで起きます。幹細胞の重要性については，研究が進んでおり，被ばくによる組織や器官の損傷を治療できる可能性があると言われています。

がんについては，放射線腫瘍学のみならず，事故や戦争での被ばく者も懸念しています。放射線は，発がん物質よりはるかに強力に細胞を殺します。放射線治療で使用される非常に高線量の被ばくは，がん細胞を死滅させますが，それは治療の目的でもあります。しかし，致命的でない程度に高い線量の放射線を受けると，DNAが変異し，がんや白血病を発生させる可能性があります。

生物学的線量評価とは，循環血液中のリンパ細胞等の生体試料等に対する被ばくの生物学的影響を調べることにより，被ばく線量を推定評価する技術であり，様々な方法があります。放射線影響研究所は，生物学的線量評価のうち，二動原体染色体の頻度，小核の発現，あるいは，「フィッシュ」技術による被ばく線量の推定評価技術の利用，開発及び技術革新を積極的に進めておられます。

高線量被ばくによる初期及び後発的影響とリスクは，よく理解されています。一方，低線量被ばくのリスクは，測定が難しく，不確実な部分がたくさんありますが，近時，細胞分子生物学技術の急速な進歩によって，低線量被ばくに伴う生物学的変化の予測と理解が可能になってきています。

ご清聴ありがとうございました。

【土肥】

ローゼンブラット先生ありがとうございました。放射線の生物学的影響を非常にシステマティックに分かりやすくご説明いただきまして，大変理解の助けになったと思います。本日は，まだこれに類したお話が多数あるかと思います。ローゼンブラット先生のお話は，私どもHICAREのメンバーが検証させていただくときに，大きな助けになるであろうと期待しております。ありがとうございました。

【司会】

土肥会長，ありがとうございました。

The damage induced by radiation to most organs is mainly caused by stem cell sterilization and hence reduced reconstitution of functional cells in the irradiated organs. I mention this, about the importance of stem cells, because today, there is intense research in the area of stem cells and therefore, the research into stem cells may have a potential as a treatment for patients that have tissue/organ damage due to radiation exposure.

The problem of cancer has always been a concern, not only for us in radiation oncology, but for radiation-exposed individuals in accidents or warfare. Radiation is a much better cell killer than a carcinogen. Very high doses of radiation, such as those used in radiation treatment, will destroy the cancer cells, and that's the purpose, these patients are treated this way. But high but non-lethal doses of radiation to specific tissues can cause mutations, DNA changes, and changes that may lead to certain types of cancer and leukemia.

Biological dosimetry is a group of techniques that allow the estimation of doses received by individuals by looking at certain biological effects of these doses on certain system of the body- in particular, on the lymphocyte cells in the circulating blood. There are several techniques around biological dosimetry. The Radiation Effects Research Foundation, has been very active in using and developing and being innovative with techniques in biological dosimetry, exactly to do this- to estimate the exposure doses based on the production of dicentrics, the appearance of micronuclei, or the "FISH" technique.

To conclude, let me say that both early and late effects and risks from high level radiation are well defined and well understood today. However, the radiation risks associated with exposures to low levels of radiation are very difficult to measure and still have major uncertainties associated with them. Rapid advances in technology, techniques in cell and molecular biology, are now making it possible to detect and understand biological changes following low doses of radiation.

Thank you for your attention.

Dr. Hiroo Dohy

Thank you very much, Dr. Rosenblatt. That was an extremely thorough, easy-to-understand explanation which I am sure will have helped to give all of us a better understanding of the biological effects of radiation on the human body, a subject which will come up again many times today. I am confident that the information that Dr. Rosenblatt has just imparted will also prove to be highly valuable for HICARE members when participating in testing. Once again, our sincere thanks to Dr. Rosenblatt.

Chair

Thank you very much, Dr. Dohy.