Radiology towards the Next Millennium
Future of Medical Imaging

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door

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Mijnheer de Rector Magnificus, zeer gewaardeerde toehoorders,

An image is worth more than a thousand words. A good illustration is often much more comprehensive than even an exhaustive description, because words may not easily express all the details that can be delineated in a picture. Leonardo da Vinci was one of the strong supporters of this idea by frequently telling his students who were studying with him the morphology of the human body: "Do not even try to describe something with words when you are not speaking to a blind".

Leonardo was able to underscore his statement with those well-known impressive drawings of human anatomy, revealing some astonishing details otherwise invisible for the external observer. These drawings became not only masterpieces of art but also an important source of information on the morphology of the human organism.

As a radiologist, or more appropriately as a medical imaging specialist, I can easily understand what Leonardo meant. And more than that, I am also convinced that he was right and that a good image provides more information than many words or other investigations could tell.

From where we come

Radiology is one of the very few medical specialties that can state precisely the date of its beginning. Almost one hundred and three years ago, on November 8th 1895, working in his rather spartan laboratory in Wuerzburg, Professor Wilhelm Conrad Roentgen noticed a glow coming from a phosphorescent screen produced by some invisible rays. To his astonishment, the rays, unlike visible or ultraviolet light, readily penetrated many opaque objects, including the flash of his hand and revealing the shadowy image of the bones of his wife's hand.

Roentgen has discovered the X-rays and gave birth to our specialty that during the following century has rapidly advanced from being a scientific curiosity to an integral part of health care.

This advancement, due in large part to the symbiotic relationship between technologic advances and improved imaging techniques, has lead to the dramatic development of interventional radiology, ultrasound, computed tomography and magnetic resonance imaging. Additionally, in response to the pressure to deliver nearly instantaneous, high-quality imaging services, radiologic information transfer, such as teleradiology developed. Because of our instrumentation and the needs of our clinical colleagues, radiology has flourished. It is poised to tackle the changes and challenges of the 21st century medicine. What remains to be seen is whether we- the medical imaging specialists- are prepared to take advantage of these changes. In other words, will this be a time of new opportunities?

The Milestones in the Development of Imaging Technology

For the first few decades radiologists relied on careful image analysis together with anatomical and pathological correlations and it was this painstaking work which built the strong foundations. The revolutionary changes which came about can be traced to remarkable technological advances, for example, image intensifiers, cine radiology, heavy duty tubes and rapid processing, to only name a few.

Catheter development too, was of great importance, as were the greatly improved manual skills of radiologists resulting in the new possibility of minimally invasive, image-guided therapy. This term describes those procedures that combine an imaging technique and a therapeutic intervention. It has made a subspecialty of radiology (vascular and interventional radiology) one of the most rapidly growing areas of medicine. The possibilities of percutaneous treatments are almost unlimited and have lead to the replacement of some difficult and risky surgical interventions like treatment of intracranial aneurysms, drainage of pathological fluid collections, thrombolysis of occluded peripheral vessels and many, many more.

The next great milestone was the introduction of ultrasonography, which was a refinement of wartime naval sonar. Since its first successful applications to medical diagnosis in the 1950s the method has made spectacular forward leaps in spatial resolution, noise reduction and applicability. The introduction of gray scale digital devices and combination of real-time imaging with color Doppler have significantly broadened the scope of non-invasive and safe diagnostic imaging.

With the discovery of computed tomography by Hounsfield in the early 1970s, for the first time X-rays were combined with computer technology. The method provided higher soft tissue contrast differentiation with cross-sectional perspective, and considerably extended our understanding of basic radiologic-anatomic relationships. As CT technology has improved, so too has our ability to detect abnormalities, characterize them, and relate them to specific processes. High-resolution, dynamic, and spiral CT were just a few of the further developments that brought the method to its actual popularity.

Undoubtedly, the biggest breakthrough was made with the introduction of magnetic resonance imaging, following the discoveries of Bloch, Purcell, Ernst, Lauterbur, Damadian and many others. MRI was continuously being advanced in university and industrial laboratories as for the first time technology development was driven by clinical utilization. The immense vitality of MR imaging is based on multiple factors. There is a large and growing community of basic and clinical scientists performing research in all the MR disciplines and advancing the hardware and software on multiple types of imagers. There is also a wide array of biophysical and biochemical parameters that modulate the MR signal and permit an almost infinite number of sequences, providing functional, metabolic, and morphologic information.

Although MR imaging is still predominantly used in studying the central nervous system, spine, extremities, and joints, other anatomic regions such as the face, neck, liver, pancreas, kidneys, pelvis, vascular system, and even the moving heart are rapidly emerging as important areas of clinical diagnostic practice. There is hardly any set of diseases for which the contribution of MR imaging is not important. MR imaging is continuing to advance at a dizzying rate and it caries the promise of being the most versatile and multifaceted diagnostic and interventional approach.

Changing Paradigm of Medical Imaging

The first century of medical imaging was characterized by the assessment of topographic anatomy and gross pathology on 2-dimensional, single plane, analog images with the sole purpose to establish a possibly correct diagnosis. The tremendous development and expansion of our specialty proves that we were quite successful in this regard. However, the paradigm for the next century is changing and medical imaging will increasingly shift attention towards assessment of anatomical details, of microscopic and even molecular alterations, towards exclusive use of digital images and data for postprocessing in different planes, and 3 dimensional viewing. The attention will additionally more and more focus on the assessment of functional and biochemical properties of the studied regions and as these newer imaging techniques allow earlier identification of smaller lesions or sometimes identify functional abnormalities before any anatomical change has occurred, it will become essential for the imaging procedure to guide the specific therapeutic interventions.

High resolution Imaging

High-resolution imaging has become a routine modality in daily practice. Special reconstruction algorithms of CT data allow to assess details of the skull base or of the lung parenchyma with its functional entities the secondary pulmonary lobules and the surrounding interlobular septae with a thickness of less than 5 microns. Such images provide information on congenital or acquired derangements of the inner ear and specific diagnosis of interstitial or inflammatory lung diseases directing or even replacing some open lung biopsies.

MR imaging with dedicated coils allows to increase the spatial resolution and demonstrate morphological details that were undetectable just a couple of years before. A high-resolution image of the wrist reveals anatomical structures like the triangular fibro-cartilage and some ligaments permitting even the detection of subtle traumatic injuries with great accuracy.

Endoluminal coils have been developed in the last years to acquire the MR signal in the direct vicinity of the device. The improved signal to noise ratio around the coils makes possible to increase spatial resolution with depiction of anatomical details. Intravascular coils are the latest development in this field. They allow to assess the different layers of the arterial wall and atherosclerotic alterations of the intima. Intravascular MR with its high soft tissue contrast provides information on the different components of arterial plaques.

3D Imaging

Volumetric data acquisition became routinely feasible after introduction of spiral CT and of fast and ultrafast MR sequences. Recent advances in image processing hardware and software enable more efficient data handling methods to be used. Even large date volumes can now be processed in real time with the possibility of on-line interpretation of reformatted images.

CT remains the method of choice for demonstration of skeletal injuries and other bony alterations. The 3D reconstructions of complex fractures, like those of the shoulder or of the spine offer a comprehensive overview over the position of the fragments and allow a better planning of the eventually necessary surgical reposition.

In some anatomic regions like the ankle, the hip, the skull base and especially the face, a method called three-dimensional printing or stereolithography has been successfully introduced for therapy planning. This technology is based on plastic models, which are constructed from computed digital raw data. The models are produced from a liquid photopolymer that changes to a solid resin on exposure to a small intense laser beam. They can be used to plan surgical interventions like the reconstruction of depressed zygomatic arch fractures or to design individual prosthetic implants.

Cross-sectional volumetric acquisition methods like spiral-CT and MRI have been increasingly used to produce vascular images. The so-called CT- or MR-angiographies are almost noninvasive high-quality images necessitating only intravenous administration of a contrast-agent. The acquired digital data may be postprocessed using different algorithms and presented as reformatted slices in any desired plane, as projection images or 3D volume reconstructions. The method has been successfully used especially in anatomically complex or for noninvasive follow-up examinations after therapeutic procedures.

By data segmentation, we refer to the process of labeling individual voxels in the volumetric scan by tissue type, based on properties of the observed intensities as well as known anatomical information. Each tissue type can be displayed in a different color allowing a good topographic overview and easy orientation. The images can be used for interactive teaching purposes and pre- or per-operative simulations.

Volumetric 3D images can be usually much better evaluated in a dynamic interactive cine-mode. Modern high performance computational tools allow to handle even large data sets in real-time. In this way, the examiner may turn around and scroll through the acquired body volume interactively. Using different threshold values, structures of a particular density like bones or contrast-enhanced vessels may be visualized exclusively within the acquired volume. Real-time volume rendering can be used in a variety of vascular alterations. Simple manipulations of window levels and application of color to voxels enables comprehensive demonstration of complex anatomic relationships.

Perspective volume rendering is computationally even more demanding. However, it permits visualization of body cavities and hollow viscoses from a unique internal view that can be used to endoscopic or fly-through images. A high-resolution 3D data set of the relevant anatomy acts as the input to the system. The user may than 'navigate' through the anatomy. Virtual endoscopy represents thus the navigation of a virtual camera through a 3D reconstruction of any anatomical region. It enables the exploration of the internal structures and to assist in surgical planning. The unique impression of a simulated flight around or within the presented region can be even enhanced by manipulating the opacity of the voxels.

Even functional information can be derived. Combining a 3D model of the pelvis with a simulated delivery for example, allows excluding birth incompatibilities. However, assessment of real, non-virtual functional processes like motion usually necessitates a fast data acquisition technique.

Functional Imaging

Cine-MRI, for instance, is composed of multiple gradient echo images obtained at different phases of the cardiac cycle, allowing to assess myocardial contractions. This technique can additionally demonstrate abnormal flow in the heart and great vessels, permitting diagnosis of valvular diseases or shunting across septal defects. Low signal intensity tags may be applied using presaturation pulses and their motion can be observed during the cardiac cycle. This gives us the potential to measure myocardial strain with very high precision. With this data, a 3D dynamic model of the heart can be reconstructed with the functional parameter coded as color.

Echo planar imaging is a rapid magnetic resonance acquisition technique, which is capable of producing images at video rates. This allows to assess for instance organ perfusion or even the renal elimination of an injected contrast agent. The signal decreasing agent may be visually traced from its arrival in the cortex throughout the outer and the inner medulla into the renal pelvis. This is the first time that an imaging method demonstrated the different zones of renal medulla in vivo.

These echo-planar MR sequences are so rapid that they even make possible to assess minimal changes of tissue composition like the rapid changes of brain circulation during its functional activity. Functional brain MRI is imaging which relates body functions to specific locations in the brain. Some special image processing is necessary to make visible the minimal alterations going along with brain function. For example when the eyes perceive a visual stimulus there is a rapid momentary increase in the circulation of the visual cortex. The difference relative to surrounding tissues causes a contrast that allows delineating the functioning cortical area. Spatiotemporal maps of cerebral activity can be produced by combining several techniques improving the accuracy and resolution of neural activity maps. This experiment shows an anatomically constrained linear estimation of integrated functional MRI and magnetoencephalography measurements using repeated word stimuli. This is the first step towards functional imaging of complex cognitive processes.

Image Guided Interventions

The motivation for the rapid progress of image guided therapy is based on the limited visualization during surgery. The surgeon cannot see beyond the exposed surfaces. Within the constraint of the surgical opening the exposed visible field lacks the spatial clues needed to comprehend all surrounding anatomic structures. These limitations are accentuated by the even greater restrictions of minimally invasive or minimal-access surgery. Limited visibility through "keyholes" during endoscopic procedures and through small incisions increases the need for intra-operative image guidance.

MR imaging, because of its high tissue contrast and spatial resolution, as well as its multiplanar and functional imaging capabilities combined with near real-time data acquisition, temperature-sensitive, and angiographic sequences while completely safe for patient and examiner, has the most appeal for monitoring and controlling therapy. Open-configuration magnets, which permit full access to the patient and are equipped with instrument tracking systems, provide an interactive environment in which biopsies, percutaneous or endoscopic procedures, thermal ablations, and minimally invasive interventions or even open surgeries can be performed.

Central to the success and safety of a MR guided interventional procedure is the accurate visualization of the used instruments relative to the surrounding anatomy. One of the most accurate techniques is based on incorporating a miniature radiofrequency coil into the instrument. The built-in coil allows determination of the three-dimensional spatial position of the instrument in near real-time. The data from the scanner may be overlayed on a previously acquired morphologic road-map image allowing good control and positioning of the device into any desired organ or vessel.

The tip tracking system has been implemented on different types of devices including biopsy needles, guide wires, and even balloon catheters used for angioplasty. The first MR guided percutaneous arterial dilatation has been performed just a couple of months ago at the University of Zurich in a patient with a stenosis of the right iliac artery and occlusion on the left. The limited quality of the images is due to the low field open MR imager used for guiding the procedure. High field systems providing better image quality and access to the patient during the intervention still have to be implemented. We hope that the Erasmus University in Rotterdam will play an important role in this development.

Future Challenges and Opportunities

It is to the next millennium of radiology - with all its challenges, opportunities, and multiple new horizons - that we now turn. Who can predict the future?

But before considering what we will be doing in the future, we should ask ourselves what do radiologists currently do and what does the health care system expect from us to be doing in future? Diagnostic radiology always has been a "service" that is tapped into by other specialties. The vital business of radiologists is to provide accurate diagnostic information to those who request it, as quickly and efficiently as possible. Usually, this information removes uncertainty from the referring physician's mind by ruling out, indicating, expanding, or contracting a brace of diagnostic possibilities or treatment options.

We are practicing medicine in an era of economic revolution and find ourselves reexamining virtually all of our beliefs, practices, rituals, habits, and ethics. This revolution is driven by economic factors that work to lower costs by restricting access to the health care system. Rethinking all that we do and formulating responses in this new era should be viewed in a positive light: opportunities abound for radiologists to revive enthusiasm, stimulate creativity, deepen their involvement, and intensify their commitment. Can we develop a vision on what our future should be? Can we develop effective strategies to dealing with change?

Managed care demands that we achieve greater cost-effectiveness through continuous process improvement; that we streamline our management structures; that we re-engineer the way our patients pass through our departments; that we become more adept in the management of state-of-the-art information, financial as well as clinical, and the many new software programs that this kind "bean-counting" entails; that we play a developmental role in the structuring of clinical outcomes and critical pathways, develop more stringent guidelines and practice standards, and better assess the cost-effectiveness of our technologies, with less time resources to do this than ever before; that we accentuate the noninvasive; that we find ways to facilitate the efforts and decisions of primary care physicians; that we consider the efforts made by administrators and even by our clinical colleagues to reduce the use of imaging resources; and in the same breath, that we accept the dictum that we will do more work for less remuneration.

Radiologists as Gatekeepers

To appreciate the role of radiology in the continuum of care, it is important to understand the purpose of diagnostic examinations. The value of a diagnostic test changes during the course of care. A primary purpose of diagnostic examinations is to *reduce uncertainty.* Uncertainty is greatest early in the course of a disease. Therefore, an examination performed earlier in the course of care has greater potential value than one performed later in the course. One reason for this is that results of an examination can confirm normality in patients who are worried but well. In addition, when a problem does exist, an early diagnostic examination can direct the most efficient and effective treatment or care.

The continuum of care begins when a person perceives disease, and ideally, seeks attention from a primary care physician, a general practitioner. This primary care provider should diminish uncertainty as early as possible by rapidly making the diagnosis with whatever diagnostic modalities are appropriate. Results of these laboratory or radiologic examinations can support a physician's view that, for instance the patient's symptoms are within the normal range or to define a specific problem that could benefit from subsequent specialty care. It has been demonstrated that expenditures can be minimized while high quality care is maintained through earlier use of diagnostic imaging.

Radiologists should prepare to be primary care extenders. Guiding appropriate patient care and defining the nature of the illness before a referral to a specialist can be an important role for us. Complete, sophisticated radiologic consultation implies a meaningful contribution to patient care. In a capitated system, the paradigm shifts from managing illness to managing health. Physicians become accountable for the health status of a defined patient population.

Providers will insist on gatekeepers. While the primary care physician is the dominant gatekeeper in managed medical care, working together with radiologists they could become the principal providers of definitive medical diagnosis.

Radiologists as Consultants

The knowledge data base in medicine has expanded so rapidly and massively in the last 20 years that it is virtually impossible for a radiologist or any other physician to keep up with the advances in the whole field and also keep up with the galloping technologic progress. Today, this knowledge gap is even more critical as radiologists are increasingly expected not only to contribute significantly to making diagnoses but also to help stage diseases, guide biopsies, and even participate in or administer therapy. These added responsibilities, along with new opportunities, are forcing the advent of subspecialists, of those who know the intricacies of and modern developments in medicine in the given field and can use this expertise to select the appropriate imaging study and interpret the images in meaningful way to help the clinician in managing the patient.

As new modalities developed during the last years particularly cross sectional techniques, many radiologists became very interested in learning, performing, and subspecializing in particular radiological procedure. The reason for and the benefit of doing this was that most of the new emerging modalities were introduced faster into the medical community and their development in different fields could be pushed further than general radiologists could. One of the arguments was also that a particular imaging technique could be learned in a relatively short time, whereas it takes years to learn clinical medicine and much effort to stay current in it. The question of the need for totally technology-oriented subspecialists arises. However, there is a preoccupation of the technology driven subspecialist toward making biased decisions in patient care. A technocrat may overemphasize his or her own technology-based specialty. On the other hand, as the imaging method matures and techniques develop, organ-oriented subspecialists routinely take over the examinations in the cross-sectional techniques.

Has this subspecialization been good for patient care and radiology? I am sure our clinical colleagues would agree that patient care has improved because of radiological subspecialization. As diagnostic radiology is a consultative specialty, it must reflect the outside world of practice medicine. That world is highly specialized and subspecialized, and radiology must adapt in order to be taken seriously and to survive. Perhaps in the past we have not had the opportunity to be consultants. However, the increasing importance of certain imaging procedures has facilitated our ability to provide consultatory services.

Radiologists as Cost Controllers

Although medical imaging accounts for less than 10% of health care costs, efforts to conserve resources have focused squarely on advanced imaging technology, which at face value is more expensive per unit study. At the institutional level, this has led to rationing the use of newer, high profile technologies such as computed tomography or MR imaging. In some health-care organizations, financial incentives for clinicians are inversely proportional to their utilization of imaging and other diagnostic resources. This trend is adversely influenced by the limited scientific research that links technology use to patient benefit. Indeed, for many conditions, it is not known whether restricting the use of advanced imaging is ultimately more or less cost-effective, or achieves better or worse clinical outcome.

Therefore, we must use judgment in our daily practice: the old concept of stepwise use of different imaging methods by first performing a conventional X-ray exam than an ultrasound, followed by a CT and finally by an MRI is no longer acceptable by today's standards. It has to be abandoned in favor of using one single or a combination of a very a limited number of appropriate techniques for establishing a correct diagnosis in the particular clinical situation.

The goal is to make diagnostic imaging more efficient by minimizing overutilization and eliminating unnecessary examinations, thereby reducing cost without diminishing quality of care.

And then we must prove that the algorithms that we are applying are cost-effective. We assume that this is true, but in many situations it has not been proved yet to the satisfaction of medical administrators. Radiologists must be active in developing the guidelines of practice for appropriate imaging use. This will not give us the right to image but will put us in the position of partially controlling imaging functions.

Radiologists as Information Managers

The role of radiologists as superintendents of a complex film-based service is being diminished by the emergence of so called "filmless" radiology, based on digital data acquisition modalities and monitored via sophisticated information systems. Managing those enormous amounts of information will have a considerable importance in our professional lives. Future radiologists will recognize that better management skills will enhance their effectiveness as diagnosticians, and they will focus and act following concepts as they relate to the management of their work and medical information. They will recognize that the demands of a more complicated health care environment require more attention to basics. In their world, the difference between the skilled and the novice will lie less in the knowledge they already have than in knowing where to look for information.

Creativity in management of information will loom large, and the new formula for effectiveness, as stated by C. Handy from the Harvard Business School, will be:

$$C + I^3 = AV$$

where C stands for caring, three Is stand for intelligence, information, and ideas, and AV means added value. Future radiologists will take pains to ensure that their customers are satisfied. They will have a better understanding of what, exactly, is valued by their customers and will strive to ensure that every process, function and product is favorably measured and checked.

As managers, future radiologists will not only be judged by their diagnostic expertise, but also by their ability to "help others do their jobs better - by developing their skills, by organizing their work more efficiently, by helping them make the most of their resources by continual encouragement and example". Managerial skills will thus be of an utmost importance, a fact that a small group of European radiologists recognized already a couple of years ago giving birth to a European Working Group for Management in Radiology. This organization, that in the meanwhile has been fully accepted as an official body of the European Association of Radiology, takes the responsibility to provide radiologists a structured education on common management issues. As one of the founding members of this group, I am definitely convinced that teaching of management has to be incorporated in our future specialty curriculum in order to cope with the demands of the new health-care environment.

Medical Imaging in 30 Years

Where does the future lead us? Where do we go? Is the answer to be seen as in Lewis Caroll's *Alice in Wonderland* in which Alice asks the cat:
"Would you tell me please, which way I ought to go from here?" and the cat answers:

"That depends a good deal on where you want to get to "
"I don't much care where," says Alice
"Then it doesn't matter which way you go" answers the cat
"- So long as I get somewhere" Alice adds as an explanation
"Oh, you're sure to do that" says the cat "if you only walk long enough"

However, as Stephen Toulmin, one of the prominent analysts of future trends stated:

" Available futures are not just those that we can passively forecast, but those that we can actively create and future opportunities do not happen of themselves, but can be made to happen, if we meanwhile adopt wise attitudes and policies".

So how could medical imaging look like in the next millennium?
The landscape of disease that we must treat in some 30 years from now will be completely changed. Genetic cures will be available for many inherited diseases and possibly for a number of cancers. The aging of the population with average life spans of around 100 years will concentrate attention on cardio-vascular and acute or chronic diseases of the loccomotory system. The emphasis on quality of care, improved outcomes, and cost-effectiveness will shift the focus

of medical care, with fewer hospitals with large day-care centers networked with many community-based outpatient facilities. Telemedicine will be an important feature of these networks, with use of videoconferencing for a variety of interactions, including two-way communication and monitoring for patients in their homes with their health providers at medical centers.

Radiology will no longer be called radiology: It will be referred to as diagnostics and therapeutics or D & T. This new designation highlights the ever expanding role of medical imaging in the full spectrum of diagnosis and support for primary care. The D & T physicians will serve as the diagnostic consultants for general practitioners by providing the gateway to other specialists as needed. As interventional radiology evolves into a wider range of therapeutic options, the treatment side of the equation will also grow fairly rapidly.

D & T will shift emphasis from conventional X-ray to mostly computed tomography and especially MR imaging. Digital plain X-ray will be still sometimes used mainly in underdeveloped areas. However, emergency and trauma imaging, bedside examinations and diagnostics during transportation will be completely replaced with smaller dedicated imaging units capable of alternately providing CT or MR images. Imaging en route to the hospital will become a common routine with satellite systems on the ambulances communicating the images and telemetry data directly to a panel of D & T physicians and other specialists in the medical centers.

Operating rooms will be commonly equipped with open MR guidance systems, allowing to exactly plan and predict the outcome of the procedure based on virtual images. Guidance of percutaneous interventional procedures will be exclusively effectuated in dedicated MR systems with the functionality of a current C-arm. Endovascular MR will become the primary technology for evaluating and guiding percutaneous vascular interventions. Catheters could be replaced by miniaturized electronic remote control devices that could be precisely directed into the desired vessels under external MR tracking. These remote control devices could be than used to deploy heat in order to destroy abnormal tissues or to place viruses containing altered DNA into target organs for gene therapy.

Is this just utopia?

Maybe it is, since as we all know predictions are difficult.

The 16th century physician Nostradamus was esteemed for his predictions of things to come. Ultimately, however, his prophecies were discredited and, in fact, condemned. The future is uncertain, however, as uncertainty increases, opportunity abounds. Therefore, it is certain that Roentgen would hardly recognize radiology in 30 years from now on.

For reaching our dreams, it is more true than ever that radiologists must heighten their presence, taking pain to educate and inform other physicians, patients, policy makers, and the public. We must find ways to make others realize the importance of expert management of the process leading to a diagnostic study or therapeutic procedure. It is imperative that everybody involved in the health care process recognizes that the value of a radiologic procedure is not just the technology. Its real worth is intimately tied to our intellectual contribution.

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