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General introduction and Outline of this thesis

INTRODUCTION

One of the major difficulties in surgery is a safe approach of the operation site. The vast amount of different surgical approaches for the same procedure exemplifies the constant surgical dilemma between exposure and tissue sparing. Iatrogenic damage to nerves and vessels still is a common complication of surgery, resulting in a wide array of postoperative complaints such as impaired wound healing and neuropathic pain. Meanwhile general public opinion appears to become less forgiving and surgeons are held accountable for iatrogenic damage. In this thesis several examples of iatrogenic damage to nerves or vessels are being linked to the clinical research questions that preceded these studies. Damage to arteries of the lateral ankle during calcaneal surgery results in high complication rates, with the rate of infection reported in up to 21%[1-5], and superficial necrosis reported in up to 14% of cases[4, 6]. Damage to motor nerves such as the intercostal- and subcostal nerves results in flank bulge after lumbotomy in up to 49%[7] as parts of the abdominal muscles are no longer innervated[8-10]. Sensory nerve damage may result in minor complaints such as numbness or paresthesia but also highly invalidating neuropathic pain or symptomatic neuroma`s are regular complications[11, 12]. For example, up to 10% of sural nerve injury[13] is reported after ankle surgery. In addition, in knee surgery 28% of the patients report irritating paresthesia after open meniscectomy[14] and it is a common complication after arthroscopy[15-17]. Furthermore, in total knee arthroplasty numbness of the anterolateral part of the knee is reported in as much as 55 to 100 %[18-19]. Especially in the knee these sensory, afferent nerves are also essential for transporting proprioceptive information. A lack of joint position perception can contribute towards joint instability which in turn leads to osteoarthritis. Less invasive techniques such as endovenous thermal ablation of the short saphenous vein in varicosis of the leg are also not without risk of complications. Since the sensory sural nerve is located closely to the vein which is ablated, thermal damage to the nerve can be a serious complication.

In the everlasting surgical dilemma between tissue sparing and exposure, iatrogenic damage to vessels, nerves and other anatomical structures can be inevitable. Nevertheless, preventing complications is of primary interest to any surgeon. Insufficient knowledge of human anatomy should never be the cause of iatrogenic complications in surgery. Despite of what plastic anatomy models, 2D anatomy books or virtual 3D anatomy-app's[20] suggest, there is an endless variation in human anatomy. Even in twins there is a wide array of differences.

In addition, differences between left and right extremities are always present in every single person. Thus, normal anatomy does not equal anatomy that is without variation[21]. The word normal is derived from the Latin word normalis which means "conform to the rule of pattern" and in descriptive anatomy the word "normal" is used for an anatomical structure falling within a normal range of characteristics. Generally speaking in anatomy the range of "normal" characteristics is rather extensive. Everything beyond "normal anatomy" is considered an anomaly or malformation. It is estimated that the incidence of minor malformations ranges from 7-40%[22, 23] whilst major anomalies are present in 2-3% of the general population[24].

For any surgeon, memorizing all variations of what we perceive as normal anatomy is close to impossible. Nor can a surgeon take into account all the different and sometimes rare anatomical abnormalities. Modern society demands complication free surgery but novel developments such as minimal invasive surgery allow for less exploration and exposure of vulnerable structures during surgery. This inadvertently has impact on the anatomical knowledge of young surgeons as the conventional way of learning anatomy, by experience in the operating room, becomes inadequate as less anatomy is dissected during a day of training. Moreover, anatomical knowledge is even more important in minimally invasive surgery than in conventional surgery, as less exposure and visibility requires more knowledge of surgical landmarks and anatomical variation. In the small area of laparoscopic views, the course of structures cannot be used for identification of an anatomical structure since only fragments of the structure can be seen. Neither can palpation be used to identify pulsatile structures since haptic feedback has not yet been introduced to laparoscopic surgery.

Furthermore, there is the difference between 'looking in from the outside' versus 'looking from the inside out'. A completely new set of anatomical perspectives arise. The most well known example is probably the 'dorsal view anatomy' of the abdominal wall at the level of the inguinal region. The Totally Extraperitoneal Procedure (TEP) in inguinal hernia repair has introduced new surgical questions and hence new answers were given by the anatomist. A new branch on the Anatomical tree developed: the endoscopic anatomy.

Experience alone is not enough to learn anatomical variations. This is most apparently shown in learning the anatomy of nerves. In contrast to vascular damage in which immediate hemorrhage is a clear sign of damage, mostly no

direct feedback is given to the surgeon when a nerve is damaged during surgery. For instance lesions due to excessive tensile forces, such as traction by wrongly placed retractors, can stay obscure because the epineurium is usually not visibly damaged. In case of ulnar nerve traction resulting in 10% of elongation can lead to internal damage to the axons without visible damage to the epineurium and the conduction velocity of the nerve can be significantly decreased[25, 26]. Unless this is noted directly postoperatively, damage to the nerve is usually only observed in the outpatient clinic, days, weeks or even months after surgery. Again, in contrast to arterial damage during surgery; as the artery starts to bleed the surgeon can quickly recollect what decisions led to the hemorrhage and he is able to learn anatomical variations in arteries by experience.

Therefore, to fulfill the increasing need for expert anatomy knowledge, a new method of mapping the variations that constitute normal anatomy needs to be developed. Complex data of multiple specimens need to be visualized and presented to residents and surgeons in an easily accessible and interpretable way. Vesalius was the first to note anatomical variations and differences. In fact, of the six anatomical structures carrying his name, only two can be considered as normal anatomy. Since then, the notion of variability has gained widespread acceptation. Mapping and comparing these variations is difficult as individual specimens never are of the same size. Contemporary ways of visualizing anatomy are drawings and photographs. Yet they lack the possibility to accurately show multiple variations and hence do not do justice to the surgical need for knowledge of the wide variation of normal anatomy.

Another way to compare variations in anatomy is to measure the location of certain structures and then adjust the measurements to, for instance, the length of a leg. Results are then presented in tables or schematic drawings. However, the shape of a specimen is not only dependent on its length, but also its width. As width usually depends on the amount of soft tissues it varies a lot and therefore the shape of a lower leg for instance differs significantly between people. Furthermore, research has shown[27, 28] that visual presentation of complex data is remembered better than when data is presented as text or tables. Moreover, text itself is memorized better when it is accompanied by a figure[29-31]. To paraphrase Confucius: "one picture tells us more than a thousand numbers".

Computer Assisted Surgical Anatomy Mapping

In this thesis a novel anatomy mapping tool, Computer Assisted Surgical Anatomy Mapping (CASAM), is described. With this method the variation of anatomy, dissected in multiple specimens, can be compared and mapped. The complex data can then be processed and visual renditions can be made that represent the whole range of the anatomical term "norma". Currently CASAM can be applied in two main pillars of modern surgery;

1. Basic surgical anatomy research: CASAM allows anatomists and surgical researchers to compare and define anatomical variations better in structures such as muscles, nerves and vessels. To simplify the vast amount of data and highlight the clinical implications, renditions can be made to depict for instance "safe zones", in which a surgeon can make an incision without having the risk of damaging a certain nerve. Similarly it is possible to compute a "zone of interest" in which a certain muscle or arterial perforator is always located. Also "directionally anatomy zones" can be computed. These zones depict the position and direction of nerves, showing the surgeon in which direction to make an incision to best avoid damage to nerves of interest. Interestingly, when vessels are depicted by CASAM also "vascular safe zones" can be defined. In this case the reversed principle is seen. Whereas a nervous safe zone is defined as a zone with no or a few nerves, the vascular safe zone is defined as a zone in which as much vessels (and subsequent anastomoses and collateral vessels) as possible are found; the more vessels, the better the potential for optimal wound healing. When multiple different zones are depicted, a surgeon is provided with a vast amount of anatomical data gathered from multiple specimens. The goal of CASAM is not be a substitute for anatomical knowledge but to provide a tool to summarize complex and variable anatomy and subsequently allow the surgeon to make more informed decisions. In a 70 year old diabetic patient with peripheral atherosclerosis the vascular safe zone might be more important than the nervous safe zone whilst the opposite might be true for a healthy 20 year old Olympic gymnast.

2. Surgical teaching: not only can CASAM be used to teach complex anatomy, also trainees can add incision lines drawn for a specific type of surgery, such as for instance the extended lateral approach of the ankle for calcaneal fractures. These drawn incision lines can then be compared to the ones drawn by their peers, surgeons or the golden standard. The incision lines can also be compared to the anatomy of multiple dissected specimens, challenging a drawn incision

line to the scrutiny of variable anatomy. This is in contrast to conventional anatomy courses in which a drawn incision line is only compared to the anatomy of the specimen the trainee has at hand and not a vast library of the anatomy of multiple specimens. The web-based version of CASAM therefore is of added value during anatomy courses, giving a surgeon or surgical resident direct and personal feedback.

CASAM consists of multiple phases. First, the surgically relevant anatomic structures are dissected and photographed in a standardized way. Secondly, each specimen is outlined and its shape is delineated using so-called landmarks. From the location of the landmarks of multiple specimens an average shape can be computed. Then each original image of a specimen can be warped to match the computed average shape. Finally, since all specimens then have the same shape, the anatomy can be compared and renditions can be made to highlight the clinical relevance in everyday surgery.

The Aim of this dissertation is to prove the basic principles of CASAM are sound and applicable in two main pillars of surgery: Anatomy and Teaching. This thesis also lays the groundwork for a future web-based version of CASAM that has its application in 3D anatomy research and also in personalized teaching and Tailor-made Surgery.

OUTLINE OF THIS THESIS

First, a brief historical overview will describe the thoughts of previous anatomists that led to the development of CASAM. Current concepts of CASAM are explained in Part I, MATERIALS & METHODS. In the first sub-chapters the general principles of Image processing, Geometry and Warping are explained. Secondly, their role in CASAM is elucidated when the four phases of the method are explained; Dissection, Averaging, Warping and Renditions.

The application of CASAM in basic surgical research is shown in Part II, CASAM in SURGICAL ANATOMY. This part is divided into three subchapters, each describing different sorts of renditions dependent on the clinical research question. In Point distribution model, the perforating veins of the lower arm are mapped as they have an impact on survival of arteriovenous fistulae created for hemodialysis (chapter 2.1). In Multiple Line model the variations of nerves and arteries are mapped in relation to kidney surgery (chapter 2.2), ankle surgery (chapter 2.3) and knee surgery (chapter 2.4), showing how complex anatomy of multiple specimens can be mapped and applied to solve surgical problems encountered in everyday clinical practice. Furthermore, as the wrist is a common site for neuropathic pain after injury of the sensory nerves, two of the radially located superficial nerves were mapped in chapter 2.5. The anatomical relation between both nerves could be compared using CASAM. This possibly explains the high rates of post-operative neuroma formation and neuropathic pain after surgery of the dorso-radial side of the wrist.

In chapter 2.6 the mapping of a Multiple area model is combined with the anatomy of the sural nerve and the short saphenous vein. The nerve partially runs below a protective fascia layer and by mapping this area in 20 specimens, a safe-zone for laser surgery is defined. A "zone of interest" was mapped by defining a zone in which three arm muscles are present in all 20 specimens without overlap of other muscles and therefore a noninvasive preoperative test for tendon transfers in tetraplegic patients can now be developed (chapter 2.7). Finally, in chapter 2.8 similar zones of interest were mapped to showcase overlap between the nerves providing sensation to the hindpaw of a rat.

To further minimize the gap between basic anatomy research and everyday clinical practice, a web-based version of CASAM is developed. In Part III, CASAM in SURGICAL TRAINING the algorithms and computations used are

described and the structure of a central server, user features and general layout are outlined (chapter 3.1 and chapter 3.2). In chapter 3.3, incisions drawn for an approach of the tibia are mapped in relation to tibial nailing and chapter 3.4 discusses the inter- and intra surgeon variability in incisions drawn for an extended approach for the lateral calcaneus. Common variables in the placement of these incision lines such as experience, surgical specialty and exposure to calcaneal surgery are related to the ability of a surgeon to draw an incision according to the "gold standard".

Discussion and future perspectives further illustrates the application of CASAM in Teaching and Tailor made surgery. Reservations regarding image manipulation in basic research and data verification of CASAM renditions will be discussed. Finally, the future perspectives of a web-based and 3-Dimensional CASAM will be illustrated providing a platform for international anatomical data collection and in theater, real time visualization of complex anatomy on the patient.

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