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Editorial

# Image guidance in orthopaedics and traumatology: A historical perspective

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ABSTRACT

In this note we summarize the history of computer aided surgery in orthopaedics and traumatology from the end of the nineteenth century to currently observable future trends. We concentrate on the two major components of such systems, pre-operative planning and intra-operative execution. The evolution of the necessary technological components, the numerous platforms and components offered commercially as well as their clinical use are surveyed.



Image guided surgery (Jolesz 2014) has been evolving hand in hand with medical imaging itself. In this paper we concentrate on the historical aspects of this development without diving into technological details of the related research and development. These are covered by excellent monographs and surveys, like (Cierniak 2011) for computed tomography, (Dhawan 2011) for medical image analysis, (Heimann and Meinzer 2009) for statistical shape modeling or (Troccaz 2012) for surgical robotics.

Two surgical disciplines have been playing a pioneer role in this process, neurosurgery (Elhadi et.al. 2012) and orthopaedics (Van Tiggelen 2001). Within a few months after the report of Wilhelm Conrad Röntgen announcing the discovery of X-rays end of December 1895, several interventions have been carried out worldwide, guided by acquired X-ray images. Beginning of February, John Cox at the McGill University in Montreal removed a bullet from the leg of a shooting victim after localizing it on an X-ray plate. The same month Hazelwood Clayton, causality surgeon at the Queen's Hospital in Birmingham identified a needle fragment in the second metacarpal interspace of the hand of a 16 years old girl. The piece, originating from a household accident in 1894 and remaining unidentified during nearly 2 years, could be removed after precise localization on the X-ray image. Somewhat later, Frans König, director of the Surgical Clinics at the Charité in Berlin acquired an X-ray image of a female patient with a tibial neoplasm before amputation. The same year the first X-ray image of a shoulder prosthesis (implanted in 1894) has been presented in Paris by the French surgeon Jules Emile Péan, the father of shoulder arthroplasty. In March 1896 Fedor Krause, neurosurgeon at the City Hospital in Hamburg–Altona published the first paper about the use of X-rays for surgery ("The Importance of Röntgen's Photograms for Surgery").

The first obvious usage of X-rays has been connected to traumatology cases, mostly for the detection and characterization of dislocations and fractures and the identification of foreign bodies. Already during the first world war, Marie Curie organized nearly 20 mobile X-ray units for supporting battlefield care, which acquired around one million radiographs. Even stereoscopic X-ray imaging techniques and devices for locating the geometrical coordinates of embedded foreign bodies have been described, too. The fast development of radiographic technology between the two world wars enabled the routine use of X-ray imaging technology for clinical diagnosis and therapy support. It is worth noting that the principles of fluoroscopy (Kryptoscope, the first fluoroscopy device for head surgery has been introduced already in 1928) and tomography (proposed by André Bocage as early as 1916, while the transformation for reconstructing volumetric images from projections has been published by Johann Radon in 1917) have also been developed during this period.

Several decades were necessary for the maturation of these basic ideas to devices with the accuracy, safety and reliability required today in the daily clinical practice. Between 1920 and 1985 other important innovations were dominant in the field,

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e.g., addressing improvements of conditions for successful interventions, such as antisepsis and asepsis based on the pioneering work of Ignaz Semmelweiss and Joseph Lister. In the musculoskeletal area surgeons advanced the use of dressings, bandages, and splints for wound management, introduced new surgical methods for arthrodesis and developed prostheses for the replacement of amputated limbs and facial reconstruction. After the Second World War the search for appropriate materials for the design and anchoring of implants for joint replacement, fracture fixation and spinal interventions were at the center of musculoskeletal research. An important landmark in the field of traumatology was the creation of a consortium for osteosynthesis (later AO Foundation) in 1958. Inspired by the pioneering work of a Belgian surgeon, Robert Danis, the founding team lead by Maurice Müller planned to better understand and optimize bone healing through research, a strategic alliance with the Swiss precision engineering discipline and case documentation for quality assurance. 1962 marked a breakthrough in the area of joint replacement. Sir John Charnley introduced his low friction arthroplasty concept, involving a small femoral steel head and an acetabular component made of high molecular weight polyethylene. His other major contribution was to use polymethylmethacrylate for component fixation to the bone. It took another 10 to 20 years until appropriate prostheses for total knee replacement became available. The late 70′s and early 80′s of the last century marked the beginning of the area of instrumented spinal stabilization. Based on the pioneering work by Raymond Roy-Camille, spinal fixators relying on transpedicular screw fixation became widely available.

In spite of this remarkable development, a routine clinical workflow for planning orthopaedic interventions based on X-ray imaging had not been established before the 60's of the last century. During this process, which can be regarded as the gold standard even today, X-ray images are used pre-operatively either in a qualitative fashion, or even quantitatively by performing measurements or using pre-fabricated templates for planning the intervention. In the latter case, the metric correction of X-ray images for compensating magnification is necessary. Even if placing these images on a light-box in the operating room, the transformation of the resulting pre-operative plan to surgical action has to be exclusively performed mentally by the surgeon.

Several major technological advances opened fundamentally new opportunities for improved surgical planning. A decisive step has been the maturation of Computed Tomography (CT). The principles of cross-sectional imaging have been investigated by Allen Cormack and Geoffrey Hounsfield independently during the 60′s. The first CT device (the EMI Mark I created by Hounsfield) has been installed in 1971 at the Atkinson Morley's Hospital in Wimbledon and has been used exclusively for head imaging due to its limited bore size. The introduction of this technology, enabling to overcome the limitations of X-ray caused by planar projection and therefore opening the way to 3D reconstruction of the anatomy of individual patients, was breathtakingly fast. Between 1974 and 1976 GE, Philips and Siemens offered their first commercial devices and during the 80′s CT has become routinely available in radiological departments all over the world.

Another important precondition of this triumphal procession was the availability of large-scale computational resources beyond the world of mainframes. This enabled not only the fast reconstruction of 2D cross-sectional slices or even 3D volumes from projections, but also provided the necessary computational power for the post-processing of the resulting images, which has become increasingly important in the decades to come. First dedicated medical image analysis procedures have been developed, concentrating primarily on segmenting anatomical and pathological objects of interest from the acquired images and on the fusion of images stemming from different acquisitions and/or imaging modalities. The development of computer graphics procedures and specialized rendering engines allowed the real-time visualization of the 3D anatomy and the interaction with the identified virtual objects.

The possibility to store, process and display 2D images on a desktop computer triggered the implementation of traditional X-ray based planning on a computer. After scanning the X-ray images (or later using digitally acquired data), all components of the original planning procedure performed on the X-ray film could be offered through a graphical user interface. These attempts, however, remained mostly restricted to the academic domain and could not be successfully introduced broadly in the clinical practice. Largely this was due to limitations in resolution and dynamic range of commercially available display devices. Instead, a fast transition could be observed towards true 3D pre-operative planning based on CT images. Combining image processing and analysis tools with interactive 3D visualization through appealing graphical user interfaces has led to complex computational platforms (available both as open source and commercial products) implementing general or application-specific environments for 3D planning. Interestingly, the more recent development of statistical shape and appearance models opened the possibility to perform 3D planning based on just a few X-ray images. Originally, these were developed as tools for automatic image segmentation by representing the variability of morphology and radiological appearance within a population in a compact fashion and applying this information to constrain the ill-posed segmentation problem. The demonstration of their ability to forecast unseen features from limited observations allows, however, using them as predictors not only for a patient-specific 3D anatomy, but also even for complete CT volumes from a limited number of X-ray acquisitions.

These achievements allow highly precise planning of interventions. Combining with recently developed additive manufacturing techniques (3D printing) orthopaedic and traumatological interventions can be prepared in a fully patient-specific fashion. Nevertheless, all these advances do not offer any support in the implementation of such carefully adapted plans in the operating room with similar accuracy.

The fundamental idea of such interventional support systems originates from neurosurgery (Levy 2016). Guiding tools for reproducible and precise navigation related to the human anatomy are actually older than medical imaging itself. C. Dittmar at the Physiological Institute of Carl Ludwig in Leipzig used a guiding device for positioning electrodes in the vasomotor center of the medulla oblongata of rats already in 1873. D.L. Zernoff, professor for anatomy at the Moscow University created the first arc-based positioning apparatus in 1889 and used it for human brain surgery in at least three cases. The first true stereotactic instrument was created by Horsley and Clarke in 1908 (patented in 1912) and applied for reproducible and systematic navigation in the monkey cerebellum based on external, visible landmarks. E. Spiegel has used two orthogonal X-ray images of the patient with an individually manufactured stereotactic frame in place for the identification of the pineal body and the thalamic region as early as 1947. The mechanical design was based on the principles established by Horsley and Clarke, while the necessary tissue contrast was achieved by filling the ventricles with air. Due to such limitations in achievable brain tissue contrast by X-rays, neurosurgery is heavily relying on anatomical atlases for target definition up to now. The first photographic representation of the human brain has been presented in 1873 by Jules Bernhard Luys. In 1894 Flatau published the first systematic atlas based on photographies of whole and dissected, unfixed human brains. In 1896 Gustav Retzius published "Das Menschenhirn", up to then the most comprehensive atlas of the human brain consisting of both drawings and photographies of fixed brain surfaces and sections. Image-based and atlas-based target defini-