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AI-guided precision liver surgery: real anatomy and digital hepatectomy

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I often think back to the liver resections I witnessed a quarter century ago as a surgical resident. Professor Makuuchi, widely regarded as having the "hands of God" in liver surgery, performed anatomical (sub)segmentectomy[1] with astonishing precision using intraoperative ultrasonography and dye staining, often without carefully reviewing preoperative imaging. He also assessed liver function using the indocyanine green retention rate at 15 min (ICG-R15) and determined the permissible extent of hepatectomy according to a four-tier classification of liver function, later known as Makuuchi's criteria[2]. These two principles became the twin pillars of his strategy for achieving both oncological radicality and preservation of liver function in patients with impaired hepatic function. By adhering to this strategy, his team performed more than 1,000 consecutive hepatectomies without a single in-hospital death[3]. Moreover, even patients with hepatocellular carcinoma accompanied by portal hypertension or multiple tumors - conditions that remain contraindications to resection in many Western guidelines[4] - achieved 5-year survival rates approaching 60% when liver function remained Child-Pugh class A[5].

Later, in Paris, Professor Gayet, under whom I had the privilege of training, successfully applied Professor Makuuchi's anatomical hepatectomy techniques laparoscopically to every liver segment, from segment I to VIII[6]. By then, three-dimensional (3D) visualization of hepatic anatomy based on preoperative computed tomography (CT) images had already begun to enter clinical practice[7]. Yet Professor Gayet did not seem to rely on these artificially reconstructed images. Rather, he appeared to synchronize intraoperative ultrasonography with the image of the hepatectomy projected in his own mind, thereby performing remarkably precise liver resections. The question is whether modern surgeons, myself included, now armed with the powerful new partner called artificial intelligence (AI), can truly surpass the results achieved by these surgical legends.

The first role that AI should play is to make the hepatic image projected in an expert surgeon's mind shareable and usable by everyone. Highly accurate simulation software is now commercially available and has entered routine clinical practice. However, I remain dissatisfied with current technology. Although it provides highly

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detailed reconstructions of the hepatic artery, portal vein, and bile duct branches, current software fails to reproduce the thickness of surrounding connective tissue and the interfaces between the liver and adjacent organs. Displaying only vascular structures through a transparent liver or hepatoduodenal ligament and freely rotating them in virtual space does not, in my view, substantially improve surgical precision. Surgery is not performed within a transparent liver. Rather, it involves deciding where to make an incision on the surface of an opaque liver or fatty tissue, how deeply to dissect, and how to safely reach the target vessel. Only when software and its interfaces can reproduce this entire process in virtual space will novice liver surgeons be able to repeatedly rehearse an operation and use the resulting mental image to improve the surgery they perform the following day.

Another key to making AI-based image processing truly useful for surgery may be integrating preoperative 3D reconstructions with intraoperative information, an approach currently under active exploration. Intraoperative data may include endoscopic imaging, ultrasonography, and ICG fluorescence imaging of liver tumors[8], the biliary tree[9], and hepatic segments[10]. For instance, imagine a system in which the liver transection line drawn directly on an ultrasound monitor with a fingertip is automatically recorded and subsequently displayed as a 3D overlay on the endoscopic image. Alternatively, the tumor and corresponding hepatic segment could be simultaneously displayed in distinct pseudocolors. Such technologies would bring virtual surgical planning substantially closer to the realities of the operative field.

AI is also expected to enhance the accuracy of liver function assessment. Although adherence to Makuuchi's criteria could reliably reduce the risk of postoperative liver failure, it is worth recalling how rudimentary liver volumetry was when these criteria were developed. Tracing paper was placed over CT images printed on X-ray film, often with slice thicknesses exceeding 5 mm, and the boundaries between hepatic segments were manually delineated by following the midpoint between adjacent hepatic veins. The drawings were then scanned into image-processing software, where the area of each region was calculated with a lasso tool and converted into segmental liver volumes. Compared with these labor-intensive methods, modern volumetric analysis based on automated vascular recognition, region-growing algorithms, and Voronoi-based segmentation represents a remarkable advance in precision. If these anatomical measurements can be integrated with blood-based assessments beyond ICG-R15, as well as magnetic resonance imaging (MRI)-derived indices of liver stiffness and perfusion, the functional reserve of individual hepatic segments could be evaluated more comprehensively and precisely. Such advances may ultimately enable safe radical hepatectomy in selected patients who fall outside the conventional indications defined by Makuuchi's criteria.

However, an important caveat must be emphasized. No matter how sophisticated preoperative image analysis becomes, it cannot fully capture the actual hemodynamics of the living liver. In recent years, the concept of the cone unit has attracted considerable attention as the basis for parenchymal-sparing anatomical hepatectomy[11], in which the resections are planned by combining multiple subsegmental territories. Yet clinically, a simple wedge or hemispherical resection can often be performed without inducing ischemia in the remnant liver, provided that the major Glissonian pedicles and hepatic veins are preserved. This may reflect the peripheral liver's biological circulatory system, which cannot be visualized on CT, including intersegmental inflow communications, blood supply from the hepatic venous side to hepatocytes, and the relatively rapid development of venous collateral circulation[12]. These physiological properties characterize the living liver rather than the liver reconstructed on a computer screen. AI may allow increasingly sophisticated anatomical resections to be designed, but greater technological sophistication does not necessarily mean that every hepatectomy should be performed in a more complex manner.

Hepatobiliary surgery carries a substantial risk of complications and, owing to prolonged operative times and extensive use of disposable devices, imposes a considerable environmental burden[13]. From the perspective of sustainable surgery[14], which has gained increasing attention in recent years, we need algorithms that can identify patients likely to derive meaningful prognostic benefit from hepatectomy and, conversely, those who may benefit more from early initiation of nonsurgical treatments such as systemic therapy. Deep learning systems that integrate conventional liver function tests and tumor characteristics with comprehensive patient data, genomic information, and preoperative imaging[15] hold considerable promise. As these systems mature, they may move beyond conventional stage-based cancer classifications to provide individualized preoperative predictions, such as the risk of severe postoperative complications and the probability of 5-year survival for a specific patient undergoing a specific procedure.

An important question, however, is whether such integrated prediction models should incorporate the surgeon factor. A surgical record may describe a procedure as "anatomical resection of segment VIII" or "extended right hepatectomy", yet the quality of the operation can differ substantially according to the surgeon's experience and technical expertise. Moreover, important operative details - including the extent of hepatic vein exposure, the degree of vascular skeletonization, and the technique of lymph node dissection - may vary considerably across countries, institutions, and surgical cultures, even when the procedures share the same name. A surgeon who undertakes operations for advanced cancers may occasionally achieve cures in a small subset of patients whose benefits are too subtle to be captured by conventional statistical analyses, while inevitably experiencing a higher complication rate than a surgeon who primarily performs lower-risk procedures. Ideally, AI-based prognostic models should account for these surgeon-related factors. The challenge is that surgical quality is exceptionally difficult to quantify and even more difficult to extract from published reports. Perhaps the most informative source of data would not be operative notes but the entire surgical video. If deep learning could analyze complete operative videos, it might finally become possible to assess surgical quality more objectively and determine its impact on oncological outcomes.

If a future generation of autonomous robotic surgeons becomes capable of performing fully automated liver resections, virtual digital hepatectomy may eventually be translated almost seamlessly into the actual operative field. Until then, however, surgery will remain a profoundly human endeavor. The more AI advances in reconstructing hepatobiliary anatomy and predicting surgical outcomes, the more important the surgeon's ability to understand, interpret, and reproduce that information in the operative field will become.

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Authors' contributions

The author contributed solely to the article.

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Not applicable.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool ChatGPT (version 5.5, released 2026-05-05) was used solely for English language editing. The tool did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. The author takes full responsibility for the accuracy, integrity, and final content of the manuscript.

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Not applicable.

Consent for publication

Not applicable.

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