Tidsskriftet Tidsskrift for Den norske legeforening

The black sand

IN BYGONE DAYS

OLE REIGSTAD

ole.reigstad@gmail.com
Ole Reigstad, PhD, specialist in orthopaedic surgery and senior consultant at the Section for Hand and Foot Surgery, Department of Orthopaedics, Martina Hansens Hospital.
The author has completed the ICMJE form and declares no conflicts of interest.

ASTOR REIGSTAD

Astor Reigstad, MD, specialist in general and orthopaedic surgery and former senior consultant at the Department of Orthopaedics, Rikshospitalet.
The author has completed the ICMJE form and declares no conflicts of interest.

Millions of people are walking around with titanium implants in their body. What makes this metal so well-suited for medical use?

It all started with the discovery of black sand in a stream. The year was 1791, and as the story goes, it was the amateur geologist and clergyman William Gregor (1761–1817) who noticed the silvery material in a stream in Cornwall (1). After closer investigation, he found out that the material consisted of iron oxide and a white metal oxide that he was unable to identify. He had discovered a new element: titanium.

> *«Unalloyed titanium is just as strong as many types of steel, but has far lower density and weight»*

An industrial product

The production of titanium metal is a complicated process. From the time of its discovery, 150 years passed before William Kropp succeeded in producing the metal with a purity of over 99 %. However, it then emerged that titanium was well suited for industrial purposes. In particular, it could be used in the defence and aerospace industries (1). This is due to its high corrosion resistance and very high melting point, which was demonstrated by Soviet researchers in the 1950s.

Unalloyed titanium is just as strong as many types of steel, but has far lower density and weight. Its strength is further increased when alloyed with other metals, such as aluminium, vanadium, molybdenum, iron or niobium (2). In addition, titanium has greater elasticity than other metals and does not break as easily. Consequently, the United States regarded titanium as a strategic material during the Cold War, and it also became a sought-after raw material in the aeronautics industry and marine applications. In 2020, global production of pure raw titanium for use as metal amounted to 210 000 tons, of which 52 % came from China and 23 % from Russia and Kazakhstan (3). The remainder was mainly from Japan.

Titanium in medicine

Even before industry was fully aware of all the benefits of titanium, researchers evaluated whether it could be used in medicine. In 1940, Bothe et al. published their experimental work on the ability of different metals to bond with bone. Titanium proved to be a material with great potential for use in prosthetics in the future. Nevertheless, the experiment did not generate any great interest in leading odontological or orthopaedic circles (4). Nor did G. S. Leventhal's work in 1951, in which titanium screws in the femur of a rat were so strongly attached after 16 weeks that the bone fractured when they were removed, lead to any great interest in clinical communities (5). The perceived wisdom at the time was that the body would reject all foreign bodies – an insurmountable biological barrier.

Per-Ingvar Brånemark (1929–2014) from Gothenburg lay the foundation for the clinical use of titanium. In the 1950s, he used a titanium chamber placed into the tibia of rabbits in order to conduct a vital microscopic investigation of blood cells. When the project ended after some weeks and he attempted to remove the titanium chamber, it had fused into the bone and was almost impossible to remove. Brånemark, a doctor and basic researcher who later became a professor of anatomy, had discovered almost by chance what was later to be termed the osseointegration of an implant. He inserted titanium screws to which teeth could be attached, into the jawbone, and had titanium implants produced for craniofacial abnormalities (6).

Brånemark was neither an odontologist nor a surgeon, and many were sceptical to his work in Sweden. In the 1960s, his applications for research funding were rejected, and he was ridiculed several times at academic meetings. The popularisation of his research to the general public led to comments such as: 'I simply do not trust people who publish in Reader's Digest' (7). The conflict culminated in the Swedish National Board of Health and Welfare's appointing a committee of three professors to scrutinise his results. But in due course, attitudes towards him changed both internationally and in Sweden. An investigation in 1977 confirmed that his results were correct, and Brånemark later became a highly respected scientist because of his basic research on implants (8, 9).

> ***«Direct contact between the titanium and calcium in the bone results in a chemical bonding»***

Osseointegration

Titanium's unique position as a biocompatible metal is due to its ability to withstand the harsh bodily environment. As soon as titanium comes into contact with oxygen, a protective oxide film is formed that is insoluble and chemically impermeable. This film protects the metal and prevents a reaction between the metal and the surrounding environment (10). The rough microstructure and surface energy of the oxide layer are vital for the cellular bone response, and stimulate osteoblast adhesion, proliferation and bone formation on the implant (Figure 1). An osseointegrated titanium implant directly bonds to the bone tissue without intervening cartilage or connective tissue (6), and has the same strength as the surrounding bone. Direct contact between the titanium and calcium in the bone results in a chemical bonding. The bonding can be seen in hard tissue microscopic images, where the implanted titanium and the bone is cut into thin slices that are polished and coloured.

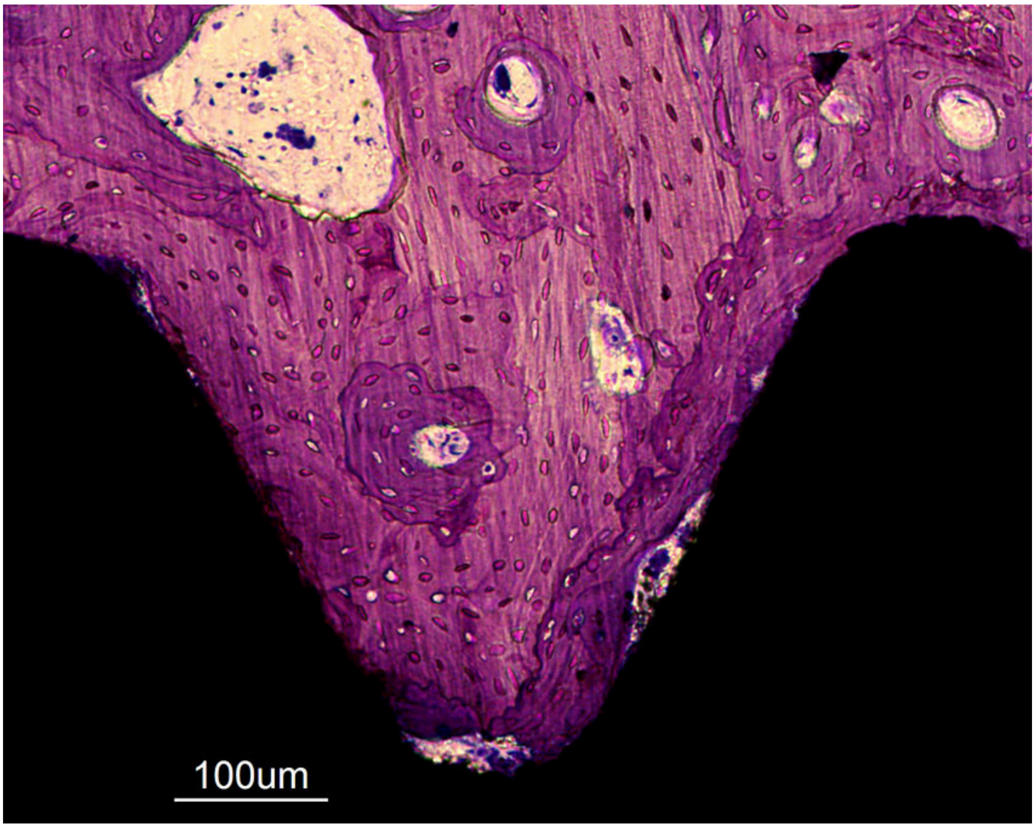


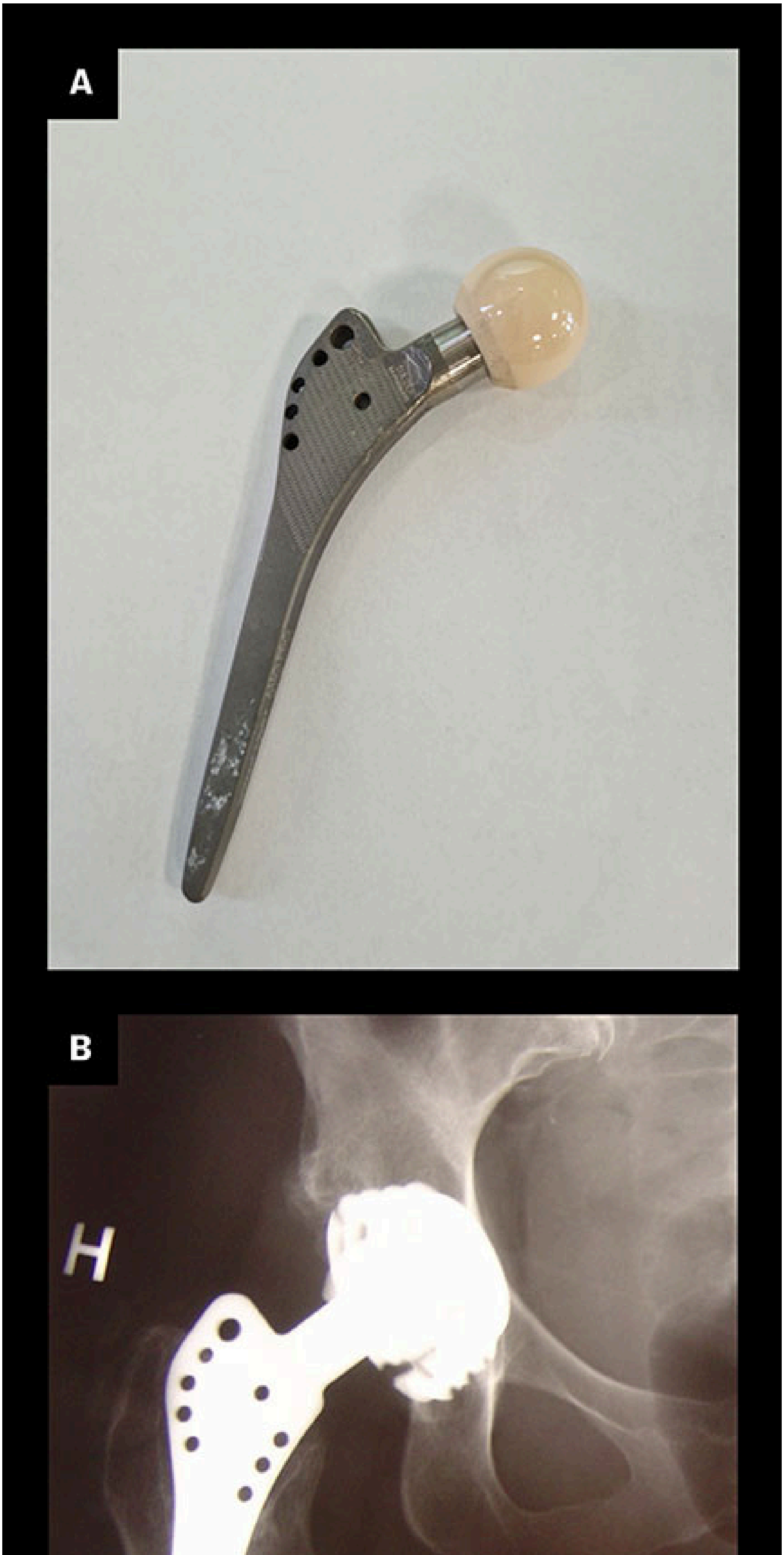
Figure 1 Osseointegrated titanium screw. Bone tissue is coloured in purple, and the implant in black. Direct contact between bone and implant is seen along most of the implant surface. Microscope 400 x, own preparation, tibia of rabbit.

The implant's contact surface with bone and thus the possibility for bone fixation is increased considerably by sandblasting or blasting with other particles to give a rough surface, as in spongy bone tissue. Titanium's bonding ability is exploited in other implants by coating them with titanium plasma (> 10 000 °C), making the surface biocompatible and promoting osseointegration of the implant. The period from implant insertion to osseointegration is fairly similar to that for fracture healing. In both cases, a certain level of primary stability is required in the first six weeks when bone ingrowth increases most (11).

Dentistry and orthopaedics

As early as the 1970s, titanium was of key importance in odontology. A typical dental implant involves drilling into the jawbone and inserting a titanium screw with a rough surface. The gum tissue is replaced over the hole so that there is no pressure on the screw for some months to allow osseointegration. Then the tooth itself or a bridge is fastened via a small abutment over the screw. The five-year survival rate of such implants is reported to be more than 95 % (12).

Interest in the orthopaedic use of titanium came somewhat later than in dentistry, but early in the 1980s it became clear that cementless hip prostheses with an alloy of cobalt, chromium and molybdenum (CoCrMo), known in medicine as Vitallium, gave poor bone fixation and weak clinical outcomes (13). These problems led to increased interest in improving cementless prostheses. Greater understanding of the osseointegration of implants resulted in the development of the first cementless titanium hip prosthesis. It was introduced under the name Zweymüller, after the Viennese orthopaedist who started testing it in 1980 (14) (Figure 2). In Norway, titanium femoral prostheses were introduced in 1984 (15). All cementless primary femoral prostheses now inserted in Norway are made of titanium, and the 20-year survival rate of such implants is over 90 % (16).


A
B
H

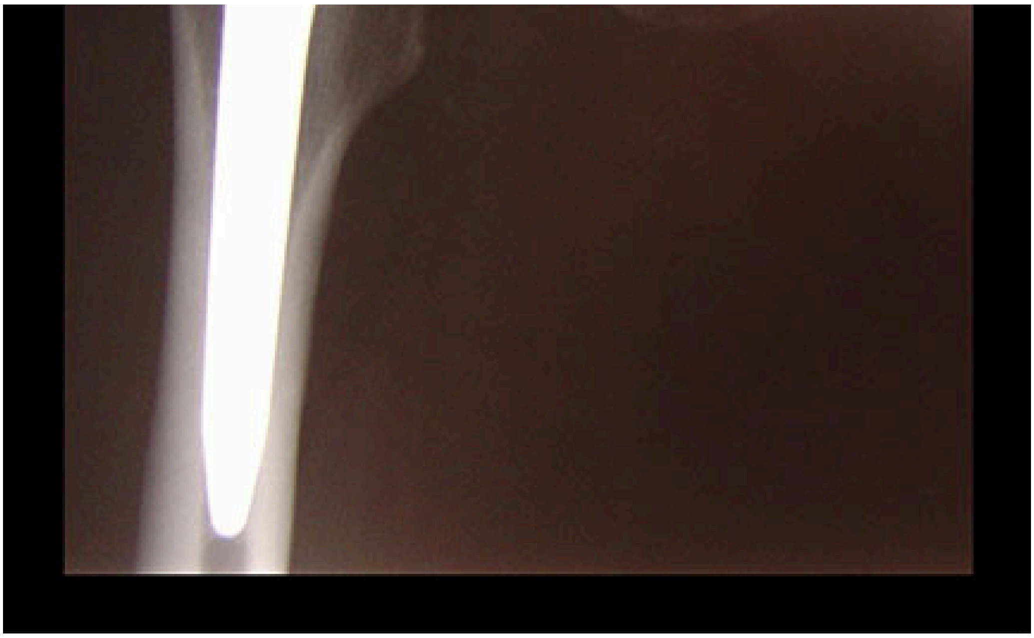


Figure 2 a) Titanium femoral component (Zweymüller) with a ceramic head (Al_2O_3) used in Norway between 1985 and 1988. b) X-ray image 18 years after insertion of the prosthesis in a 55-year-old woman. Stable, osseointegrated titanium femoral component with a ceramic head.

Titanium's active surface means that the metal is unsuitable as a sliding surface in joints. For the femoral head of the hip joint, an alloy of cobalt, chromium and molybdenum, steel or ceramics is preferred. When long bones are fractured, surgical steel is preferred. However, plates, screws and intramedullary nails of titanium are used for osteosynthesis in smaller bones. In the case of amputees, intramedullary titanium nails that protrude from the skin can be attached to external prostheses in a similar manner to dental implants. This can, for example, provide prosthetic function in patients with short transfemoral or transhumeral amputation stumps, where it is otherwise difficult to attach external prostheses. Patients receiving this type of prosthesis acquire a kind of 'osseoperception' via the osseointegrated intramedullary nail that gives a more accurate sensation of how the prothesis moves and what the underlying ground surface is like. Ulceration and infection in the area between skin and intramedullary nail can occur, but this is a minor complication (17).

> ***«As is often the case with innovations in medicine, titanium metal had a long and difficult journey to acceptance»***

Other areas of use

Sound transmission via titanium implants to the inner ear was developed almost 40 years ago (18). Bone conduction of sound increases the effect, and this assistive tool has improved the hearing of many patients. Bone-anchored hearing aids, where screws in the bone behind the ear provide an abutment for external sound processors, were introduced later (19).

Titanium has replaced cobalt, chromium and molybdenum alloys in mechanical heart valves, which together with polycarbonate valves represent approximately 20 % of the valves currently used in Norway. The remaining 80 % are biological valves. Aneurysm clips for cerebral arteries are usually made of titanium, as are vascular clips for haemostasis during all kinds of surgeries. Suture clips for bowel anastomoses and the closure of incisions is another area where titanium now dominates.

Modern imaging diagnostics can accurately calculate bone defects following cancer surgery, deformities and injuries. Titanium implants can be custom-made to match the patient's anatomy, replacing and perfectly adapting to the bone loss. The implant is produced using 3D printing and is surface treated, then anchored in the remaining bone around the skeletal defect (Figure 3). This can, for example, help recovery of gait function after removal of a pelvic tumour, compensate for cranial defects, restore face shape and improve the masticatory function (20, 21).

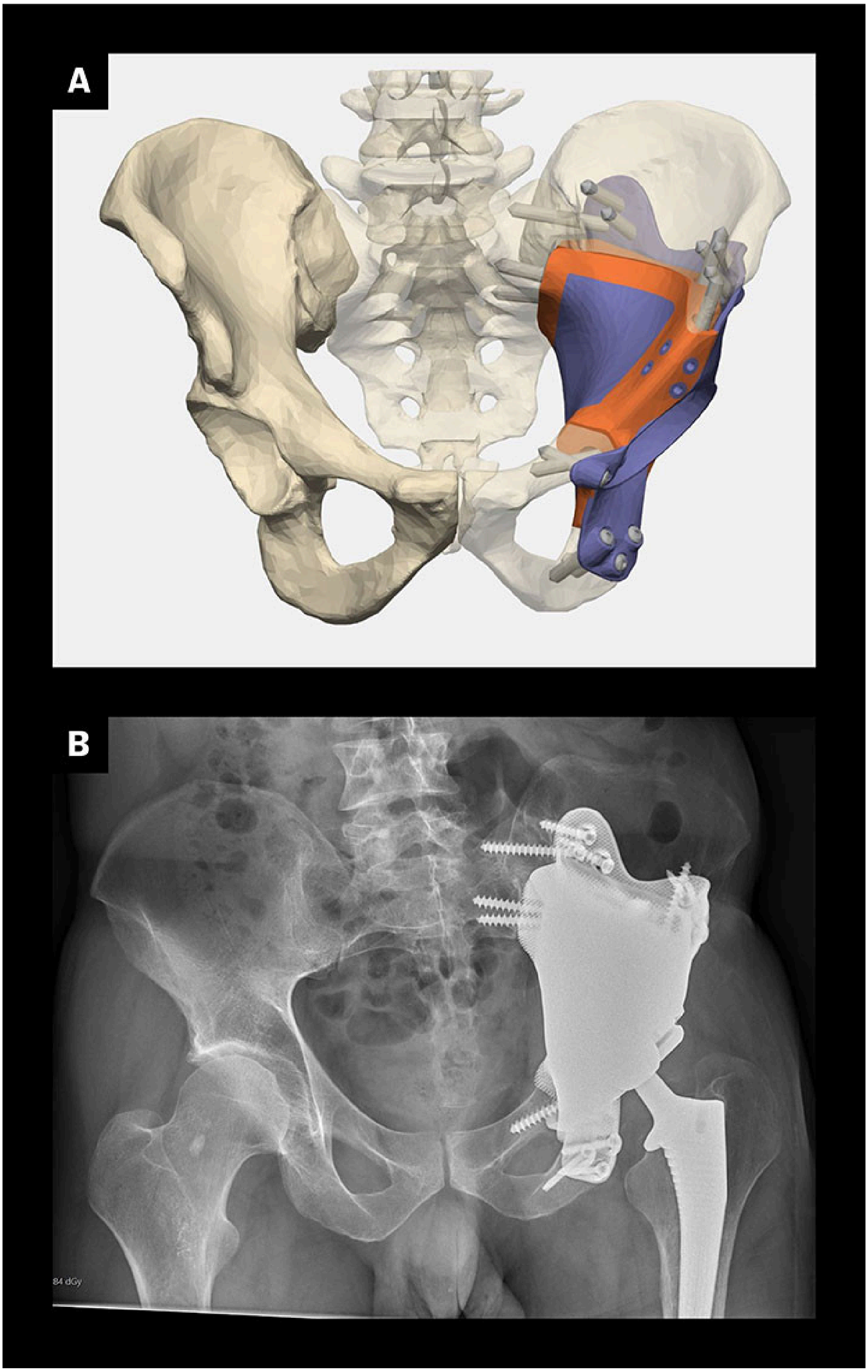


Figure 3 a) Computer-aided 3D reconstruction after removal of a bone sarcoma in the acetabulum. 3D printed titanium prosthesis with trabecular sand-blasted metal and screw fixation with the acetabular polythene component cemented in this. Standard cementless femoral titanium component. b) X-ray image of the front of the pelvis from the same reconstruction. Images by senior consultant Simen Sellevold of the Sarcoma research group, Oslo University Hospital, Radiumhospitalet.

As is often the case with innovations in medicine, titanium metal had a long and difficult journey to acceptance. The possible uses of titanium were first understood in odontological circles, and it was here that basic research on the metal had its humble beginnings. Now the metal is used in all other areas of medicine and is implemented with the most modern technology to improve patient treatment.

REFERENCES

1. Wikipedia. Titanium. https://en.wikipedia.org/wiki/Titanium Accessed 5.5.2024.

2. Guo CY, Matinlinna JP, Tang AT. Effects of surface charges on dental implants: past, present, and future. Int J Biomater 2012; 2012. doi: 10.1155/2012/381535. [PubMed][CrossRef]

3. United States Geological Survey. Titanium Statistics and Information. https://minerals.usgs.gov/minerals/pubs/commodity/titanium Accessed 5.5.2024.

4. Bothe RT, Beaton LE, Davenport HA. Reaction of bone to multiple metallic implants. Surg Gynecol Obstet 1940; 71: 598–604.

5. Leventhal GS. Titanium, a metal for surgery. J Bone Joint Surg Am 1951; 33-A: 473–4. [PubMed][CrossRef]

6. Albrektsson T, Brånemark PI, Hansson HA et al. Osseointegrated titanium implants. Requirements for ensuring a long-lasting, direct bone-to-implant anchorage in man. Acta Orthop Scand 1981; 52: 155–70. [PubMed][CrossRef]

7. Tamar L. Per-Ingvar Branemark, Dental Innovator, Dies at 85. New York Times 28.12.2014. https://www.nytimes.com/2014/12/28/health/per-ingvar-branemark-dental-innovator-dies-at-85.html Accessed 10.5.2024.

8. Albrektsson T, Chrcanovic B, Jacobsson M et al. Osseointegration of Implants – A Biological and Clinical Overview. JSM Dent Surg 2017; 2: 1022.

9. Frankelius P. Innovationen som tog skruv. Lakartidningen 2015; 112: 18–9.

10. Emsley J. Nature's Building Blocks: An A-Z Guide to the Elements. Oxford: Oxford University Press, 2003.

11. Reigstad O, Franke-Stenport V, Johansson CB et al. Improved bone ingrowth and fixation with a thin calcium phosphate coating intended for complete resorption. J Biomed Mater Res B Appl Biomater 2007; 83: 9–15. [PubMed][CrossRef]

12. Fiorillo L, Cicciù M, Tozum TF et al. Endosseous Dental Implant Materials and Clinical Outcomes of Different Alloys: A Systematic Review. Materials (Basel) 2022; 15: 1979. [PubMed][CrossRef]

13. O'Leary JF, Mallory TH, Kraus TJ et al. Mittelmeier ceramic total hip arthroplasty. A retrospective study. J Arthroplasty 1988; 3: 87–96. [PubMed]

[CrossRef]

14. Zweymüller KA, Lintner FK, Semlitsch MF. Biologic fixation of a press-fit titanium hip joint endoprosthesis. Clin Orthop Relat Res 1988; 235 (&NA;): 195–206. [PubMed][CrossRef]

15. Reigstad A, Røkkum M, Bye K et al. Femoral remodeling after arthroplasty of the hip. Prospective randomized 5-year comparison of 120 cemented/uncemented cases of arthrosis. Acta Orthop Scand 1993; 64: 411–6. [PubMed][CrossRef]

16. Cruz-Pardos A, García-Rey E, García-Cimbrelo E. Total Hip Arthroplasty with Use of the Cementless Zweymüller Alloclassic System: A Concise Follow-up, at a Minimum of 25 Years, of a Previous Report. J Bone Joint Surg Am 2017; 99: 1927–31. [PubMed][CrossRef]

17. Ortiz-Catalan M, Mastinu E, Sassu P et al. Self-Contained Neuromusculoskeletal Arm Prostheses. N Engl J Med 2020; 382: 1732–8. [PubMed][CrossRef]

18. Hainarosie M, Zainea V, Hainarosie R. The evolution of cochlear implant technology and its clinical relevance. J Med Life 2014; 7: 1–4.

19. Stöver T, Lenarz T. Biomaterials in cochlear implants. GMS Curr Top Otorhinolaryngol Head Neck Surg 2009; 8: Doc10. [PubMed]

20. Zoccali C, Baldi J, Attala D et al. 3D-Printed Titanium Custom-Made Prostheses in Reconstruction after Pelvic Tumor Resection: Indications and Results in a Series of 14 Patients at 42 Months of Average Follow-Up. J Clin Med 2021; 10: 3539. [PubMed][CrossRef]

21. Lim HK, Choi YJ, Choi WC et al. Reconstruction of maxillofacial bone defects using patient-specific long-lasting titanium implants. Sci Rep 2022; 12: 7538. [PubMed][CrossRef]

Publisert: 24 June 2024. Tidsskr Nor Legeforen. DOI: 10.4045/tidsskr.23.0465
Received 4.7.2023, first revision submitted 8.12.2023, accepted 10.5.2024.