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Nanotechnology

Summary

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SUMMARY

Nanotechnology is an umbrella term covering a wide range of technologies concerned with structures and processes on the nanometer scale. A nanometer is one-billionth of a meter (10–9 m), and marks a threshold where quantum physical effects increasingly play an important role.

Because of its potential to change fundamentally whole fields of technology, nanotechnology is regarded as a key technology which will not only influence technological development in the near future, but will also have decisive economic, ecological and social implications.

There is no generally recognised definition of nanotechnology to date. In a pragmatic approach the present report uses the following definition:

1. Nanotechnology deals with structures which are smaller than 100 nm in at least one dimension.
2. Nanotechnology exploits characteristic effects and phenomena which occur in the transitional zone between the atomic and mesoscopic level.
3. Nanotechnology describes deliberate manufacture and/or manipulation of individual nanostructures.

There are two fundamental strategies for penetrating the nanodimension. On the one hand there is the »top-down« approach, which is predominant particularly in physics and physical technology. Here,starting from microtechnology structures and components are more and more miniaturised. On the other hand there is the »bottom-up« approach in which increasingly complex structures are specifically assembled from atomic or molecular components. This approach is primarily featured in chemistry and biology, where dealing with objects of the nanometer scale has long been familiar practice.

A characteristic feature of moving to the nanometer scale (besides the growing domination of quantum physical effects) is that properties of surfaces or boundary layers play an increasing role compared with the bulk properties of the material. Also, in many cases self-organisation phenomena occur.

Basic structures of nanotechnology are: pointlike structures smaller than 100 nm in all three dimensions (e.g. nanocrystals, clusters or molecules), linear structures which are nanosized in two dimensions (e.g. nanowires, nanotubes and nanogrooves), layered structures which are nanosized in only one dimension, »inverse« nanostructures (i.e. pores) and complex structures such as supramolecular units or dendrimers. Without processes and tools capable of manufacturing and analysing the basic structures cited above, nanotechnology would be inconceivable. Accordingly, the associated technologies are also discussed.

Nanotechnology requires a high degree of interdisciplinary and transdisciplinary cooperation and communication. This is due to the fact that at the nano level the terminology of physics, chemistry and biology overlaps and blurs, and also to the fact that techniques from a single discipline can or must be supplemented by techniques and expertise from other disciplines.

RESEARCH AND DEVELOPMENT – AN INTERNATIONAL COMPARISON

An international comparison of research and development activities based on bibliometric data and patent indicators shows Germany as having a strong position in the field of nanotechnology.

Germany is one of the most frequently publishing actors in nanotechnology, outperformed only by the USA and Japan. China follows in fourth place. Regarding Europe, France and the UK follow Germany as the countries with the largest number of publications. In terms of the share of nanotechnology in the total volume of scientific publications, Germany lies in fifth place behind China, South Korea, Russia and Japan, but is still significantly above the international average. The fastest growth rates in publications in the field of nanotechnology are shown by South Korea, China and Israel: the figure for Germany is in line with the international average, the USA lags significantly behind this.

In patent applications, Germany ranks second, behind the USA but ahead of Japan. These are followed by France and the UK. In contrast to the volume of publications, China is not among the top 10 actors here. The German share of patents relevant to nanotechnology in total patent volume is slightly above the international average, but the annual growth rate in patent applications is slightly below average. In all the countries studied, the growth rate in patent applications relating to nanotechnology is significantly higher than the growth rate for patent applications as a whole.

The important matter for German research is to maintain this strong position in the field of nanotechnology, and – if possible – expand it further. Considerable efforts are being made to do this. Of key importance in this area is the funding by the Federal Ministry for Education and Research, which dates back to the start of the 1990s, has grown from c. 35 million in 2000 to over 88 million in 2002 and is planned to rise to 112 million in 2003. The initiative »nanotechnology centres of competence« has been in existence since 1998, a young scientists competition in nanotechnology since 2002. The Federal Ministry of Economics and Labour and the German Research Foundation are also involved in promoting nanotechnology. The Max Planck Society, the Helmholtz Association of National Research Centres and the Leibniz Association are heavily funding the further development of nanotechnology. In all, public funds totalling c. 200 million were invested in nanotechnology in 2002, compared with c. 150 million in 2001.

This meant that Germany accounted for over half of the total public funding for nanotechnology in the EU.

OVERVIEW OF IMPORTANT AREAS OF APPLICATION

The reduction of size into the nanometer area often results in characteristic properties of subsstances and materials which can be exploited for new applications and which do not appear in macroscopic pieces of the same materials. These include e.g. significantly higher hardness, breaking strength and toughness at low temperatures and superplasticity at high temperatures, the emergence of additional electronic states, high chemical selectivity of surface sites and significantly increased surface energy.

Controlled assembly of macroscopic bodies from atomic and molecular components enables deliberate selection of their properties. Understanding the molecular fundamentals of new materials opens up perspectives for manufacturing new »switchable« materials which cannot be produced using conventional methods.

Overall, the state of development of products, product ideas and concepts in nanotechnology varies widely, with a time for realisation ranging from the present to a distant future. A range of applications are currently in the realisation phase, with top-down approaches dominating. Innovative applications – predominantly the bottom-up approaches – are likely to emerge only in the medium to long term.

Surface functionalisation and refinement

From the point of view of market relevance, nanotechnology in the field of surface functionalisation and refinementis already in a relatively advanced stage. Nano-multilayers and nano-composite-layers with improved mechanical and tribological properties are already in industrial use in some cases. Other examples are quasi »self-cleaning« surfaces which combine hydrophobic and oleophobic properties. Also in use are optical-functional surfaces for façades, vehicles, solar cells etc (e.g. for antireflective surfaces, sunshade glazing, antireflective coating for instrument panels).

The addition of nanoparticles to conventional coatings yields new and improved nano-based colour effects. Black pigments consisting of agglomerated nanoparticles are already in use in high-quality black coatings. Coatings which can be switched, e.g. can change their colour or are self-healing are under discussion.

Catalysis, chemistry and materials synthesis

Catalytic nanoparticles are already in use in the chemical industry. In the nanosector, completely new materials can be made accessible for development as catalysts (e.g. gold nanoparticles). Nanoreactors (e.g. dendrimers) make possible a completely new type of spatial process control on the nanometer scale. So-called supramolecular host-guest structures are opening up new synthesis routes in organic chemistry. Regioselectivity and stereoselectivity of catalysts can be increased. Surface active membranes, nanoporous (bio)filters and adsorption agents can be optimised from the nanotechnology point of view, e.g. for sewage treatment, pollutant removal and byproduct separation.

Nanotechnological improvement of existing catalysts (e.g. zeoliths) is making available substrate catalysts with new properties. Controlled deposition of catalyst particles on nanoscale substrates makes possible precise control of catalyst properties. In future it will be increasingly possible to customise heterogeneous catalysts for desired reactions. Molecular imprinting makes it possible to assemble specific polymers (MIPs) with high selectivity. This allows to produce biomimetic enzyme-like catalysts which have advantages over enzymes, including use in extreme reaction conditions.

Energy conversion and use

Nanotechnology can be used to increase the efficiency of energy conversion. The emphasis here is on improvements of materials (e.g. the use of nanotechnological materials in solar cells and fuel cells). Another key area is low-loss storage of energy. One challenge here is still the efficient storage of hydrogen. Microstructuring and nanostructuring technologies can increase e.g. the fraction of hydrogen-mass in chemical storage. Further research is being carried out into storing hydrogen in carbon-nanotubes and other fullerene derivatives, in the expectation that storage density can be increased.

Nanomaterials can be used to improve the capacity of batteries, from mini-rechargeables (e.g. by using nanotubes in lithium ion rechargeables) and electrochemical condensers (supercondensers). The combination of supercondensers with batteries for traction purposes is also promising (e.g. storing braking energy in electric cars). The high losses in electricity transport make the use of superconducting lines interesting. Currently, hopes are placed in nanotubes, where a superconductivity property at room temperature is considered possible.

Construction

Decisive material properties (hardness, wear resistance etc) can be deliberately improved by introducing characteristic structures on the nanometer scale. Many applications of nanocrystalline materials derive from the distribution of nanoparticles in a ceramic, metallic or polymer matrix.

For example, introducing nanoscale particles in metals improves the mechanical properties, which can contribute substantially to lightweight construction. Polymers modified with nanoparticles have characteristics which lie between those of organic polymers and inorganic ceramics. Possible uses of such optimised materials lie in particularly demanding areas of lightweight construction or high-temperature applications, but also in mass applications like plastic casings or cladding. An important instance e.g. is the ductile behaviour of nanostructured ceramics, which were previously known only as brittle materials. In practice, this yields a wide range of innovations in ceramic technology. Major improvements in properties are also possible in construction materials with nano-additives (e.g. high-performance concretes with greater compressive strength and improved wear and erosion resistance).

Nanosensors and actuators

Nondestructive measuring techniques with nanometric accuracy are needed for measuring microstructures and nanostructures. Many sensors are only possible via nanotechnology. For detecting mechanical quantities, for example magnetic field sensors are used (e.g. in airbag systems, read heads on hard drives). Infrared sensors can give high thermal and spatial resolution – currently, the most advanced are infrared detector mosaics of quantum well infrared photodetectors. Commercial marking (»thermolabels«) based on nanotechnology are being offered in the pharmaceutical and food sectors: these discolour to show temperatures which are too high or low. The scanning thermal microscope measures thermal conductivity or temperature distributions e.g. of electronic components with high resolution. Many oxides can only be used as sensor materials in nanocrystalline form, for example as chemosensors (e.g. glucose sensor that indicates blood sugar concentration by changing colour). An example of biosensors are the so-called lab-on-a-chip systems.

Data processing and transmission

The most important areas of application for nanoelectronics in the field of data processing and transmission are electronic, optical and optoelectronic components. Nanotechnology is expected to lead to lower cost or more precise processes in the field of manufacturing technology for these components.

The technically manageable scale of logical and storage components in the currently dominant CMOS technology is increasingly shifting to the nanometer dimension (quantum dots, carbon nanotubes). Photonic crystals have potential for use in purely optical circuits, e.g. as a basis for future information processing based solely on light (photonics). In molecular electronics, nanotechnology can be used to assemble electronic components with new characteristics at atomic level, with advantages including potentially high packing density.

New concepts for components are based particularly on exploiting quantum mechanical effects to achieve smaller, faster or otherwise better components. In the longer term, use of nanotechnology in the information and communications sector will also make possible new architectures. An example of a new biochemical computing concept is so-called DNA computing.

Life sciences

The use of nanotechnology is expected to result in improvements inter alia in medical diagnosis and therapy, »enhanced performance« in humans and improved yields in animals and plants. Possible applications include chemical analysis and diagnostics, nanotechnological production of active ingredients, precise delivery of active ingredients, and production of biocompatible materials and surfaces.

In food, the emphasis is currently on nanotechnologically produced packaging and dyes and additives. In future nanotechnology will probably also play a role in the field of »functional food«, where it will increase the availability of bioactive substances. Nanoparticles are already being used in cosmetics, e.g. for sun protection with improved properties.

Security and defence

The use of nanotechnology in defence equipment opens up ways to improved weapons, innovative materials and new application areas. In land and air vehicles, conventional structural materials could be replaced by more rigid and lighter materials. Improvements could also be achieved in direct (armour) and indirect protection for military vehicles (camouflage and mislead, e.g. through colour changes with »intelligent« surface coatings). Important impacts of nanotechnology on the operation of military platforms can also be expected in the conversion and storage of energy (e.g. more efficient solar cells, suitable membranes and catalysts for operating fuel cells, and enhanced performance batteries). Nanoscale electronic, sensoric and electromechanical components could make control and steering of vehicles more effective and robust. The current trend towards unmanned and autonomous systems in air, sea and space could be further reinforced by this.

There are many possible applications in military reconnaissance based on the use of nanotechnology components in sensors, sensor systems and sensor networks. Weapons and munitions are also being directly affected by the improved sensory capabilities, enhanced computing power and storage capacity due to nanotechnology. Another option is the development of nanoscale powders for use in propellants and explosives, enhancing the energy yield and speed of explosion.

Nanotechnological developments will probably have significant impacts for military personnel, including at the level of personal equipment (keyword: »soldier as a system«). The focus is on the effort to equip soldiers with additional functionalities without significantly increasing the weight of their equipment.

DETAILED ANALYSIS: APPLICATIONS IN SELECTED INDUSTRIES

There is potential for nanotechnology applications in virtually all industries, including those which are usually regarded as low-tech industries. The six industries studied here – automotive, aerospace, construction, textile, energy and chemical – represent a significant section of the future potential of nanotechnology in industry as a whole.

Automotive industry

In future automotive engineering, nanotechnological competence will be one of the core capabilities required for this industry (with its huge importance for the German economy) to remain internationally competitive. The spectrum of nanotechnological innovation efforts in automotive engineering ranges from components already in use through concrete development activities to ideas with at best long-term potential for realisation. Some of these are fundamentally new developments with far-reaching impacts on the product. Spinoff effects are expected in many other industries.

Nanotechnological developments can play a role in all automotive subsystems and components. Examples include:

- nanoparticles as a filler in car tyres (realised, further development)
- antireflective coatings (realised)
- nanoparticle-reinforced polymers and metals (development phase, partly realised)
- nanotechnologically modified adhesive technologies and adhesive primers (in development)
- catalytic nanoparticles as a fuel additive (research stage)
- nanoporous filters to minimise the emission of particles on the nanometer scale (future)
- hydrophile surface coatings as anti-fogging coatings (future)
- »self-healing« coatings, e.g. through self-organisation (long-term at best).

Aerospace industry

In the medium to long term, there are also extensive possibilities for applications of nanotechnology in the aerospace industry. These are particularly numerous and varied in the space industry, where demands on the technological capability of components are often extremely high. There are economic barriers because of the financial cost of developing nanotechnology products for limited of production, particularly in the space sector.

Key areas for application are structural materials (e.g. saving weight and energy by using light-weight, ultrarigid materials based on nanotechnology), Information and communications technology (e.g. more efficient design of data transfer between space vehicles and terrestrial information networks using electronic and optoelectronic nanotechnology components), sensorics (e.g. improving medical monitoring of astronauts with sensors based on nanostructured materials) and thermal protection and control (e.g. improving thermal control systems through nanostructured diamond-like carbon coatings).

Construction

There are a wealth of possible applications for nanotechnology developments in construction as well. For example, silicon dioxide nanoparticles can be used in synthetic silicic acid (nanosilica) as an additive for sprayed and high-performance concrete, and help improve bond tensile strength and bond shear strength between concrete and reinforcing steel. Nanometer-thin multilayer coating from conducting polymers makes possible improved protection against corrosion when using carbon steel or stainless steel as a construction material. Additional applications are to be found in the field of thermal insulation for buildings (e.g. the use of windows for transparent thermal insulation by applying an invisible silver coating of a few nanometers thickness), in façade design (e.g. implementing functions such as self-cleaning, anti-graffiti protection or high scratch and wear resistance in plastics through appropriate coatings) and in the interior (e.g. use of titanium dioxide nanoparticles as additives in coatings to protect from discoloration under artificial and natural light).

Textile industry

In the textile industry, research and development efforts are aimed particularly at integrating new functional characteristics into textiles to generate additional benefits (and thus competitive advantages). On the one hand there are a few rather unrealistic visions, such as the integration of nanobots to give an article of clothing the capability to mend itself. On the other hand, there are promising efforts to improve characteristics and functions such as crease resistance, breathing properties, wear resistance, spot and water repellence, antistatic properties, active ingredient storage or fire protection.

Energy industry

Developments in nanotechnology are expected to have major impact on future energy production and distribution. Particularly noteworthy are nanotechnology advances in solar cells, energy storage and fuel cells.

There is controversy over the prospects of using nanotechnology materials which are superconducting at room temperatures to reduce the high transmission losses in our centralised energy supply.

Chemical industry

The chemical industry is closely linked to the development of nanotechnology both as a supplier of crucial base materials and a future user of nanotechnology-based innovations in process technology. Nanotechnology is expected to enable the chemical industry to generate a new wave of innovation.

Many chemical industry products which are classified today as nanotechnology have been around for decades. However, there are signs of new nanoproducts in many areas which have commercial relevance because of their potential market volume.

The main areas of application of nanotechnology in the chemical industry are catalysis, the extenders, pigments, coatings and lubricants, micro/nanoreaction technology, membranes and filters, and pharmaceuticals and cosmetics.

DETAILED ANALYSIS: APPLICATIONS IN INFORMATION AND COMMUNICATION TECHNOLOGY

Information and communication technology is an important and still rapidly growing industrial sector with a high rate of innovation. After decades of weakness, German industry has made enormous progress in catching up in recent years, and today has good prospects of mastering the challenges of the coming years, and particularly the transition from traditional to nanotechnology electronics.

This development is based on the »top-down« evolution of microelectronics to nanotechnology, i.e. growing miniaturisation to the limits of solid state physics, where a transition to »bottom-up« nanotechnology is becoming essential. However, the latter approach is still largely in the fundamental research stage. Nanotechnology concepts and processes will secure the future growth of the electronics industry and its industrial continuity in the medium term, starting in the period 2005–2010. There are numerous products, product ideas and concepts whose date of realisation ranges from the present to the remote future.

Nanotechnology approaches will play an important role in new logic and storage technologies. For example, we can expect to see the introduction of magnetic RAMs and resonant tunnel elements in logical circuits in the near future. Approaches promising success in the medium term include e.g. rapid single-flux quantum (RSFQ) logic or single electron transistors. By contrast, a completely molecular electronics – whether based on carbon nanotubes or organic macromolecules – still lies in the distant future. Overall, the goal here is to make ideas from fundamental research usable for industrial technology development. There is a tendency here – as there was in the past with CMOS technology – for solutions in the storage field to run several years ahead of solutions for logic circuits. Non-classical CMOS technology marks an advance of familiar microelectronics deep into the nanometer dimension. Here, attempts are being made with new production processes and materials to respond to needs by filling identified technical and commercial gaps along the vertical added value chain. Regardless of the success of alternative approaches, CMOS technology will continue to be the mainstay of the semiconductor industry for the foreseeable future.

Nanotechnology's market breakthrough in information and communication technology could accordingly happen in two steps. First, »top-down« miniaturisation will take conventional microstructures across the boundary to nanotechnology. In the longer term, »bottom-up« nanoelectronics and nanosystem engineering will emerge, using »genuine« nanotechnologies, e.g. ones using self-organisation processes to assemble circuits and systems.

Novel system architectures using nanotechnology are the most remote in terms of the future. Both DNA computing and quantum computing, for example, are still in the stage of fundamental research. The fundamental functional principles have only been experimentally demonstrated relatively recently. There is accordingly no likelihood of practical use in the short to medium term. At least theoretically, both technologies have tremendous potential for increasing computing speeds because of the possibility of massive parallel processing of data. Both also have inherent advantages. DNA computing, for example, has advantages everywhere where the interface to biochemical processes is important (something which will become increasingly important in the future). By contrast, quantum computers will make it possible to solve problems for which there are no efficient classical algorithms.

Because of the major uncertainties involved, quantum computers are being developed on the industrial side by companies which have a tradition of near-fundamental research. These include specifically IBM, Hewlett-Packard and Lucent Technologies (formerly Bell Labs). There are hardly any German actors. As quantum cryptography is being developed primarily for military and intelligence applications, there is a risk for Germany of dropping out of this potentially important area of information and communication technology at an early stage.

It should, however, be clear for both approaches that they are very unlikely to replace the classic computer in universal applications in the private and corporate sectors because of the comparatively high complexity and cost of the equipment. It remains to be seen, therefore, how broad the areas of application ultimately are where DNA and quantum computers can make use of their inherent advantages. It is accordingly too early to answer the question whether these are future key technologies. This is particularly true given that the development of nanoelectronic components will also give a further considerable boost to the performance of conventional architectures.

An important role for innovation efforts in information and communication technology is the paradigm of ubiquitous computing systems. This vision depends on important contributions from nanotechnology for its technological base. For example, the advocated total and seamless networking of humans and machines is only possible through the development of ultra-integrated (opto) electronics combined with powerful wireless technology as low-price mass products. Nanotechnology is expected to be an important driver for ultraminiaturisation, the design of innovative sensors, and the possibility of producing cheap and powerful polytronic circuits. However, this application area also has a range of technology-driven implications. For example, the possibility of collecting, disseminating and processing a range of partly person-related data faces technology, state and society with numerous problems in terms of individual rights – specifically, data protection, information self-determination and the growing dependence of important social functions on technological infrastructures.

DETAILED ANALYSIS: APPLICATIONS IN THE LIFE SCIENCES

The life sciences in the narrow sense of the term are biology and human and veterinary medicine, together with their applied disciplines, e.g. medical engineering, biotechnology. There are points of contact with the biotechnological developments there including e.g. new biomedical therapies (gene therapy, cell therapy, xenotransplantation, etc), artificial implants (tissues and organs), individualised medicine (pharmacogenomics etc) and also telemedicine. In the broader sense, life sciences can also include pharmacology, cosmetology, ecotrophology, agronomics, forest science and the environmental sciences. The emphasis in this section is on applications of nanotechnology in the biomedical sectors.

Nanotechnology and the life sciences complement each other in a number of different areas of application. Currently, a broad range of technical developments are emerging in the field of nanotechnology and the life sciences. Points of contact between nanotechnology and the life sciences arise particularly where nanotechnology is used to achieve goals of the biosciences and/or where nanotechnology benefits from knowledge and processes from the biosciences.

»Nano2Bio« designates the use of nanotechnological processes and materials to study biological problems. From this perspective, nanoanalysis, nanomanipulation techniques for biological structures and objects, nanotechnologically produced active ingredients for living organisms, nanocarriers for transporting active ingredients, nanomachines, nanobots for research, diagnostics and therapy, nanotechnologically coated implants and nanoelectronic (particularly neurological) implants are possible applications. »Bio2Nano« refers to bio(techno) logical materials and designs for producing technical nanosystems. These could be exploited in information and communication, energy, environment and many other areas for technical applications. These include e.g. nanotechnology applications based on biological paradigms, the use of biological components on the nanometer scale for technical systems, or nanoelectronics and nanoinformatics using biological components, functional or organisational principles.

Generally we can say that there are signs of marketable applications in the next few years, particularly in implants and transplants and in drug delivery systems for medicine, and in nutrition and cosmetics. In analysing nanostructures, a leading technique is scanning probe microscopy. Several nanotechnological products are striking for their innovative range of action or high effectiveness. The launch of such products, which are continuations of existing developments, has been widespread without particular public awareness of their relationship with nanotechnology.

The present report was primarily concerned with fields of application, although the processes used were a secondary consideration. Many projects are currently still in the stage of fundamental research, so that their relevance to application is partly a matter of speculation. The following summary covers the most important applications of nanotechnology, specifically in biomedical fields.

Diagnostics

Diagnostic chips for diseases and genetic predispositions are being developed by a number of startup companies. Nanotechnology can help in optimising these biochips. Diagnostic chips of this kind can be used to analyse thousands of genes simultaneously. For this, gene fragments with known properties produced in the laboratory are bonded to the chip surface. A diagnosis depends e.g. on which gene pieces the DNA from a patient's blood gets deposited on. Nanoparticles linked to DNA fragments, for example, enable identification of defined DNA sequences. Viruses and cell types can be identified on the basis of surface properties which make them stick to certain nanostructures.

Demand for such diagnostic chips can be expected e.g. for biomedical analysis which can be performed in any doctor's practice or by patients at home, for example for regular monitoring of the mother's blood statistics during pregnancy. There are synergies with telemedicine: chronically ill or risk patients can be monitored with the help of implanted sensors on the nanometer scale. There is also interest in forensic technology in processes which can work with very small samples.

In research there is need for sensors which can track the behaviour of biomolecules and cell organellae in vivo. Ultra-small sensors which can be implanted in biological organisms could provide information about external stresses and the physiological state of the organism. Small sensors which recognise the early symptoms of an illness, e.g. cancer or heart attack, also have high market potential.

There is demand in the fields of labour and environmental medicine for small biosensors which can make differentiated measurements of pollutant levels in a wide range of locations and outperform conventional products in sensitivity and range of detectable substances. Nanobiosystems make it possible to achieve such improvements.

Active ingredients

There is considerable need for tools which efficiently transport biological active ingredients – particularly drugs – to their target, and often also provide a protective coating. Because of their size, nanoparticles can penetrate biological barriers (e.g. cell membranes) relatively easily, and accordingly represent suitable transport systems for active ingredient molecules. Nanoparticles can be used not only to transport and protect biological active ingredients, but are also suitable for releasing such active ingredients at a particular rate over periods of up to several months. Particular efforts are being put into vehicles with the capability of responding to the body's own signals. There is great demand in medicine for dosage systems which release bioactive ingredients in a controlled manner, making them easy for patients and therapists to use and offering a good price-performance ratio. Currently, such biological dosage systems are in development. Thyroid cells or pancreatic islet cells, for example, are already implanted encapsulated in partly-permeable casings. They produce the previously missing hormones in the bodies of the recipient patients.

An important supplement to or improvement in these approaches to therapy could be so-called nanobased micropumps. At end-2004 the market launch is planned of a small micropump which is convenient for patients and dispenses insulin. The idea of linking this pump with a biochip which continuously monitors the blood sugar level is being studied. Intensive research is also in progress into an implantable chemotherapy system on the nanoscale.

Processes, materials and instruments

Research and development work on biomedical nanomachines is being done internationally. Currently, research is in progress on motors made of DNA molecules and actin and myosin. To date, this is predominantly still fundamental research. Nanomachines capable of realisation in the foreseeable future are very small mobile endoscopes, which could be equipped with additional instruments, e.g. gripper arms on the nanoscale. Heavy demand is expected for such machines.

Another current area of application is magnetic field-induced heat treatment. At the Berliner Charité hospital a project is currently in progress on destroying tumour cells with the help of magnetic nanoparticles. In another process currently being researched, nanostructures which bond selectively with tumour cells are being given a payload of radionucleides. The aim is to destroy tumour cells without significant damage to the surrounding tissue.

Nanotechnology can also help produce coatings for medical equipment which are antimicrobial, hardly get dirty or are easy to clean, and prevent corrosion during sterilisation or disinfection. In the medium term, nanomaterials can be used as transplants, e.g. »artificial skin«, or support the production of such transplants from cell cultures. Synergies between stem cell therapy and nanotechnology are conceivable in which nanotechnology materials provide a stencil which enables the growth of new tissue with the help of stem cells. Nanotechnology processes could improve the biocompatibility of artificial implants. It is also expected that nanoimplants will remain functional in the body for longer than current conventional implants. Another area of development is nanoelectronic neuroimplants which compensate for injury to sensory organs or the nervous system, or boost the performance of these organs. There is already intensive work internationally on microimplants, particularly ones which restore the functionality of vision and hearing.

Further applications for nanotechnology in the life sciences

With the help of nanobiotechnology, food quality could be improved, the bioavailability of important active ingredients enhanced, and optical characteristics, taste and consistency modified. Nanotechnologically optimised production processes and packaging materials are under discussion which monitor the condition of the packaged food and – for example – provide warning if the cold chain is interrupted or a food is spoiled. Demand can also be expected for suitable nanoanalytic processes. For example, nanoanalytical methods using DNA chips are being developed to test foods for genetically modified ingredients.

Nanotechnology will help in cosmetics, primarily in further development of existing products. In cosmetics, vehicles which transport active ingredients (e.g. vitamins or UV filters) to their point of action, for example in the deeper skin layers, are performing an important function. With the help of nanoparticles, active ingredients will be better distributed on and in the skin, and more effectively applied. Titanium or zinc oxide nanoparticles, for example, are being used in sun protection. According to our current state of knowledge, sun protection products with nanoparticles offer greater effectiveness and better skin tolerance than conventional products. Nanoparticles can accordingly be expected to find increasing application in cosmetics in future.

VISIONS

Nanotechnology is a highly visionary theme. Both long term visions with a time horizon of over 15 years and short term visions, developed particularly in environment of the US »National Nanotechnology Initiative« (NNI) shape – for good or evil – the image of this technology among the interested public.

At least two visionary discourses need to be distinguished – first, the discourse in research policy, science and business about the potentials of nanotechnology, which are concerned primarily with relatively realistic sounding short-term visions, and second the highly futuristic (and predominantly highly optimistic) discourse surrounding the »Foresight Institute« founded by K. Eric Drexler. The latter's basic assumptions about future developments are also shared by futuristic pessimists like Bill Joy.

The visions of Drexler, Joy and other extreme futurists – and also some of those developed in the environment of the »NNI« – are based extensively on assumptions about the future interactions between a number of new technologies. Such visions of the convergence of different technologies are the drivers of hopes of extensive and far-reaching changes to the conditions of human existence.

Technological futurism paints a picture of a future in which the ancient human dreams (overcoming poverty, scarcity, death etc) come true. However, pessimistic futurists warn of possible major risks. A particularly threatening vision is the idea of the destruction of all life on earth by self-replicating nanobots (»grey goo problem«). This future technology popularised by Drexler back in the 80s also plays a central role in visions of a future world of universal prosperity. Many scientists regard such visions of self-replicating nanobots with great scepticism. However, scepticism about the futurism of authors like Drexler, Joy and Ray Kurzweil should not make us lose sight of the fact that very far-reaching optimistic visions have also been developed in the environment of »NNI«.

The enthusiasm which optimistic futuristic visions can evoke is being deliberately utilised in the USA as a means of promoting technology development. However, such a »hope and hype« strategy is always precarious. Besides the positive effects of this strategy (e.g. incentives for young scientists, or arousing and sustaining political and business interest), there are conceivable adverse effects. First, there is the danger that expectations of nanotechnology will be set too high, making disappointment inevitable. Second, it may popularise the reverse of the optimistic futurism – a pessimistic futurism involving apocalyptic fears and visions of horror.

A critical approach to visions of horror, even if this initially made them even more popular, would be an important contribution to a rational discussion which does justice to the problems of the potential – positive and negative – of nanotechnology. This does, however, still leave us with the problem that such an approach would tie up intellectual and material resources which might then not be available for an assessment of problems of TA with apparently higher priority in the field of nanotechnology (e.g. the impacts on health and the ecology of nanoparticles, or the ethical implications of nanotechnological applications in medicine).

POTENTIALS AND RISKS OF NANOTECHNOLOGY

Commercial aspects

Nanotechnology is tied to hopes of substantial potential sales in almost all sectors of business. While the market penetration of nanotechnological processes and products is still very much in its infancy, a number of products and processes have already made their way to the market.

The influence of nanotechnology on marketable products has been apparent for years in the fields of electronics manufacture, data storage, functional coatings and precision optics. In recent years, results from nanotechnology have increasingly benefited the fields of biology, chemistry, pharmacology and medicine, and this trend will probably continue. Already, nanotechnology is clearly influencing multibillion markets in drug production, medical diagnostics, analysis or chemical and biological catalyst surfaces.

It is important to distinguish between direct sales of nanocomponents and sales of products which incorporate nanotechnologies. The data on the commercial importance of nanotechnology is, however, still very patchy (not only in Germany), and there is still no generally recognised broad basis.

A study by the Sal. Oppenheim jr & Cie. bank shows that ultimately the leverage of the new technology is decisive for the market volume. According to this, it is not the direct sales and profits from nanotechnology products which are important, but rather the diverse impacts of the technology in the widest possible range of applications. Companies focusing on nanotechnology will be forced to master the difficult transition from scientific research to mass business. The development of strategic partnerships will often be useful in this.

Positive consequences for health and the environment

Significant benefits from the use of nanotechnologies are anticipated or hoped for in the fields of health and the environment. Positive effects of nanotechnological developments on health include the development of new diagnostic and therapeutic processes, considerable advances in knowledge in the biosciences and the understanding of biological processes, development of new drugs and agrochemicals and optimisation of existing ones.

With the help of nanotechnology-based diagnostic tools, it may be possible to recognise illnesses or predispositions to illnesses at an earlier stage than presently possible. The development of lab-on-a-chip technology will further advance the emerging trend towards individualised medicine. In therapy, there is the prospect of using nanotechnology to develop more specific treatment which is free from side effects. The widespread use of nanoparticle dosage systems could lead to advances in drug therapy. Nanotechnology processes can improve the biocompatibility of artificial implants. By way of qualification, it should be noted however, that – with few exceptions – the positive effects of nanotechnology on human health are so far predominantly hypothetical.

There may be beneficial effects for the environment from the conservation of material resources, the reduction in the volume of pollutant byproducts, increased efficiency in energy conversion, reduced energy consumption and the removal of pollutants from the environment.

Possible negative consequences for health and the environment

A key point in this debate is the question of the impacts of the uncontrolled release of nanoparticles. Generally, the state of research into the health and environmental relevance of nanotechnologies can be summed up as suggesting that the current results of studies on the impact are limited. Concern about possible negative consequences of inhaling nanoparticles has so far been based primarily on analogies with the results of available studies on the effects of ultrafine particles.

Ultrafine particles have been shown to catalyse chemical reactions in the body. The incorporation of ultrafine particles into cells can initiate immune system reactions. Many applications of nanotechnology involve nanotubes, which as fibres reaching the lungs could possibly have similar implications for health as asbestos fibres. Nanoparticles could relatively easily penetrate cell membranes, and so lead to both desired and undesired transportation of active ingredients across biological barriers. Knowledge of the pharmacokinetics of active ingredients administrated with nanoparticles is still only in its infancy.

The human organism is already brought into extensive contact with nanoparticles through food and cosmetics (e.g. dyes, UV filters), with the boundary between drugs and cosmetics becoming increasingly blurred. In addition, advances in cosmetics are changing social demands on the appearance and physical »perfection« of humans.

Artificial nanostructures may enter the environment e.g. through emissions by the nanoindustry or the creation of nanoparticles in everyday use of nanoproducts. So far, we have virtually no knowledge of how they disperse and their impacts on the environment, and specifically long term consequences. Particularly noteworthy here are materials which do not occur in nature, like fullerenes or nanotubes, which constitute new materials.

In addition, various effects on the environmental media must be anticipated. In air pollution control, we currently rely on data on ultrafine particles deriving from traffic emissions. With regard to water, high mobility of nanoparticles is assumed. Waste water from mines, for example, contains a comparatively high concentration of heavy metals, and nanoparticles could move these heavy metals to rivers etc.

Ethical and social aspects

To date, little attention has been paid to nanotechnology in practical philosophy and ethics, and there has been relatively little research into possible increased use. However, there is agreement in research policy and science that more research projects, other scientific activities and research policy efforts are needed. Already, some fundamental considerations of ethical problems and possible impacts of nanotechnology on selected social areas can be stated.

In visions of nanotechnology, we repeatedly see aspects which dissolve the boundaries between what constitutes a human being, and what they can create with the help of technological achievements and applications. Such aspects relate e.g. to the penetration and modification of the human body by attempts to supplement or replace its biological components by nanotechnology components, and to network it with external machines or other bodies or body parts. Such ideas, together with other visions of nanotechnology, resemble visions of other new technological developments, or even relate directly to these. The emerging convergence of various technologies are strengthening not only hopes of technological progress but also concerns about the consequences of this. The further development of nanotechnology should accordingly be accompanied by ongoing research on ethical and political questions relating to the changing relationship between humans and machines and nature and technology.

Problems of distribution and equitable use of the fruits of technological progress are other likely societal consequences of the use of nanotechnology. They are particularly interesting in view of the need for political action. Questions of the distribution of opportunities could become urgent in at least two ways – first, within technologically more developed societies, and second in relation to less developed societies. Concerns of a possible »nanodivide« between these two are based on the assumption that nanotechnology can contribute to both new and expanded options for individual self-determination (e.g. in the healthcare sector) and also considerable improvements in the competitiveness of economies. Political measures can promote equality of opportunity and sustainable global development. There are further political responsibilities in terms of avoiding damage, e.g. in terms of possible adverse implications for patient data protection of new medical diagnosis and monitoring possibilities.

Another field in which considerable progress is expected as a result of nanotechnology is military applications. There could also be security policy problems between developed countries and less developed countries in terms of a »nanodivide«. The further development of nanotechnology is accordingly likely to involve increased need for action in security policy. There is also (primarily, but not only, in the USA) considerable interest in military applications of nanotechnology. Although several of the possible security problems arising in scientific debate (e.g. from self-replicating nanobots) may seem less urgent, there will probably be growing calls for security and arms control policy measures in future as a result of further advances in nanotechnology military research and development.

NEED FOR ACTION

The prerequisites for successful further development of nanotechnologies and the broad commercial and social use of their potential must be created or improved. This results in diverse need for information and action. As nanotechnology – as a whole – is still in a relatively early stage of development, requirements for state action are very important.

Nanotechnology must continue to be a priority in state promotion and funding of research, so that German research can maintain its current strong international position in the field of nanotechnology. The potential for application and the economic and societal benefits expected should be given significant weight in the criteria for evaluation of whether research funding is to be given. The nanotechnology competence centres could play a more active and expanded role in implementing the results of nanotechnology research and development activities.

The state of research into potential environmental and health impacts of the production and use of nanotechnological processes and products is unsatisfactory. Considerably greater research efforts are urgently needed here, as the lack of knowledge of the environmental and health consequences could create barriers to the market launch of nanotechnologies.

Research into societal and ethical aspects of the development and widespread use of nanotechnology should be initiated now. Questions of data protection (specifically in the medical sphere) and protection of privacy should be scientifically studied regularly in terms of relevant new nanotechnology developments, and publicly debated.

Comprehensive information for the general public is a prerequisite of a rational societal debate on nanotechnology. Something to aim for would be a central information point for the general public on the topic of nanotechnology. Access could be had here to the information provided by the individual competence centres and other information portals at national, European and extra-European level.

Advances in nanotechnology – and the increasing convergence of various areas of technology and research are posing new challenges in education policy. Interdisciplinary approaches in training and young entrant promotion in nanotechnology and related areas of technology must be continuously and increasingly promoted. More use should be made than in the past of sociological and liberal arts research into technology. The need for nanotechnological qualification on the part of various vocational and professional groups should be studied in detail, and possibly covered through various training and upgrading courses.

Political decisions on the need for nanotechnology specific regulations will have to be taken in the foreseeable future. An objective basis has to be laid for such decisions. This includes – besides a significantly improved data basis on the impacts of nanotechnological processes and products on the environment and human health – a systematic and comprehensive study of the legislative framework currently relevant for applications of nanotechnology. Consideration should be given to establishing a monitoring programme tracking the further applications of nanotechnology which would assist decision-making.

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