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The consequences of the discovery by W. C. Röntgen for present-day medical physics and radiation protection

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Abstract. When the German physicist W. C. Röntgen discovered X-rays, which were named after him, he introduced a new development in medicine and biology: together with the discoveries of A. H. Becquerel and M. Curie, radiology with its diagnostic and therapeutic methods was made possible. The medical physicist has an important task to fulfill in modern radiotherapy, nuclear medicine and radiodiagnostics. The longtime interdisciplinary collaboration has won the international recognition of medical physics as a scientific discipline, a health care profession and a university subject. Several incidents, including contemporary ones, show that the efforts made towards radiation protection must remain an important domain of the specialist.

Key words. History; medical physics; radiation protection; radiology; Röntgen.

Introduction

From today's view it can be stated that the discovery of X-rays in 1895 was not entirely a surprise, considering the enormous amount of work spent on cathode-rays. Before W. C. Röntgen, famous scientists like W. Crookes, J. W. Hittorf and P. E. A. Lenard had been working in this field and may have produced X-rays without knowing it. In the second half of the last century scientific research in the electrical behaviour of gases was an important field in physics. When W. C. Röntgen noticed a faint light flash on the fluorescent screen in his laboratory in Würzburg – or maybe his institute assistant drew his attention to the phenomenon – his conclusion was that the flash on the screen came from something entirely new[4]. This realization was the most important contribution of W. C. Röntgen.

Subsequently he carried out detailed and systematic tests, describing the physical characteristics of the 'new rays' which he called X-rays, a name which survives in English. In W. C. Röntgen's honour X-rays in German are called 'Röntgen-Strahlen'. It was a characteristic of W. C. Röntgen to prepare and carry out his tests carefully to avoid theoretical speculations. In three short publications in the years 1895–1897 W. C. Röntgen reported his results and interpretations.

At that time the press reported in detail the 'sensational discovery'. An old dream had come true – something obscure had become visible. Radiation sources like X-ray tubes or radioactive substances, discovered by A. H. Becquerel in 1896, emit signals for which man does not possess any sense of perception. This explains the great sensation and publicity, which went against W. C. Röntgen's sensitive nature. Very quickly the experiments were repeated worldwide in other scientific institutes because they could be carried out very easily due to the relatively small technical effort required[19]. Within the first months of the discovery attention was drawn to the medical possibilities of diagnosis of bone injuries and illnesses with the aid of X-rays. Very quickly the new method of medical examination was used by physicians, although with simple cathode-ray tubes and high voltage generators exposure times of 10 minutes up to one hour were necessary. In 1896, which was also the year after W. C. Röntgen's first publication, 1044 reports and scientific works on the field of X-rays and its applications were published.

In 1945 F. Dessauer reported in this journal about his own experiences in the development of radiation techniques on the occasion of the 50 years' jubilee of the discovery of X-rays[5]. It was a well-deserved honour that W. C. Röntgen was awarded the first Nobel prize in physics in 1901. How significant and important his work was is shown by the fact that the succeeding Nobel prize winners in physics were professionally very closely connected with Röntgen: A. H. Lorentz (1902), J. W. S. Rayleigh (1904), P. E. A. Lenard (1905), J. J. Thomson (1906) etc. (see fig. 1).

That the benefit of W. C. Röntgen's discovery spread so fast is certainly a tribute to W. C. Röntgen's unselfish character. He did not apply for a patent and was always of the opinion that his discovery belonged to the general public and should be used for their benefit as much as possible. He also declined commercial advantages arising from his discovery. Temporarily this attitude disturbed his relationship with one of his best friends, the Swiss physicist L. Zehnder (1919–1936 professor at Basel University), who was at the time undertaking patent negotiations for X-ray tubes.

Effects of Röntgen's discovery

Seldom in the history of physics have discoveries set in motion such significant and rapid developments in the

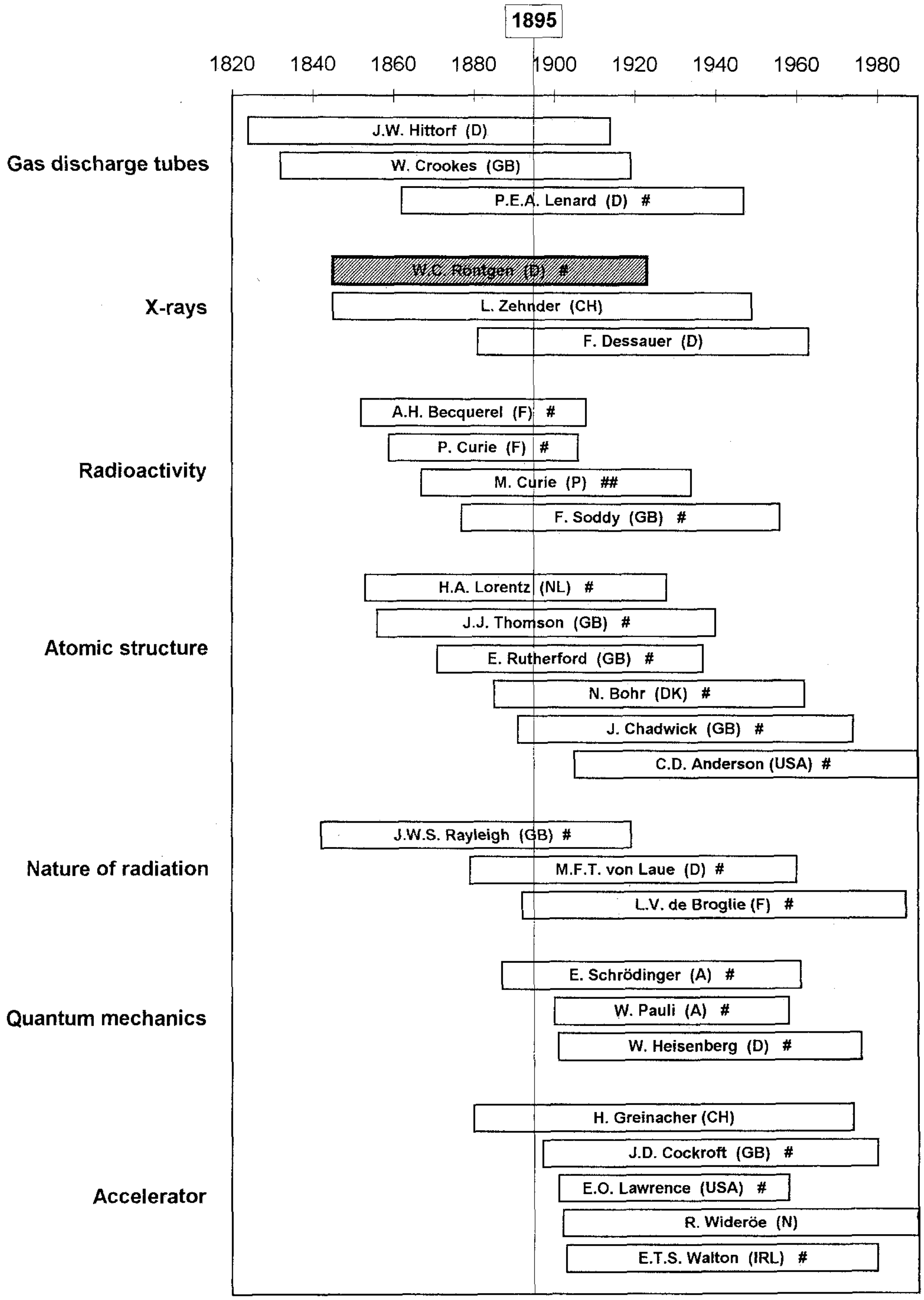

Figure 1. A selection of famous physicists around the time of Röntgen's discovery 100 years ago. Most of them were Nobel prize winners (#).

medical and biological sciences as the discovery of W. C. Röntgen 100 years ago. Together with the discoveries of A. H. Becquerel (1896) and M. Curie (1903) it made radiological diagnosis and therapy possible.
The discovery of X-rays also had a strong effect on the further development of physics in the 20th century, especially on atomic physics (fig. 1). X-rays later made the fine-structure analysis of crystals and other substances possible. In the last century the existence of atoms became obvious from developments in chemistry and the theory of heat, but no idea of atomic structure existed at that time. The existence of atoms was still disputed at the beginning of the 20th century. Of particular significance was the proof by J. J. Thomson (1896) that the electron was a carrier of the elementary charge. It was M. F. T. von Laue (1905) who recognized the true nature of X-rays as electromagnetic waves. In experiments he proved that X-rays were not just 'a kind of

rays', and not longitudinal waves in the ether, but were electromagnetic transverse waves, comparable to visible light but with a considerably shorter wavelength.

With that, a way to the understanding of substance and its atomic structure was available. An important milestone was the clarification of the unexpectable relation between radioactivity and chemistry by M. Curie, showing the change in chemical element in radioactive processes[9]. In the years 1910 to 1920 E. Rutherford was running experiments elucidating internal atomic structure (mass of atoms in a small nucleus in the centre of the electron shell), and discovered nuclear reaction. The 1920s saw the beginning of quantum mechanics which theoretically described the nuclear world, devised by L. V. de Broglie, N. Bohr, E. Schrödinger, W. Heisenberg and W. Pauli. The significance of X-rays for the understanding of the structure of matter has been described in detail by P. Niggli and E. Brandenberger at the 50 years' jubilee of X-rays' discovery in this journal[12].

A further important step in the understanding of the atomic structure and the development of radiology followed the discovery of the neutrons by J. Chadwick (1932)[1]. The existence of anti-matter was proven when C. D. Anderson discovered positrons. New studies in the field of chemistry by F. Soddy and G. K. von Hevesy led to new understanding of the characteristics and application possibilities of radioactive isotopes. Progress in accelerator technique by J. D. Cockroft, E. T. S. Walton, R. Wideröe and E. O. Lawrence permitted higher particle energies to be reached, fostering the development of nuclear physics as well as its application.

The electron shell and the atomic nucleus are test objects of physics. The overlap with chemistry enriches both disciplines. With the inclusion of physical parameters like number and volume, chemistry became a science in the 18th century. Since that time it has been a part of physics, profiting from the availability of physical instruments, from the pH-meter to nuclear spin resonance and X-ray spectrometer.

Fundamental developments in physics and the considerable progress in technique provided many new applications in biology and medicine. However, initial ignorance of the radiation effect on biological systems led, besides the successes, to a high level of radiation damage. Eventually, this recognition made radiation protection necessary.

Developments of medical physics

Medical physics covers fields in applied physics, dealing with the application of physical principles in medicine and transmission of physical methods to medicine, its objective being the extension of medical diagnostic and therapeutic procedures. It is undeniable that the subject of medical physics received an enormous boost on the discovery of ionising radiation, from which point radiophysics has achieved its present status. In earlier times physicians were more often occupied with natural science, using physical methods and the preconceptions of the medical profession. Soon scientists also dealt with medicine. An example is the investigation by Leonardo da Vinci 500 years ago into the mechanics of the skeletal and muscular system and the hydrodynamics of blood circulation. The application of electromagnetism in the last century permitted the development of new medical examination and treatment methods. By applying ionising radiation in medical diagnosis and therapy, medical physics progressed significantly and to date these are the main activities of medical physicists.

Physical methods increasingly play a part in the progress of medicine. Often it is difficult to translate the complicated and abstract physical concepts into the familiar language of medical thinking. However, to make use of a technique the physician does not need to understand how it functions. Optimization, and the realization of requests of physicians, is done by physicists and engineers. A series of highly qualified physicists made basic and important discoveries in the medical application of radiation, as described in the previous section. Although these scientists did not directly take part in clinical application, their discoveries enabled the development of a medical discipline, radiology. Therewith a new discipline of applied physics, radiophysics, was required.

From 1910 on physicists, especially in England, were employed in radiological departments. The measurement of radiation was one of the first tasks of medical physicists. In 1926 R. M. Sievert published a test comparing the biologically based skin erythema dose (SED), and measurement using an *ionisation chamber*[17]. The mean value varied between 50 and 200%, so for an equivalent skin erythema dose one radiotherapist was able to apply a dose four times higher than another radiotherapist. The present standard of dose-measurement amounts to $\pm 2\%$ guaranteed by international dose-comparison measurements. Additionally in most countries standards laboratories are available and regulations have been produced demanding regular calibration measurements of dosimeters. Radiology was the first medical speciality realizing the need for physicists; development in this field has progressed up to the present time and a similar development is being observed in other medical disciplines.

In the last few years quality assurance has become a new duty for medical physicists. Regular quality assurance programs, including physical-technical checks of accelerators in radio-oncology, and of X-ray equipment, imaging processing and gamma-cameras in nuclear medicine, have been recommended, e.g. by the WHO, and are legally prescribed in many countries. In bigger hospitals observance of radiation protection as well as its supervision is also one of the tasks of the medical physicist. Besides ionising radiation, methods like ultrasound, hyperthermia, magnetic resonance, imaging processing, EDP (electronic data processing) etc. are in use. It is the medical physicist's responsibility to contribute to the optimal use of such expensive and complicated instruments. Instruments and equipment needed for clinical work require further developments in the physical-technical field as well as controls and services in clinical practice. The introduction and application of new methods often require qualified scientists.

The education of specialists is an important field. The EFOMP (European Federation of Organisations for Medical Physics) recommend a practical training of at least 3 years in a hospital and a theoretical education in medical subjects after completing studies in physics. In most cases this kind of education and training is approved by national organizations for medical physics. After completion of this education recognition of the qualification of the medical physicist can be obtained. In many countries the employment of a qualified medical physicist is required for the handling of an accelerator in radio-oncology. The necessary exchange of ideas is in general more guaranteed in larger hospitals with a team of physicists than in smaller hospitals with just one medical physicist. Therefore a great demand exists for various national and international science organizations and working groups. They are active not only in the scientific field, but also in the professional field. The national organizations are united internationally by the IOMP (International Organization for Medical Physics).

Dosimetry

Dosimetry is the field of measuring interactions of ionising radiation with matter, originating from physics and also from medicine. The word 'dose" indicates its origin in medicine, used as a quantity-specification for 'medicines' (pharmacology). After the discovery of X-rays and radiation with radioactive decay, a method had to be found to measure the amount of ionising radiation so that it could be correlated as well as possible with the biological effects. While in pharmacology the dose describes the quantity of medicine delivered to the body, only the absorbed dose produced by the ionising radiation is effective in the body. Therefore, the radiation re-emitted from the body does not contribute anything to the absorbed dose.

A radiation-source emits ionising radiation, building a radiation-field. In a medium in the radiation-field, interactions between ionising radiation and atoms or molecules take place. During the interactions energy is being transferred from the radiation to the substance, possibly resulting in biological effects (see Fritz-Niggli in this issue). In the course of radiation-exposure in

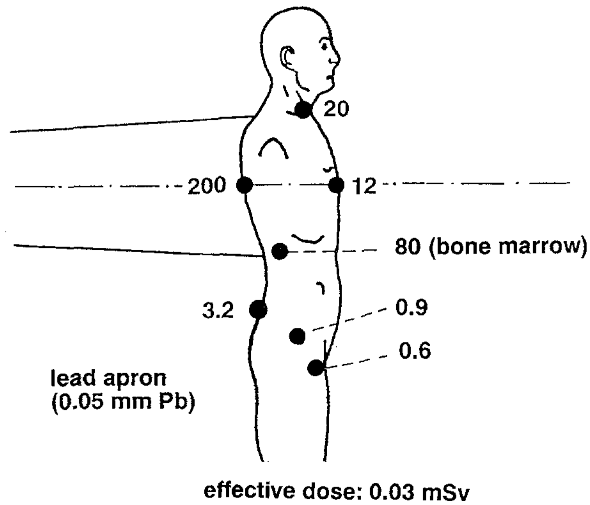

Figure 2. Organ doses and effective dose for a X-ray chest examination. Values given in mSv.

various places on and within the body, very different doses may be absorbed (fig. 2). Therefore a comparison of different radiation exposures is difficult, because the part of the body or the organ the absorbed dose refers to must be indicated.

At the turn of the century different methods of radiation quantification came into use with the medical application of X-rays. Around 1920, e.g. at the beginning of the use of X-ray therapy, the effect of radiation on human skin was proposed by L. Seitz und H. Wintz as a basis of a biological dosimetry. The skin erythema dose (SED) described a radiation quantity which under certain conditions caused a slight skin reddening (erythema). By today's standards it corresponded to approx. 5 Sv (see ref. 11). From the beginning the measurement of ionisation produced in air by X-ray was common. In his second publication in March 1896 W. C. Röntgen reported tests with ionisation chambers. He showed that X-rays produce a conductivity proportional to the air pressure. Ahead of his time, the Swiss mathematician, physician and radiation scientist T. Christen (1913) proposed the definition of the 'physical dose'. This definition corresponded to the 'amount of energy deposited by the radiation per unit of volume'. The important observation of T. Christen was that the volume-related dose in water and in air behaved like densities of both materials, i.e. the absorbed energies referred to the mass with the same exposure are similar to both materials. In 1928 the ICRU (International Commission on Radiation Units and Measurements) introduced the dose-unit still familiar to many people. Today the quantity exposure including the unit Roentgen has lost its significance and should not be used anymore. The absorbed dose describes the absorbed energy of ionising radiation in any material referred to the unit mass of material. According to the international unit-system SI the unit is Joule per kilo-

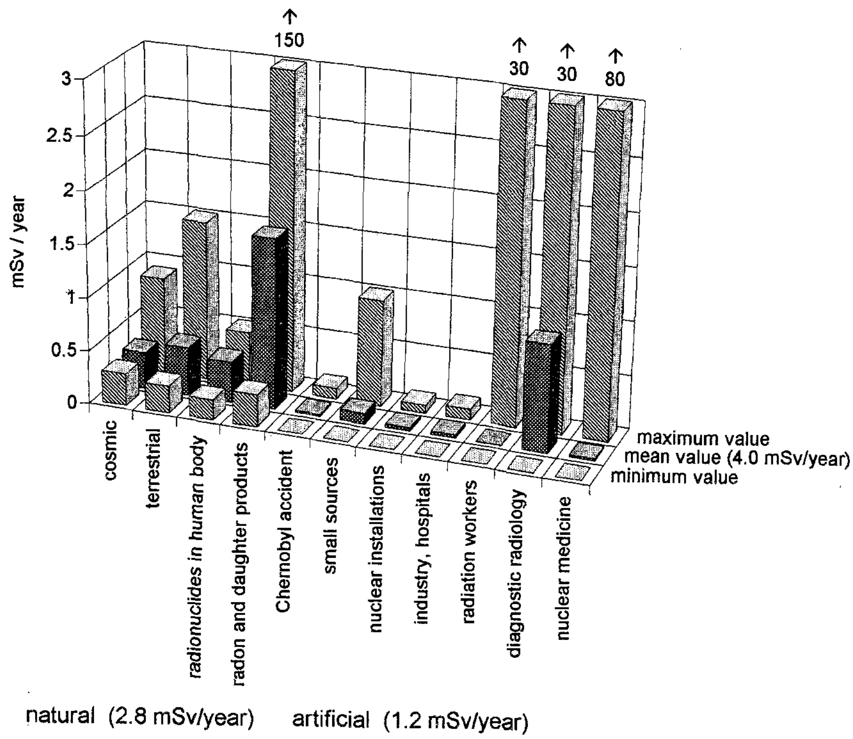

Figure 3. Mean annual effective doses and their ranges of fluctuation of the Swiss population (according to ref. 2), resulting from natural and artificial sources of ionising radiation.

gram with the special unit-name Gray (Gy). This unit cannot be measured directly in routine medical radiation applications.

The dose equivalent is mainly used in radiation protection, and takes into account the fact that different types of radiation with the same absorbed dose produce different effects due to variations in relative biological effectiveness. This is described by a dimensionless quality factor. The SI-unit of the dose equivalent is Joule per kilogram with the special unit-name Sievert (Sv). For a more profound description of dosimetry, especially concerning its quantities and connections, please refer to H. Reich[13].

To compare radiation risks of different irradiations of a part of the body or total body (e.g. external and internal radiation exposure), the definition of the 'effective dose' with the Sievert unit was introduced. Taking into account the relative radiation-sensitivity in single organs and tissues, doses are weighed and summed up in the whole body. In principle the risk of a comparable total body irradiation is calculated with the help of single organ sensitivities. According to epidemiological tests with exposed persons the radiation risk of the single organs related to the whole body after ICRP[7] are defined as follows: 20% for gonads (risk of genetic damages); 12% each for red bone marrow (risk of leukemia), lungs, colon and stomach; 5% each for breast, thyroid, bladder, liver and oesophagus; 1% each for bone-surface and skin; 5% for the rest of organs and tissue.

These weighting factors are average values of the female and male population of the age between 18 and 65 years. It appears that the effective dose was defined especially for the radiation protection of radiation-exposed working people. For medical radiation applications specific weighting factors according to sex, age etc. have to be considered. Even today these factors are almost unavailable. The definition of the effective dose is difficult because all doses in the relevant organs have to be known. But the effective dose permits the comparison of different irradiations, e.g. an X-ray examination with a nuclear-medical examination or with natural irradiation (fig. 3).

Mankind does not possess any sensory perception of ionising radiation. Various interactions of radiation with matter are converted by detectors to electrical signals, in order to measure the type, intensity and energy of radiation (table 1). Ionisation is the most common process, used by the historic Geiger-Müller counter, in thimble and condenser chambers. In scintillation counters flash-lights produced by radiation are registered. Photographic films, solid state detectors, chemical effects or heating effects on tissue are also used as radiation measuring equipment or dosimeters.

Developments of X-ray tubes and medical imaging

At the beginning of 1896 the 'Deutsche Medizinische Wochenschrift' reported on successful localization of a glass-splinter in the joint of a middle finger with the aid

Table 1. Examples of dosimeters often used in medicine.

Irradiation effect	Method of dosimetry	Application in medicine
Ionisation in air	ionisation chamber Geiger-Müller counter	all fields of radiology radiation protection
Ionisation in solid state material	diode	radiotherapy (in vivo measurements) automatic film exposure CT in diagnostic radiology
Scintillation	scintillation counter	nuclear medicine (e.g. gamma cameras) spectrometry in vitro measurements
	thermoluminescence	radiation protection in vivo dosimetry phantom dosimetry
Chemical effects	film blackening	dose distribution in radiotherapy radiation protection

of an X-ray photograph. Very soon the diagnosis of illnesses was recognized as a considerable advantage of X-rays. The enormous interest hastened the technical development of X-ray equipment and techniques. Since ca. 1905 X-ray tubes have been available, supplying X-rays with sufficient energy and intensity for medical examinations. Developments in diagnostic radiology were influenced by the progress in technique, using improved X-ray tubes with a smaller focal spot to produce more contrasty pictures. Later on, electronic image intensifiers led to a considerable reduction in previous high doses with fluoroscopy.

The technical development of diagnostic radiology was mainly achieved by the industry. The same applies to developments in equipment today. The growing consciousness of radiation protection caused clinical physicists to concentrate more on such tasks in this field. Today the creation of X-rays is still based on the same physical mechanism as at the time of Röntgen's discovery. Substantial progress was made by converting the gas discharge tube to the high vacuum tube and therewith the independent regulation of tube current and voltage. Additionally the induction coils were replaced by a transformer. For a more detailed description of the early development of X-ray technique, please refer to the two publications which appeared 50 years ago. H. B. G. Casimir and W. J. Oosterkamp described the at the time up-to-date X-ray tube-technique[3], and E. A. Zimmer reported on the first 50 years of medical radiology[20].

Around 1900 a maximum tube current of approx. 5 mA existed. Today tube currents of more than 1000 mA are used. Exposure-times diminished to milliseconds, whereas before they had been as much as 15 min. Principally the overall efficiency of X-ray production amounts to just about 1%, depending on the tube voltage and the anode material, with the rest of energy in the anode being converted to heat. In 1929 A. Bouwers developed the rotating anode tube. Therewith the previous load-capacity maximum of 0.3 kW/mm^2 (static anode tube) was increased to 2–4 kW/mm^2. Correspondingly the focus-spot size was diminished and the geometrical resolution in a picture improved. Today X-ray tubes have a capacity of over 100 kW/mm^2 provided that rotating anode-tubes giving up to 10,000 rotations per minute are used. Efficient circuits provide higher electrical power for X-ray tubes. From the original one-pulse generator (half wave rectification, 50 X-ray pulses per second), to the two-pulse-generator (4 full wave rectification) 6-, 12- or 24-pulse-generators with three-phase current are generally used today. Not only can the power be increased but also the tube high voltage is more constant, similar to direct voltage. These improvements show the high efficiency of today's X-ray tubes and generators. Nevertheless, there are imaging systems – especially combinations of films and intensifying screens – too sensitive for some X-ray apparatus to achieve an optimal degree of film blackening.

Up to the 1970s medical imaging consisted of conventional radio-diagnostics and angiography (pictures showing blood vessels by the aid of contrast media). Since that time diagnostic possibilities have been extended significantly by the introduction of ultrasound, computerised tomography, digital radiography and magnetic resonance (fig. 4). Ultrasound and magnetic resonance do not use any ionising radiation (see Elke in this issue). An important step towards stereoscopic imaging was the development of computerised tomography. It should not be concealed that this kind of modern examination technique generally requires very high doses for the patient compared to other radiological examinations. Effective doses between 10 and 20 mSv per examination are common.

The digital technique, initially used in computerised tomography, and particularly in projection radiography, has become increasingly significant. With today's high-capacity computers it is possible to deal with an

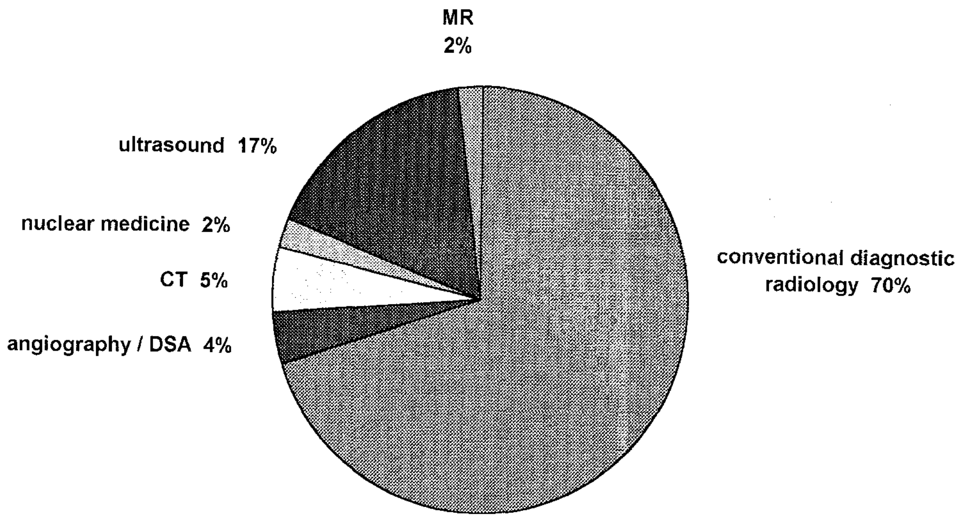

Figure 4. Frequency of the different methods of examination in diagnostic radiology.

enormous amount of data. Instead of the blackening of an X-ray film, the radiation picture is dissected into a matrix of single points (pixels), building the spatial resolution. The image of the numerical data (digital X-ray picture) can be varied in contrast and brightness, enlarged sectionwise, subtracted from another picture (digital subtraction images) and stored. Misexposures – which occur in 10–15% of all exposures in conventional radiodiagnostics – and the necessity of repetitions can be avoided. The processed image of numerical data can finally be transformed into an analogous picture on a television monitor.

The magnetic resonance method is based on the demonstration in 1946 of the precession (movement of a spinning top) of the nucleus in a magnetic field, for which F. Bloch (Zurich) was awarded the Nobel prize (1952). Magnetic resonance imaging uses the precession of the nucleus of the hydrogen atoms, abundant in the tissue, by placing the body into a strong magnetic field and emitting radio waves at the same time. The different chemical combinations (e.g. hydrogen atoms on a molecule of fat or albumen) lead to different signals, thus enabling a very sensitive comparison of tissue-structures which are not visible by radiography.

Of all application fields of ionising radiation, on average radiodiagnostics contribute most to artificial radiation exposure within the population (fig. 3). Radiation doses during an X-ray examination can vary considerably according to the technique used, field size, number of pictures or fluoroscopy-time or the sensivity of the imaging system (film, electronic image, intensifier etc.) (fig. 5). Doses in organs in most X-ray examinations typically vary between 1 and 100 μSv per exposure (exceptions: computerised tomography), as can be seen in table 2. The dose-rate during an X-ray exposure with a short exposure-time is up to 600 mSv/h, whereas natural radiation exposure only amounts to approx. 0.4 mSv/h. Thus the dose-rate is up to a factor 1.5×10^6 higher and may have a significant influence on the radio-biological effect which generally increases with the dose-rate (see Fritz-Niggli in this issue).

According to new experiments in Switzerland[10], an average of 1.5 examinations and 2.6 images in radiodiagnostics per person and year must be reckoned with, which in most cases are related to chest (37%) and teeth (17%)[18]. Radiation exposure during X-ray picture can be reduced by an optimal field size and a very high sensitivity of the screen-film combination used. Such reductions should especially be utilized for children.

Developments of measurement techniques in nuclear medicine

After the discovery of radioactivity by A. H. Becquerel in the year 1886 it took until 1923 before G. K. von Hevesy introduced the tracer technique as a biological method using radioactive substances. The subsequent establishment of nuclear medicine was made possible by numerous results from different scientific subjects like physics, biochemistry and engineering and also many medical disciplines. On the basis of nuclear physics and biochemistry a serial of clinical methods was developed. Milestones in the development of nuclear medicine were the discovery of artificial radioactivity (J. Curie and F. Joliot, 1934), and the development of the Geiger-Müller counter (H. Geiger and W. Müller, 1928) and the scintillation-camera (H. O. Anger, 1958).

A new era of nuclear medicine began after the Second World War with the application of radioisotopes produced in the reactor (see Rösler in this issue). At that time nuclear medical diagnostics consisted of measuring impulse-rates above particular organs. The first imaging of activity-distribution was carried out in 1951 (by the American physicist B. Cassen). With the aid of a mechanical writing recorder fixed to a detector, the measured impulses were transferred to paper. In this way a

Table 2. Maximum dose (skin), effective dose and frequency of some examinations in diagnostic radiology. Effective dose according to ICRP 60 (ref. 7) for adults. The frequency is estimated from the data given in Mini (ref. 10) and UNSCEAR (ref. 17).

Examination	Maximum skin dose, mSv	Effective dose mSv	Frequency %
Chest			37
Radiography p.a.	0.40	0.05	
CT	50	14	
Mass miniature	4.0	0.20	
Dental			17
Status	11	0.16	
Extremities			14
Elbow	0.30	0.013	
Knee a.p.	0.50	0.015	
Skull			5
Radiography a.p.	2.3	0.10	
CT	46	1.5	
Pelvis, hips			4
Pelvis a.p.	4.6	0.62	
Hip joint a.p.	4.0	0.13	
Spine			3
Cervical a.p.	2.3	0.18	
Thoracic a.p.	3.6	0.44	
Lumbar a.p.	4.0	0.70	
GI tract			3
Stomach a.p.	3.5	0.44	
Colon a.p	2.1	0.51	
Abdomen			2
Radiography a.p.	3.7	0.53	
CT	45	11	
Other			15

real display of radioactivity-distribution – a scintigram – was obtained. The relatively long duration of measurement did not permit an analysis of fast body organ functions and was only possible with the introduction of the so-called scintillation-camera (gamma-camera, H. O. Anger, 1958). The great advantage of this method was that the signals reflected on the oscillograph corresponded at any time to the area examined. The area investigated by the gamma-camera could be examined at the same time.

The radioisotopes used up to this time – mainly I-131 – proved to be unsuitable due to their relatively high gamma-energy. More favourable was the application of radioisotopes Tc-99m (E. Segre and G. T. Seaborg, 1938). This kind of radioisotope, with its positive physical characteristics, is the most commonly applied isotope in nuclear medical examinations today.

In nuclear medical diagnostics gamma-emitters are applied exclusively to patients where local and temporary distribution can be measured outside of the body. Today, radionuclides used are produced artificially (table 3). In Switzerland the yearly frequency amounts to about 10 examinations per 1,000 inhabitants. 45 nuclear medicine institutes in Switzerland consume an approximate total activity of 28 TBq, about 84% of which is the

Table 3. Radionuclides most often used in nuclear medicine and radiotherapy and their physical properties. All radionuclides are artificially produced for nuclear medicine.

Radionuclide	Physical half-life	Emission type	Most important photon-energy
Tc-99m	6 hours	γ	140 keV
Xe-133	5.3 days	β^-, γ	80 keV
Tl-201	73 hours	γ	80 keV
I-131	8 days	β^-, γ	360 keV
I-123	13 hours	γ	160 keV
Y-90	64 hours	β^-	-
P-32	14 days	β^-	-
Co-60	5.3 years	β^-, γ	1170 and 1330 keV
Cs-137	30 years	β^-, γ	660 keV
Ir-192	74 days	β^-, γ	320 keV

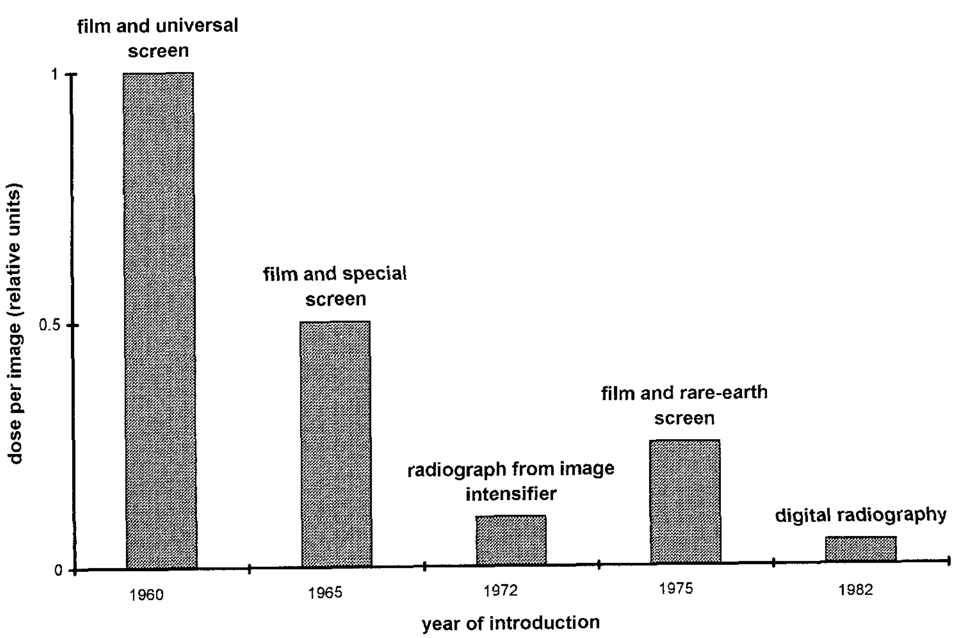

Figure 5. Dose to the imaging system (e.g. film) per image in diagnostic radiology in the last 35 years.

Table 4. Effective dose and frequency of nuclear medicine procedures in Switzerland (ref. 14). Effective dose according to ICRP 60 (ref. 7) for adults.

Examination	Radiopharmaceutical		Activity, MBq		Effective dose mSv	Frequency	
	radioisotope	pharmaceutical	mean	range		examination	per radioisotope
Bonescan	Tc-99m	phosphate	600	400–800	3.55	43%	
Thyroid	I-123		15	5–20	2.67	15%	47%
	I-131		2	1–4	36.23		11%
	Tc-99m	pertechnetate	70	30–160	0.81		42%
Lung perfusion	Tc-99m	MAA	120	70–200	1.37	14%	
Lung ventilation	Xe-133		400	300–500	0.07	6%	89%
	Xe-127		100	100–150	0.01		11%
Lung inhalation	Tc-99m	aerosol	50	30–70	0.31	1%	
Myocard	Tl-201		80	70–90	15.73	5%	
Renography	Tc-99m	DTPA	400	200–500	2.14	3%	5%
	Tc-99m	DMSA	60	30–100	0.33		7%
	Tc-99m	MAG3	110	100–150	0.80		21%
	I-123	hippuran	20	5–40	0.26		54%
	I-131	hippuran	11	10–13	0.55		13%
Miscellaneous						13%	

short-living Tc-99m. Therapeutic purposes make up 6% of the total activity, using I-131 almost exclusively. These figures result from an inquiry made in the years 1989 and 1990[14]. The effective dose for the single examination depends very strongly on the radioisotope and activity required, see table 4. Nuclear medicine contributes about 0.02 mSv per year to the radioactive exposure to the average population.

Radiation exposure depends on physical characteristics (physical half-life, type of radiation) as well as on the biological behaviour of radiopharmaceuticals in the organism. For diagnostic applications preference is given to short-living isotopes, emitting pure gamma-radiation. Generator systems have proven to be an advantage in supplying a nuclear medicine department with short-lived radio nuclides on the spot. With the radioactive decay of a long-living mother-nuclide an appropriate daughter-nuclide is established and can be washed out with a solvent. A common example is the molybdenum-technetium-generator, whereby Mo-99 (physical half-life 2.8 days), produced in the cyclotron, decays into Tc-99m.

With modern gamma-cameras measured signals are digitalized and processed in a computer to give an image of a temporal and/or spatial interpretation. SPECT (Single Photon Emission Computed Tomography) is a further development of the digitalized gamma-camera technique. During the examination 1 to 3 detector-heads rotate around the patient and the radiation emitted from the body is recorded from different angles, covering the whole cross-section of the body. The signals recorded from different angles are processed in a computer, similar to the computerised tomograph. The image of the organ structures is possible within various projection-levels. Positron-emission-tomography (PET) is the most sensitive nuclear medical method with the highest spatial and temporal resolution. However, the technique demands a closely synchronized radionuclide-production, since the physical half-life of the positron-emitters in most cases lasts just a few minutes. The principle is that the positron (positively charged electron), emitted from the nucleus by radioactive decay, joins with an electron and transforms into two photons. The position of the positron decay can be reconstructed by contemporary measurement of both photons. A great advantage of PET is the possibility of using radioisotopes of natural biological components like C-11, N-13 or O-15 in vivo.

Developments of accelerators in radio-oncology

In 1896 cancer treatment with X-rays was carried out in America and in 1899 T. Sjögren and T. Stenbeck reported the first successful treatment of skin cancer after more than 100 irradiations with X-rays. Very early in radiotherapy local implantation of radium tubes was applied. Technology has extensively advanced the progress of irradiation, especially by increasing radiation energy which made treatment of deep-seated tumours possible (see Birkenhake and Sauer in this issue).

Nuclear reactors, developed during the Second World War, enabled radioactive isotopes to be produced in higher quantities. Around 1950 the worldwide distribution of the so-called Telecurie machines started, initially equipped with Cs-137 and later on with Co-60 sources. Cs-137 has a physical half-life of 30 years, with a small specific activity. Such radiation sources have a relatively large volume, which means a relatively small activity. Therefore Co-60-machines were required, which remained the dominating treatment equipment in radiotherapy for deep-seated tumours until the end of the

1970s. Today these machines are still commonly used. Co-60 has a physical half-life of 5.3 years, a gamma-radiation with an energy of about 1.25 MeV and a relatively high specific activity. The possibility of producing high activities at low costs has contributed to the widespread use of this equipment. The physical half-life stipulates a continuous correction of irradiation time, and a source exchange after some years.

In the 1930s X-rays were produced with an energy of over 1 MeV with the aid of electrostatic generators (R. J. van de Graaff) and cascade-generators (H. Greinacher). In 1928 R. Wideroe outlined a theoretical concept for a circular accelerator with electrons. On this basis D. Kerst (1940) built the first ready-to-use circular accelerator, called the Betatron. Besides highly energetic X-rays, electron rays in the range of 10–20 MeV were initially used. In Switzerland R. Wideroe together with Brown Boveri & Co. as well as H. R. Schinz in Zurich and later on A. Zuppinger in Berne, had considerable influence on the improvement and application of the Betatron in favour of radiotherapy. In the last few years the Betatron has almost disappeared and been replaced by the linear accelerator, which is today's routine machine for photon and electron irradiation in radiotherapy. Today's common equipment provides energies of 4–25 MeV with high dose-rates, permitting short irradiation periods even at a suitable distance (mostly around 100 cm). Recently another circular electron accelerator came into medical use, the microton.

Heavy particles are frequently used for radiotherapy, to provide a more exact dose-deposition in deep-seated tumours and therewith improving the chance of a cure. Specific properties of particles are required to achieve a higher biological effect in the tumour tissue. The application of neutrons and pions did not fulfill expectations and their clinical application is limited due to the enormous equipment costs. Today's expectations are directed to successful results using protons and heavy ions as well as by the capture of neutrons in boron.

Over a long period of time brachytherapy (using sealed radioactive sources inserted into the body) has been carried out with radium. Because of problems in radiation protection and the risk of leaky radium tubes, an alternative to radium was needed. For many years brachytherapy has experienced a 'renaissance' in new sources. In particular, the so-called afterloading technique is being applied where the sources are inserted through a tube from a deposit container into the tumour tissue, thus achieving a reduction of radiation exposure and an improvement in treatment quality.

The individual plan in radiotherapy is important today to apply a high and if possible homogeneous dose, which will destroy tumour cells and protect the surrounding tissue. Significant progress has been made in the use of computerised tomography, where position of structures can be determined. A dose-distribution is calculated by the computer. Treatment parameters can be altered as long as the most favourable dose-distribution will be reached for the requested target volume and the surrounding tissue. Additionally, careful fixation of the patient, simulators, in vivo dosimetry and field controls during irradiation lead to a high precision. The applied dose should be within 5% of that planned.

For the time being development concentrates on the exact conformity of treated volume with tumour volume, depending on methodical and technical alterations and an adaption of treatment plan. Within the target volume doses of up to 80 Sv are applied to destroy diseased tissue. By applying new radio-biological perceptions improvements in the near future can be expected.

In Switzerland approx. 12,000 patients per year are treated in radio-oncology. For these treatments ca. 24 accelerators and 20 Co-60 units are available. Additionally, about 100 dermatologic X-ray therapy apparatuses (tube-voltage 10–100 kV) as well as about 50 more with tube-voltages between 100 and 300 kV, are in operation, most of them in private practices.

Radiation protection

In the years after the discoveries of W. C. Röntgen, A. H. Becquerel, M. and P. Curie and E. Rutherford, an impetuous period of research on X-rays and radium followed. This uncontrolled pioneer time continued for about half a century. Relatively early the deleterious effect of too intensive irradiation was recognized. Following radiation burns the fingers of numerous scientists, radiologists and dentists had to be removed, and later on it became evident that many scientists and radiologists had a noticeably shorter life expectation.

The first organized and international warning was given in the year 1928, connected with the foundation of the ICRP (International Commission on Radiological Protection)[8]. This was the beginning of radiation protection. However, it still took quite a long time to achieve sufficient scientific and technical experience in this field and to satisfy legal demands. The national regulations did not become effective before 1960, when all exaggerations and presumptions came to an end.

Up to 1950 only the so-called deterministic effects of the ionising radiation (see Fritz-Niggli in this issue) (skin burnings, loss of hair, sterility and acute mortality) were sufficiently known to recognize the effects of a dose-threshold. As long as the threshold is kept low, nothing is going to happen. Additional security margins were built in to compensate for biological and dosimetric uncertainties, and the first dose limits were set. The existence of stochastic effects like leukemia, cancer, genetic damages, appearing only after a certain latency period, was at first just a presumption, then proven in animal experiments and finally confirmed by epidemiological studies on the human body. Science showed that these late effects are connected with stochastic hits of radiation on the DNA molecules. In this connection the limited ability of the DNA molecules to repair themselves is of great importance.

In epidemiological studies on survivors of Hiroshima and Nagasaki the relationship between absorbed dose and cancer induction was quantified in the course of time[7], showing that this connection in the first approximation is linear. By doubling the absorbed dose the probability of cancer production will be doubled. This linearity might be extrapolated back to zero. After that, stochastic effects would not show any threshold, but would complicate radiation protection, because one would have to operate with probabilities.

In order to fix the protection limit for radiation workers, statistics of various professions were consulted. Thereafter limits were set in order to show the degree of the unacceptable. The practice of a job on the whole should not increase the probability of a premature death by more than 3%. The ICRP[7] recommended fixing the dose limit for radiation workers at 20 mSv/year. This recommendation is included in the Swiss legislation for radiation protection. For the general public the dose-limit is set to a factor of 20 lower i.e. to 1 mSv/year, taking into account more sensitive population groups like children, pregnant women or sick people.

Today cancer induction is a reference in radiation protection. Besides ionising radiation there exist a considerable number of activities and habits causing cancer. The dose limit for the population (1 mSv/year) corresponds to about 1 to 2 cigarettes per week. Should science be able to avoid or cure cancer completely, today's strict radiation protection would more or less lose its motivation.

Radiation protection is based on three first principles: a) justification of activity; b) optimisation of protection; and c) limitation of individual doses. As a measure for the quantitative observation of radiation exposure in most cases reference is made to natural radiation, to which all human beings are exposed. Man is exposed to cosmic, terrestrial and incorporated radiation sources as well as to the radioactive inert gas radon and its daughter products in the house (fig. 3). This leads to a mean dose of 2.8 mSv/year (ref. 2), with a range between 1 and approx. 150 mSv/year. Additionally, artificial radiation sources have to be taken into consideration. This radiation exposure amounts to an average of 1.2 mSv/year, and medicine takes the greatest part with approx. 1 mSv/year. On average we accept – more or less voluntarily – a dose of almost 4 mSv/year. The contributions of single radiation sources show different fluctuations. In this way doses for an individual can diverge very strongly from the average value, mainly due to the contributions of radon, of medicine and the atomic energy industry.

The accident in Chernobyl and its radiological consequences for us

At the end of April 1986 the most severe accident in the history of the peaceful utilization of nuclear energy took place in Chernobyl (Ukraine) in a graphite moderated reactor cooled by light water (a construction specially favoured by the former Soviets). Careless treatment of a test experiment when switching off the reactor and neglect of operating instructions led to overheating and a fire in graphite and finally to an explosion in the reactor building. A considerable amount of volatile radionuclides from the reactor (J-131, Cs-137 etc.) escaped, was carried into the atmosphere and spread extensively. Due to rain in various parts of Europe the ground was locally contaminated (see Fritz-Niggli in this issue).

Persons within the reactor area and in the near surroundings as well as rescue personnel were exposed to heavy radiation doses which led to deterministic damage and deaths. Of 203 patients exposed to doses of 0.8–16 Gy, 31 deaths were registered within 3 months after radiation. So far no definite information exists about the victims of the fire and clearing personnel. According to reports precautions had been gravely neglected, but this must be considered in the context of the political system and its ethical principles at that time. The precautions did not in any way meet international standards.

Due to this severe incident the population of most European countries was subjected to an additional radiation exposure. From radioactive contamination subsequent incidents of stochastic nature in all European countries have to be expected. The extent thereof can only be estimated mathematically. For Switzerland – as a consequence of the nuclear catastrophe – an average dose of 0.15 mSv was determined in the first year after the accident, half of it occurring from external radiation outdoors and the rest from absorption in food. In the south of Switzerland maximum doses of 2 mSv were registered in the year of the accident[6]. According to English data[6] the relatively long-living Cs-137 will disappear with an effective half-life of approx. 10 years. The accumulated dose in the 50 years after the accident cannot be estimated yet. It is presumed to be about 0.5 mSv, and a danger for adult persons cannot be estimated therefrom. On the other hand 75 additional cases of thyroid cancer of children, including 8 deaths, have to be expected if the recommendations given at that time (e.g. no supply of fresh milk to small children) were neglected. By following these recommendations this number might be reduced to approx. 60 cases of cancer, i.e. 6 deaths. Statistically these figures cannot be determined in the population.

Outlook

In view of the unexpected and rapid evolution in all fields of medical physics mentioned, statements about the future development are very difficult. In some fields developments will also be advanced and improved in the near future.

Within medical imaging further developments of radiodiagnostics with new CT-scanners and digital radiography are in progress, in addition to new imaging technology without photographic films. Data processing with modern computers is an important field providing three-dimensional reconstructions and purposeful treatment, and the description of a great amount of data material. Imaging methods with the help of ionising radiation will also in future be necessary for medical diagnostics. Conventional X-ray pictures still participate in between 70% and 80% of all examinations. By taking up methodical steps and new technologies, an effort will be made to refine procedures to reduce radiation risk to patients. Today diagnostic radiology includes several techniques with non-ionising radiation, especially ultrasound and magnetic resonance imaging. Nuclear spin spectroscopy allows characterization studies of tissue. New supra-conductive materials, improvements in light-conductor technique etc. are also very important in further developments.

In nuclear medicine the digitalizing of measured data will continue. Different imaging methods will be connected to simplify clinical diagnostics. Three-dimensional reconstructions permit functional measurements in anatomic organs. The significance of radio-chemistry will increase, by the production of cell-specific antibodies against tumour-cells. Premature recognition of metabolic illnesses will be possible with the application of specific tracers. By the use of α-radiation when treating metastases, the local radiation effect will be increased at the same time as protecting the healthy tissue.

Among the most important tasks for the near future in radio-oncology is the development of dynamic treatment, adapted to the target volume as well as three-dimensional treatment planning, considering the radiobiological characteristics of tumours and normal tissues. In addition, precision, optimization of treatment techniques and quality assurance have all to be improved.

The high expectations of several medical specialities focus on new techniques. At present the number of medical physicists in industrial countries is about 10 per 1,000,000 inhabitants. In this respect Switzerland constitutes a developing country, with less than 30 medical physicists or about 4 medical physicists per 1,000,000 inhabitants[15,16]. For future development the professional attraction of this physicists' domain, concerning tasks as well as the economical situation and medical status is of significance. It is the responsibility of physicians, particularly specialists in the field of medical radiology, to foster and support scientific and technical developments for the health of the patient. Therefore the existing scarce possibilities must not only be supported, but be extended as well.

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