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Implementation of Intraoperative Hyperspectral Imaging in Kidney Transplant Surgery

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Abstract: Intraoperative hyperspectral imaging (HSI) provides a non-contact, quantitative method to assess tissue oxygenation and perfusion during kidney transplantation. Within the TESIT study, a standardized five-timepoint (T1-T5) HSI protocol was integrated into the surgical workflow. Early results show a pronounced post-reperfusion increase in StO_2 and NIR values, clear perfusion differences between living and deceased donor grafts. These findings highlight the feasibility and clinical potential of HSI to detect perfusion abnormalities in real time and to support improved intraoperative graft assessment.

I. Introduction

Kidney transplantation is the only curative therapy for end-stage renal disease, yet early postoperative graft dysfunction remains a major clinical challenge [1]. Such early impairment is associated with increased morbidity, prolonged hospitalization, and poorer long-term graft survival [2]. A central contributor is insufficient microvascular perfusion immediately after reperfusion - yet surgeons currently rely on subjective visual assessment to evaluate graft viability [3]. In Germany, the severe shortage of donor kidneys demands optimal utilization of every available graft [4]. However, objective intraoperative tools for assessing graft viability are lacking [5]. Hyperspectral imaging (HSI) may help close this diagnostic gap by providing objective, real-time perfusion metrics to support intraoperative graft assessment and enable early detection of perfusion deficits during surgery. HSI provides a non-contact, quantitative method to assess tissue oxygenation and perfusion in real time [6]. Although early studies have demonstrated its potential, systematic intraoperative workflows and reproducible acquisition protocols remain underdeveloped [7]. To address this gap, the present work implements a standardized five-timepoint (T1-T5) HSI protocol and characterizes the physiological evolution of perfusion parameters during transplantation.

II. Material and methods

This work is part of the TESIT study (Human Tissue Examination using non-invasive Spectral Imaging Techniques), a prospective monocentric research framework at the University Medical Center Göttingen focusing on intraoperative hyperspectral imaging (HSI) during kidney transplantation. A standardized five-timepoint HSI protocol was implemented using the TIVITA® 2.0 Surgery system: T1 (Backtable, cold ischemia), T2 (warm ischemia in situ), T3 (3 min after reperfusion), T4 (10 min after reperfusion), and T5 (20 min after reperfusion). The system generates perfusion-related parameter maps (StO_2, NIR, OHI, THI, TWI, TLI) via spectral unmixing of oxy- and deoxyhemoglobin absorption profiles. The NIR (Near-Infrared Perfusion Index) represents a relative measure of deep-tissue perfusion derived from near-infrared absorption and is less influenced by superficial surface effects than StO_2. Acquisition geometry was standardized (50 cm working distance, 90° camera alignment). White-reference calibration, dimmed operating lights, surface glare reduction, and sterile-mounted camera fixation minimized optical artefacts. Device precision is ±0.01 (normalized units); small numerical differences were interpreted cautiously and trend-based. Image acquisition was synchronized with the surgical workflow to avoid procedural interference. Two anatomically standardized ROIs were defined per measurement (renal hilum and cortical region 2 cm distal to the upper pole). Hyperspectral cubes were exported in raw format, kidney tissue was segmented to exclude background, and ROIs were algorithmically placed using a custom Python pipeline. Mean parameter values were extracted for all timepoints and temporally aligned to enable comparison of intraoperative perfusion dynamics.

III. Results and Discussion

15 kidney transplantations were included (5 living, 10 deceased donors), yielding 75 HSI acquisitions across five intraoperative timepoints (T1–T5). Perioperative variables such as ischemia times, urine output, and postoperative creatinine/eGFR were collected for exploratory correlation. Figure 1 summarizes the temporal evolution of the HSI parameters. In Figure 2 (T1), the NIR map shows absent perfusion, consistent with the physiological state of a non-perfused graft. At T3 (early reperfusion; Figure 3), the NIR

map demonstrates a marked increase in deep-tissue perfusion and early cortical homogenization, illustrating the characteristic "reperfusion jump" - the rapid rise in microvascular perfusion after clamp release - also reflected in the quantitative parameter curves. Living donor kidneys exhibited higher StO_2 and NIR values at T3 than deceased donor grafts (StO_2: 0.71 vs. 0.60; NIR: 0.60 vs. 0.58), consistent with shorter ischemia times and superior microvascular recovery; this difference is visually reflected in more homogeneous cortical perfusion and faster reperfusion dynamics. HSI parameters correlated with postoperative creatinine/eGFR, indicating that intraoperative spectral perfusion assessment captures physiologically meaningful patterns and may help identify early graft dysfunction. From a technical perspective, the standardized acquisition and segmentation-based ROI pipeline ensured stable spectral quality, reduced operator dependency, and enabled automated batch analysis across timepoints. Overall, these findings demonstrate that the standardized intraoperative HSI protocol reliably captures physiologic perfusion dynamics and highlight the potential of computational HSI workflows to support objective real-time graft assessment.

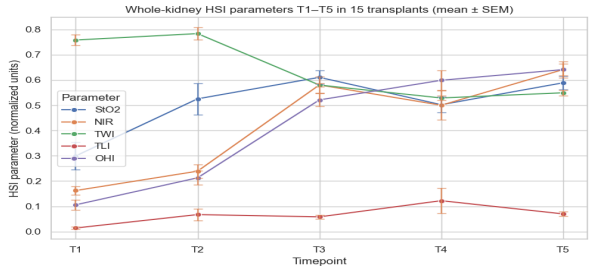

Figure 1: Temporal evolution of whole-kidney HSI parameters (StO_2, NIR, TWI, TLI, OHI) from T1-T5 in 15 kidney transplants (mean ± SEM).

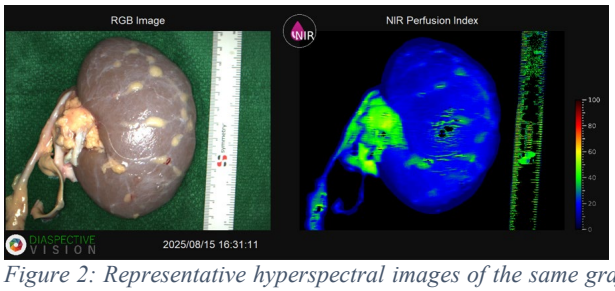

Figure 2: Representative hyperspectral images of the same graft at T1 (Backtable, cold ischemia).

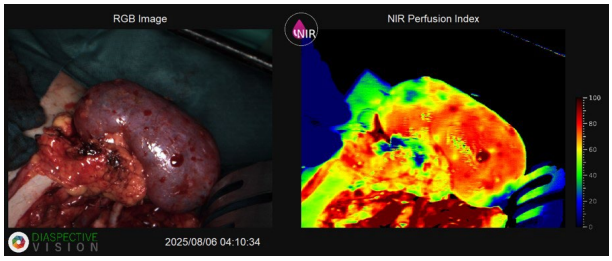

Figure 3: Representative hyperspectral images of the same graft at T3 (early reperfusion), illustrating the reperfusion-associated increase in perfusion.

IV. Conclusions

Intraoperative HSI can be reliably integrated into the time-critical workflow of kidney transplantation and provides objective, reproducible metrics of microvascular perfusion. The standardized T1-T5 protocol captured physiologically meaningful dynamics, including the characteristic "reperfusion jump" at T3 and distinct differences between donor types. These results demonstrate that HSI enables real-time visualization of perfusion patterns that are not accessible through conventional assessment. By linking intraoperative perfusion metrics with postoperative renal function, HSI may enhance early prediction of graft outcome and contribute to the improved utilization of scarce donor kidneys. Future work will focus on automated ROI detection, real-time perfusion analytics, and integration with surgical video streams to support intraoperative decision-making and postoperative outcome prediction.

Author's Statement

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