Classic Texts in the Sciences

Uwe Busch
Editor

Wilhelm Conrad Röntgen
A Shining Life for Science

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Classic Texts in the Sciences

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KONGLIGA SVENSKA
VETENSKAPS-AKADEMIEN

har vid sitt sammanträde den 12 Nov. 1901 i enlighet med föreskrifterna i det af

ALFRED NOBEL

den 27 November 1895 upprättade testamente beslutat att tilldela det pris som detta år bortgifves 'åt den som inom fysikens område har gjort den viktigaste upptäckt eller uppfinning' till

WILHELM CONRAD
RÖNTGEN

såsom ett erkännande af den utomordentliga förtjenst han inlagt genom upptäckten

“Nobel Prize certificate for Wilhelm Conrad Röntgen from the year 1901” (source: The original document is located in the University archive Würzburg)

Preface

The name Wilhelm Conrad Röntgen is associated with terms like “ingenious,” “unique,” “groundbreaking,” “revolutionary,” and much more. His name is known worldwide as is the global significance of the new type of radiation he discovered. The special significance of the X-rays (later named after him) to medical and scientific research has already been highlighted in numerous biographies.

The special focus on the discovery of X-rays, however, does not do justice to the work and achievements of Wilhelm Conrad Röntgen. In the field of experimental physics, Röntgen was an outstanding scientist of his time. This is reflected, for example, by looking through the appointment lists of the physics chairs that were vacant at the time.

A mechanical engineer by training, Röntgen devoted his entire university life to the field of precision physics. Following the credo of a classical natural scientist, he was an advocate of the most precise observation of nature and the resulting need to answer questions in order to discover its secrets. Within the scope of his scientific work, he carried out both classical basic research and very concrete applied research, in particular to improve physical measurement technology and the measurement methods available at that time.

As a prototype of the modern, interdisciplinary, and creative thinker in the natural sciences, Röntgen became a seal of quality and a trademark for the highest achievements in research and development in Germany around 1900: With his work, Röntgen played a major role in establishing the “Made in Germany” trademark of engineering, technology, science, and research in this country. As the first Nobel Prize ever, Röntgen’s award set high standards and established corresponding demands and requirements for the award of the subsequent Nobel prizes.

In this book, an attempt is made to characterize the natural scientist and physicist Röntgen and his spirit of research more closely by means of selected research works in the sense of an opera selecta. In addition, original photographs from his estate are published here for the first time. Röntgen was one of the few scientists at the time who used his great passion for photography to document his experimental results. The photographic documents in the archive of the Deutsches Röntgen Museum have been able to be assigned to individual paragraphs of his famous first publication on X-rays. However, their exact analysis remains difficult, since his laboratory book with exact details of his experimental procedure is unfortunately no longer available.

In today's society, which is overwhelmed by the media with information, Röntgen's universal message "Stop for a moment and take a closer look" can not only provide a general new orientation but will result in a new experience and enhanced knowledge. This principle is still followed by numerous (natural) scientists today. Röntgen is thus not only a role model for researchers but also for young people who want to become such. With their statements to be found in the epilogue, modern X-ray researchers make one thing very clear: X-ray has a bright future.

My sincere thanks go to all authors for their contributions.

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Last but not least, I would like to express my sincere thanks to Dr. Arpan Banerjee, Birmingham, UK, for his cooperation and help with the English translation of the book.

I wish all readers exciting new insights into the life and work of a fascinating natural scientist.

Remscheid, Germany Uwe Busch

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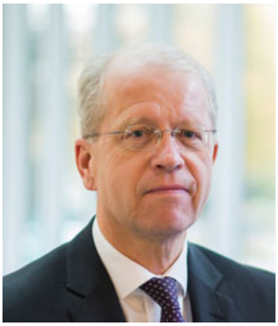

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[1] Nobel Prize in Chemistry 2009 was awarded to Ada Yonath.

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The Founding Father of Radiology

1

Gerald Antoch

Gerald Antoch (© University Hospital Düsseldorf. Reprint with kind permission)

The discovery of X-rays by Wilhelm Conrad Röntgen on November 8, 1895 is without doubt one of the most important discoveries in medicine. Examination procedures based on the use of these X-rays, such as conventional X-ray, fluoroscopy, or computed tomography, now form an integral part of the diagnostic basis of almost all diseases. Through interventional, X-ray-based procedures, radiology today is also an integral part not only of diagnostics but also of therapy. X-ray technology is subject to continuous change through scientific and technical innovation. In the 125 years since the discovery of X-rays by Wilhelm Conrad Röntgen it has been possible to develop new X-ray-based examination procedures and to improve X-ray technology both, in terms of resolution and accuracy, all with a reduction in radiation exposure of patients. New developments such as automatic

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dose modulation and special reconstruction algorithms now make it possible to perform an examination with only a very low dose of radiation. Highly specialized software enables X-ray images to be viewed in different planes, reconstructions and multidimensional views, thus further increasing diagnostic accuracy. In the meantime, computer-based techniques are no longer only used for the preparation of X-ray examinations and image representation, but increasingly also for the evaluation of the X-ray images. In the future, it can be expected that radiologists will be supported in the evaluation of X-ray examinations by methods of artificial intelligence. These new computer-based evaluation methods will make it possible to extract additional information from X-ray images. The scientific activities of the radiologists organized in the German Radiological Society (Deutsche Röntgengesellschaft e. V.) are making significant contributions to this continuous innovation thus enabling the further development of the "shining" possibilities created by Wilhelm Conrad Röntgen. On this 175th birthday of Wilhelm Conrad Röntgen, however, it is also important to preserve the past. The Röntgen birth house in Remscheid-Lennep is the central example. Deutsche Röntgengesellschaft e. V. acquired the house in 2011: it reopened in 2020 in a renovated state to mark the 175th birthday of Wilhelm Conrad Röntgen. A combination of exhibition space and conference rooms will interactively communicate the "shining life" of Mr. Röntgen and create space for scientific exchange.

A shining life for science gives you an insight into the life and scientific work of Wilhelm Conrad Röntgen. Above all, however, this book deals with the influence of the X-rays he discovered on medicine, physics, and other areas of daily life. The book will be both, informative and entertaining for physicians, non-physicians, and the general reader interested in the life of this remarkable man.

Introduction

2

Helmut Dosch, Gerhard Adam, Anca-Ligia Grosu, and Matthias Purschke

The Importance of X-Rays for the Natural Sciences

Helmut Dosch

Helmut Dosch, Chairman of the DESY Directorate (© DESY. Reprint with kind permission)

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In our everyday lives, we continuously use top products made by material scientists: these include materials with electrical, magnetic, optical, mechanical and biocompatible properties. Today and in the future, little can be done without high-tech materials; they are the basic building blocks for all modern technologies, from information and communication to medicine, energy and the environment to traffic and transportation.

Sometimes it is worth looking back to understand the highly technological world we live in and the rapid development we have undergone.

The year is 1895 and the predominant technology is electromagnetism, we have electric motors that help us in everyday life and we use a variety of metals and metal alloys because of their electroconductive and advantageous mechanical properties. In medicine, the situation is still grim: The existence of viruses is unknown.

Then scientific advances come every year:

- 1895: Wilhelm Conrad Röntgen discovers his unknown rays—a scientific sensation that literally turns the world upside down and makes Röntgen the first world star in physics. Röntgen's new rays can suddenly peer into the interior of solid materials and make previously invisible structures visible. For the general public this is almost incomprehensible.
- 1897: Joseph John Thomson and Emil Wiechert almost simultaneously discover electrons, which, as it later turns out, are the source of X-rays of unknown radiation and at the same time mediators of all the above-mentioned material properties.
- 1900: Max Planck discovers the quantization of energy—an affront!
- 1905: Einstein explains the mysterious photoelectric effect as a quantum phenomenon (incidentally, he turns our cosmological world view upside down).

Within only 10 years, our physical world view has thus changed dramatically—an explosion of knowledge, but one that has not yet revealed the consequences it would have for our society. The nano age begins in physics laboratories and will revolutionize industry and society in the coming decades. Wilhelm Conrad Röntgen, with his millennium discovery, has opened the door to this strange, invisible nanoworld.

In this article, I will largely omit the medical revolution triggered by the discovery of X-rays and concentrate mainly on the equally spectacular effects on materials research.

Here the year 1912 was decisive: Max von Laue discovered in Munich (motivated by Ewald's doctoral thesis) that X-rays, when passing through crystals, are deflected from the regular arrangement of the atoms and produce a characteristic interference pattern on the screen, which for the first time allowed direct conclusions to be drawn about the atomic structure of the material: the birth of crystallography. In the coming decades, X-ray crystallography will decode all existing materials atomically and pave the way for knowledge-based material design. Today's high-performance magnets, highly integrated components, superconducting materials and superalloys for extreme conditions (e.g. in aircraft turbines) would be inconceivable without X-ray's discovery.

The structures that attracted the attention of the general public were X-ray interferences of biological substances. X-rays allowed us to peer into the molecular engine room of life. In 1957, James Watson and Francis Crick were able to decipher the structure of DNA, the carrier of genetic material, and to identify the molecular origin of heredity in the double helix. The famous X-ray ("Photo 51") of a DNA structure is shown in Fig. 5.11. In 2009, Ada Yonath, Thomas Seitz and Venkatraman Ramakrishnan were awarded the Nobel Prize in Chemistry for decoding the ribosome, the nanorobot made up of millions of atoms that reads the genetic code in our cells and synthesizes protein molecules from it. X-rays have solved one of nature's greatest mysteries.

Thus we have arrived back in the modern age in our journey through time. X-ray analysis of materials has become a powerful branch of scientific research. Today, the most modern X-ray facilities can be found at major research centers that provide highly collimated intense X-rays and dedicated measuring stations that enable high-precision insights into the nanoworld. These large-scale X-ray laboratories use the brilliant X-ray light that comes from electron storage rings, bears the somewhat unwieldy name synchrotron radiation and was originally a waste product of particle physics. In the ring facilities of particle physics, the circulating electrons lose an enormous amount of energy through forward radiation of intense X-ray light. As early as the 1960s, physicists at the Deutsches Elektronen Synchrotron (DESY) experimented with synchrotron radiation and explored its usefulness for solid state research.

Synchrotron X-rays have enormous advantages over laboratory sources: Their intensity is many orders of magnitude higher, and their wavelength can be continuously adjusted—even during an experiment. The research groups carrying out measurements at today's large-scale research facilities can "order" an X-ray beam with any energy, polarization, focusing and time structure. The sophisticated computer-controlled measuring stations provide highly precise information about the atomic, chemical, electronic and magnetic structure of materials (Fig. 2.1).

A prime example is the European Synchrotron Radiation Facility (ESRF) in Grenoble, which went into operation in 1988 and is a cooperation of many European countries and international partners. The ESRF operates more than 40 measuring stations, provides more than 3000 scientists with tailor-made X-ray analysis every year and produces more than 1200 publications in the most renowned journals every year.

Today, the X-ray applications in these large laboratories have long gone beyond von Laue's interference experiments: X-ray diffraction, X-ray spectroscopy, X-ray tomography and imaging X-ray methods are offered in many variants, all under environmentally and industrially relevant measurement environments. Even the extreme environment in our earth's interior or on other planets can be generated on a laboratory scale for geophysicists and astrophysicists and precisely explored with finely focused X-ray light.

X-ray microfluorescence tomography is particularly popular among art historians, which they use to decipher microscopic details in valuable paintings, for example, without destroying them. At the synchrotron radiation source DORIS III at DESY, a self-portrait behind a painting by van Gogh ("Grasgrond", 1887) was made visible with this X-ray

Fig. 2.1 European Synchrotron Radiation Facility ESRF in Grenoble (© ESRF. Reprint with kind permission)

method in 2008 (Fig. 2.2). Uwe Bergmann from the National Accelerator Laboratory (SLAC) in Stanford succeeded a few years ago in discovering the original manuscript of the ancient mathematical genius Archimedes, which was hidden on so-called palimpsests from the twelfth century.

In recent decades, synchrotron radiation has proved to be a veritable goldmine in the research of new solid state properties, the development of new materials and in structural biology. One might be inclined to believe that this has quenched the thirst for knowledge in the understanding of the nanoworld.

Well, this has always been the holy grail of nanoscientists, namely the vision that the movement of atoms and electrons in materials during a chemical reaction or biological process can be followed in real time, i.e. within a few quadrillionths of a second. In a way, this would make it possible to watch nature at work and thus solve some of nature's stubborn mysteries.

A quadrillionth of a second, the time cycle in the nanocosmos, that's just 0,000,000,000,000,001 s. So atoms perform one quadrillionth of a second of motion. If such an atomic step were to last 1 s, then it would take more than 30 million years for this one quadrillion motion steps! This ultra-short time span—physicists speak of a femtosecond—appears at first glance to be unattainable for short-term structural elucidation.

The second persistent problem is that a high-intensity X-ray laser is needed to obtain usable information from such nanoprocesses in this short time. For many years, such a

Fig. 2.2 (**a**) Experimentierstation P11 bei PETRA III (courtesy of © DESY). (**b**) Vincent van Gogh, Patch of Grass. Painted over one of the 50 farmer's heads: Head of a woman (© Nuenen Collection Kröller-Müller Museum, Otterlo, the Netherlands. Reprint with kind permission). (**c**) The colored central part was reconstructed using synchrotron XRF scans, the b/w outer part by means of MA_XRF in situ. This visualization of the painted-away first painting became possible thanks to the University of Antwerp, TU Delft, DESY and the Kröller-Müller Museum (courtesy of © Nuenen Collection Kröller-Müller Museum, Otterlo, und University of Antwerp, TU Delft, the Netherlands. Reprint with kind permission)

femtosecond pulsed X-ray laser was more than a Holy Grail, rather a futuristic dream, even for the optimists among physicists, until Evgeny Saldin, a DESY scientist of Russian origin, published a theoretical paper in 1984 that showed that it should still be possible.

The theory is complicated, so we won't go into that here. For the technical realization, one needs tiny well-formed bunches of electrons, which are accelerated to very high energies in the billion-volt range. These ultra-relativistic electron bunches are shot through a magnetic field arrangement several 100 m long, which, according to Saldin's theory, causes laser radiation in the X-ray range: This is the principle of the free-electron laser.

The FLASH (Free-Electron Laser) test facility in Hamburg was built at DESY in the late 1990s as part of an international collaboration to experimentally test Saldin's theory. The core piece was a 200-m-long superconducting linear accelerator, the technology of which was developed at DESY and accelerated electrons to an initial energy of 500 meV. The breakthrough was announced on 22 February 2000: "first lasing". Just over 100 years after Röntgen's discovery, laser light in the soft X-ray range was generated for the first time—a pioneering achievement by accelerator physicists.

For many years, the Hamburg Test Facility has been a much sought-after large-scale research facility on which scientists from all over the world experiment. The success of FLASH has changed the scientific agenda worldwide:

Today, several X-ray free-electron lasers are already in operation worldwide, and many are currently under construction. The American laser LCLS has been in operation since 2009, followed by the Japanese laser SACLA. Among the European X-ray lasers, the European X-ray laser European XFEL in Hamburg, which went into operation in 2017 and is the most powerful laser of its kind to date, deserves special mention.

Synchrotron radiation sources are, as already mentioned, extremely high intensity X-ray sources. An X-ray image today takes less than 1 s. With free-electron lasers the situation is quite different. Saldin's laser process predicts that all the electrons in a bundle, about 10 billion (that is a nano-coulomb of charge), emit X-ray light in common mode. This leads to an increase in the X-ray intensity of each electron bundle by a factor of ten billion! An X-ray laser flash that is only a few femtoseconds short contains the same intensity as a conventional 1-second X-ray at the synchrotron. Free-electron lasers thus enable structural analyses to be carried out in time with molecular movements. If one could string together many such individual images, one would be able to see the structural changes of a molecule during a chemical reaction: Quantum cinema is now within our grasp.

The fields of application for free-electron lasers have not yet been fully explored. We are at the beginning here, just as we were in 1912 when von Laue saw the first signals from the nanocosmos and probably would not have bet on the fact that 45 years later this would solve the atomic structure of DNA. Intensive experiments have been conducted on and with free-electron lasers for about 10 years. Many new phenomena have been discovered and revolutionary new X-ray concepts developed. At present, work is feverishly underway to follow the processes in photosynthesis down to the last detail, or better, to the nearest femtosecond. Here we could learn from nature how to split water in an environmentally friendly way to produce hydrogen as an energy carrier and at the same time clean the environment of CO2. Another important topic is the precise understanding of the atomic processes involved in catalysis. Today, it is assumed that these catalytic processes involve so-called short-lived transient states that have a decisive influence on the catalytic process. With the X-ray lasers, experimental access to these non-equilibrium states would now be possible for the first time.

Experiments at the free-electron laser no longer have anything in common with the measurement concepts at conventional X-ray sources, including synchrotron radiation sources. An X-ray flash produces an image in high-frequency pulses. The samples are no longer located on sample holders and are no longer moved in the beam with goniometers, but are shot into the interaction zone with a micro nozzle and scanned by a single X-ray

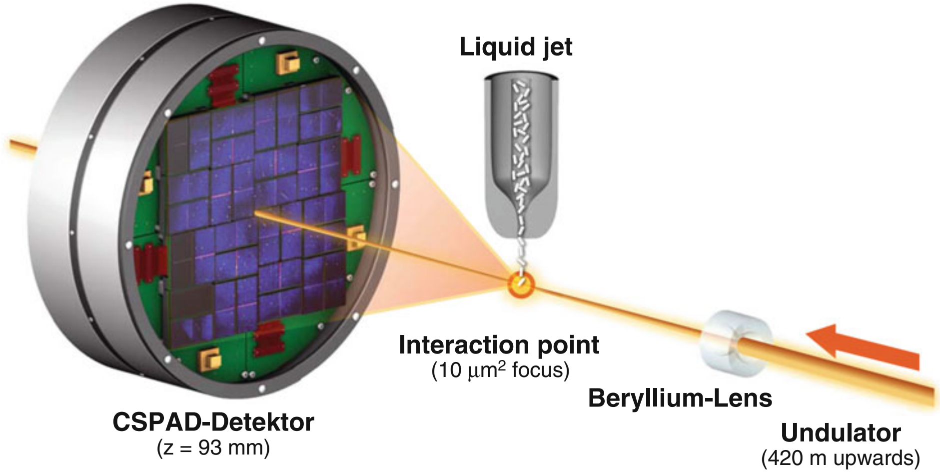


Fig. 2.3 Principle of an X-ray experiment on a free-electron laser image (© DESY. Reprint with kind permission)

laser flash. Large area X-ray detectors produce gigabytes of data every minute, which are evaluated with new algorithms (Fig. 2.3).

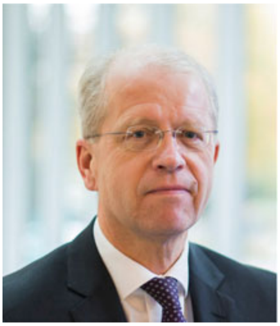
What will the future bring us in the field of X-ray analysis? Well, for one thing, we will see what new territory the X-ray free-electron lasers discover and explore. The synchrotron radiation sources are currently being converted to a new storage ring technology that will further increase the quality of the X-ray radiation by two to three orders of magnitude. The future here is to switch X-ray diffraction and X-ray spectroscopy to imaging mode. We will then obtain microscopically resolved images of any material properties. In autumn 2017, all 19 operators of European synchrotron radiation and X-ray laser sources joined together to form a new European consortium called the League of European Accelerator-based Photon Sources (LEAPS) with the aim of working together even more efficiently to provide better coordinated software, sample environments and data formats for academic research and industry.

In recent decades, the X-ray facilities have become larger and larger, including large storage rings and linear accelerators several kilometres long. Accelerator physicists are currently working on reversing this trend. They are counting on a new type of electron acceleration, which takes place in charged plasmas and enables acceleration voltages that exceed the current ones by a factor of 1000 (!). When such plasma accelerators become reality, such facilities will shrink back to laboratory scale. Hospitals could then have such facilities in their basements for high-resolution X-ray imaging of patients with far less radiation exposure than today.

We imagine Wilhelm Conrad Röntgen sitting on a cloud and observing all this. He would be very proud of his heirs.

The Future of Radiology

Gerhard Adam



Gerhard Adam (© UKE Hamburg. Reprint with kind permission)

The revolution in the natural sciences and medicine triggered by the discovery of X-rays is omnipresent and well-known. The natural sciences and medicine became transparent, what was previously hidden and opaque became visible, and the boundaries of the natural sciences were redefined, crossed and reassessed. The epochal change brought about by the discovery in 1895 can only be compared in medicine with that of James Watson and Francis Crick [1], who were the first to describe the structure of DNA.

How will this groundbreaking discovery develop in the future? How will radiology influence the medicine of the future? How will medicine influence radiology? How will the medicine of 2050 differ from that of 2020?

While in the industrialized countries medicine is most strongly influenced by aging and demographic change, in the non-industrialized countries population growth with its consequences for nutrition and hygiene will be the determining characteristics.

For medicine, ageing populations mean an increasingly complex treatment of tumour and cardiovascular diseases, neurodegenerative diseases and degenerative diseases of the musculoskeletal system. Growing young populations present medicine with other challenges: Adequate supply of food, clean (drinking) water and ensuring standards of hygiene and infectious medicine are probably the greatest challenges. Thus, the medical care of the world population will be characterized by the most complex high-tech medicine as well as hygienic and infectious disease medicine.

Radiology will adapt and change to the requirements of patient- and disease-centered care. Radiological procedures will have to be made available more widely than in the past to broad sections of the population in all parts of the world in order to demonstrate their added value in medical care.

Elementary drivers of change in diagnostic imaging medicine will be scientific progress in physics, biology, chemistry, electrical engineering, engineering sciences and information technology.

Imaging information is already available today, regardless of where it originated. Imaging technologies will become faster and more precise. They will combine existing methods and be more hybrid. New imaging technologies will be developed to address the first two aspects. Imaging technologies will be miniaturized and more mobile, defining and enabling precision medicine. Imaging will be a key element of Big Data Analytics, providing hybrid health data by combining clinical chemistry, microbiology, pathology and patient history.

Radiology will be the central information broker and information trader in an increasingly complex high-performance medicine. Interventional radiology will replace surgical interventions. Imaging technologies will increasingly transform the invasive medicine of the surgical disciplines to a minimally invasive surgery, to an image-guided intervention.

Today, radiological information is available at the point of examination in fractions of a second. This is made possible by the evolution of computed tomography (CT) to multi-line spiral CT [2, 3] and magnetic resonance imaging (MRI) [4–6] to time-resolved volume tomography as well as the use of digital detectors in projection radiography. Technological progress in the further processing of imaging information will accelerate these processes even further. In the future, we will have image post-processing methods at our disposal that will allow highly integrated mobile post-processing of volumetric data sets. Further development of the software will be the main driver of development. Radiologists will “fly” through a morphological and metabolic data set in real time to analyze and evaluate, for example, intravascular changes in the arterial wall in the context of atherosclerosis and then select the appropriate drug-coated stent to treat a vascular wall lesion and implant it under controlled imaging.

Imaging today is high-resolution. CT, MRT and also metabolic imaging with positron emission tomography CT (PET-CT) or MR-PET allow anatomical and metabolic imaging on sub-millimeter scales. In the future, this information will be used more and more for a more precise evaluation of therapies. For example, the evaluation of a specified chemo- or radiotherapy can be recorded at an early stage, thus reducing the toxicity of the therapy. Precision imaging will be used for the targeted verification of a focus of disease. In combination with liquid biopsy methods [7], which quasi initiate a holistic search for a tumor, high-resolution anatomical and metabolic imaging will be used for precise tumor search. This also requires the integration of molecular and imaging information. At the same time, digital analysis of the volume data sets makes previously unused quantitative imaging information available in the form of radiomics data, which gives us a next level of quality in the interpretation of disease foci [8].

The integration of this data will give rise to a new group of doctors whose art will also consist in using information technologies to channel the flood of data in the best sense of the word and at the same time combine them with each other in such a way that added value is created in the detection and treatment of diseases, not only in imaging medicine. Approaches to this already exist which have demonstrated the complexity of the task and also the possibility of failing at such a task [9]. Medicine and informatics must find a common language to accomplish this task. The medical curricula of 2050 will have to take this into account and strengthen the field of e-health [10] and take it into account in student teaching.

The use of intelligent algorithms in digital image analysis and reporting is obvious. Artificial Intelligence or Augmented Intelligence will help to redefine the workflow in radiology [11]. It will make it possible for radiologists to turn their attention back to their patients in the first instance and not get lost in the flood of imaging information that is already generated today, for example, by reading a high-resolution PET-CT or a multiparametric MRI of the prostate.

Once the neural network has read and processed sufficiently annotated and validated image information, it is integrated into the diagnostic process and provides the radiologist with an initial diagnosis to work with initially. One can imagine systems—some of which are already integrated into Radiology Information Systems (RIS) and Picture Archiving Communication Systems (PACS) or Clinical Workplace Systems (KAS)—that help to separate urgent from less urgent cases, complex from less complex and emergencies requiring immediate clinical action are made directly available for further processing. Such systems will soon have their place in the radiologist's reading room, once medical quality has been assured.

Just like Alexa, who takes the medical history digitally in the emergency room and thus determines the first step in the treatment of patients: If the patient's medical history is more indicative of a surgical or internal clinical picture, does the patient need to be seen quickly by a doctor, or can he or she be discharged to outpatient care for further treatment?

These intelligent systems will also shape the training and further education of our young medical professionals and provide important support in everyday medical practice, for example by offering initial suspect diagnoses during night duty, which can then be used as a basis for further work. They will help to improve further training by being able to offer knowledge from a wide range of institutions, from primary care hospitals to university hospitals, in an aggregated digital compendium. Digitised education and training will help improve the standard and quality of medical training [12].

In research, such assistance systems will channel the flood of data and, in the best sense of the word, help to find the famous needle in a haystack or to form an image from apparently unconnected pieces of the puzzle of diagnostic medicine, thus allowing radiomics-based data sets to mature into an important element of clinical medicine. The information that we obtain today from large epidemiological cohort studies, some of which include imaging information, will only be able to be integrated into a meaningful scientific context using big-data approaches and integrate the data volumes into a research approach that is then also hypothesis-driven [13].

Will artificial intelligence put radiologists out of work [14]? Yes, at least those who also want to work in 2050 as in 2020. Today, the radiologist sits in front of his PACS console in the dark, trying to analyze a vast amount of image data and integrate it into a clinical context. In the future, he will experience considerable relief by being supported in the analysis and integration of the data, and will have more time for the patients on the one hand, and more time for the targeted information transfer to his clinical colleagues on the other.

As a result, radiology will in future, even more than today, become the central information exchange in the communication of clinical data. The radiologist will become the information broker of twenty-first century medicine, whose commodity will be highly aggregated imaging information. It remains to be seen whether 1 day there will be no radiologists at all, since the algorithms of neural networks will independently make diagnoses and communicate them to patients and clinical colleagues. It is conceivable.

From today's perspective, this is perhaps just as likely as a therapy consultation with a clinical psychologist, which is conducted autonomously by a computer, or a pancreatectomy with multiple loop reconstruction, which is performed from skin incision to skin suture exclusively by a surgical robot.

Radiological information is sent to any place in the world in fractions of a second, where it is evaluated by experts. Teleradiology [15, 16] is the most widespread and already well-established application of telemedicine and enables the provision of imaging diagnostics even without the presence of an expert at the place of examination. As a result, imaging can be further disseminated , enabling it to benefit larger patient groups Prerequisites are imaging hardware and access to the Internet, where bundled expert knowledge is available 24/7/365 worldwide. One can imagine the power of swarm intelligence if one succeeds in configuring telematic expert networks with the help of which even the most complex and rare differential diagnoses can probably be easier diagnosed.. Training programmes could also be carried out in this way, e.g. projects in paediatrics in countries without direct access to specialist radiological knowledge [17]. Teleradiology thus enables the unlimited provision of highly specialized expert knowledge.

Radiology with its information will also increasingly become the basis for image-guided therapy [18]. This applies to the applications of interventional radiology with which we are familiar, such as vessel opening and vessel-closure procedures or image-guided biopsies. "Smart" interventional equipment will help to ensure that the therapy can be carried out in an even more targeted and gentle manner and with fewer complications. Tumours could thus be better treated by targeted computer-controlled injection at the site of the greatest biological tumour activity. The greatest toxicity could thus be directed to the site of greatest biological aggressiveness, while other tumour parts could be omitted. The future will belong to the combination of molecular imaging information with a minimally invasive imaging-controlled therapy. The hybridisation of the methods known so far will also help to improve radiotherapy. Already today, MR-PET systems [19] in combination with MR-guided radiotherapy [20] enable highly targeted treatments that were unthinkable until recently. Metabolic-topographic activity maps could thus contribute to a further reduction in radiotoxicity.

Today, modern operating theatres are unimaginable without imaging systems. Major heart valve surgery of the twenty-first century is based on interventional cardiology and cardiac surgery today is planned and guided by imaging [21, 22]. This field will continue to expand with the refinement of imaging systems and image post-processing algorithms. Already today, the number of open surgical interventions on the aorta is in the minority, the outcome data are similar to the open procedure [23]. This trend will continue in other surgical disciplines.

Which new imaging methods will enrich radiology, the “imaging sciences”, in the future? We do not know.

Today, other procedures are on the horizon in addition to the classic sectional image modalities such as CT and MRI, but they have not yet made the step into translation. Magnetic Particle Imaging (MPI) as a scanning tomographic method, whose information content is based on the signal selection of magnetic iron nanoparticles in the organism, is a promising method with great potential in vascular and cellular imaging [24].

Spectral X-ray imaging is on its way to the clinic [25]. It could open up completely new possibilities, for example in quantitative lung imaging. The first prototypes of phase-contrast CT are about to be explored. Here too, interesting applications can be envisaged, e.g. in vascular imaging [26]. High-resolution quantitative ultrasound methods will certainly help to improve clinical imaging.

Moreover, nanomedicine can play an important role in the radiology of the twenty-first century [27]. Smart contrast enhancers for CT and MR imaging or for the MPI are conceivable—as are nanoparticle-based theranostics, which are controlled by imaging to recognize the focus of the disease and, once they have reached it, treat it simultaneously.

The future of radiology is promising and continues to offer radiologists an exciting field of work. From today’s perspective, it will be shaped by further developments in the natural sciences, computer science and information technology. The vision will be expanded by scientific developments in the field of molecular medicine. The image of the clinical and research radiologist will change, the focus will be on the ability to integrate imaging data into clinical and molecular contexts and to fit them into the clinical workflow.

The radiologist will be *the* information broker of the twenty-first century in clinical medicine. Wilhelm Conrad Röntgen, who was the prototype of the modest scientist and therefore one of the great role models of modern scientific history, would not have dared to predict which new imaging systems would support him in this.

The Future of Radiotherapy

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