PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Optical simulations for determining efficacy of new light source designs for excitation-scanning high-speed hyperspectral imaging systems

Browning, Craig, Deal, Joshua, Gunn Mayes, Samantha, Parker, Marina, Rich, Thomas, et al.

Craig M. Browning, Joshua Deal, Samantha Gunn Mayes, Marina Parker, Thomas C. Rich, Silas J. Leavesley, "Optical simulations for determining efficacy of new light source designs for excitation-scanning high-speed hyperspectral imaging systems," Proc. SPIE 11216, Multiscale Imaging and Spectroscopy, 112160W (2 March 2020); doi: 10.1117/12.2545201

SPIE.

Event: SPIE BiOS, 2020, San Francisco, California, United States

Optical simulations for determining efficacy of new light source designs for excitation-scanning high-speed hyperspectral imaging systems

Craig M. Browning[1,2], Joshua Deal[3,4], Samantha Gunn Mayes[1], Marina Parker[1,2], Thomas C. Rich[3,4], Silas J. Leavesley[1,3,4]
[1]Chemical and Biomolecular Engineering, University of South Alabama, AL 36688
[2]Systems Engineering, University of South Alabama, AL 36688
[3]Pharmacology, University of South Alabama, AL 36688
[4]Center for Lung Biology, University of South Alabama, AL 36688

ABSTRACT

Positive outcomes for colorectal cancer treatment have been linked to early detection. The difficulty in detecting early lesions is the limited contrast with surrounding mucosa and minimal definitive markers to distinguish between hyperplastic and carcinoma lesions. Colorectal cancer is the 3rd leading cancer for incidence and mortality rates which is potentially linked to missed early lesions which allow for increased growth and metastatic potential. One potential technology for early-stage lesion detection is hyperspectral imaging. Traditionally, hyperspectral imaging uses reflectance spectroscopic data to provide a component analysis, per pixel, of an image in fields such as remote sensing, agriculture, food processing and archaeology. This work aims to acquire higher signal-to-noise fluorescence spectroscopic data, harnessing the autofluorescence of tissue, adding a hyperspectral contrast to colorectal cancer detection while maintaining spatial resolution at video-rate speeds. We have previously designed a multi-furcated LED-based spectral light source to prove this concept. Our results demonstrated that the technique is feasible, but the initial prototype has a high light transmission loss (~98%) minimizing spatial resolution and slowing video acquisition. Here, we present updated results in developing an optical ray-tracing model of light source geometries to maximize irradiance throughput for excitation-scanning hyperspectral imaging. Results show combining solid light guide branches have a compounding light loss effect, however, there is potential to minimize light loss through the use of optical claddings. This simulation data will provide the necessary metrics to verify and validate future physical optical components within the hyperspectral endoscopic system for detecting colorectal cancer.

Keywords: Endoscopy, Colonoscopy, Colorectal Cancer, Light Emitting Diode, Spectroscopy, Hyperspectral Imaging, Light Guides, Optical Pathways

1. INTRODUCTION

Lung and colorectal cancer are among the top three cancers in incidence and mortality rates, in the United States.[1,2] The aforementioned diseases are high risk yet we have the ability to visualize the organ in which they mutate and form. The limiting factor is how good are the scopes that are used for visualizing their respective organs? Studies viewing the colorectum documented limitations that include: low contrast of early stage or small lesions to the surrounding mucosa and the inability determine a lesions metastatic or invasive potential.[3,4] Pulmonology studies have similar detection results as gastroenterology when examining the main airways. The other major setback in detecting lung cancer is the inability to visualize the lung past the fourth bifurcation (peripheral lung).[5,6] Newer modalities have been developed for enhancement of visualizing these major organs including: chromoendoscopy (CE), narrow-band imaging (NBI), autofluorescence imaging (AFI), radial endobronchial ultrasound (R-EBUS) and optical coherence tomography (OCT).[5,7–9] Unfortunately, newer macroscopic imaging techniques (CE, NBI and AFI) show minimal improvements for detection accuracy and exterior scans for the peripheral bronchial tree are in the infancy stages of development. Optimal visualization of these organs and the detection of lesions is needed to be able to contrast normal tissue to abnormalities and determine the composition of those abnormalities (non-cancerous and cancerous, metastatic potential). We believe the answer to these imaging limitations is to incorporate hyperspectral imaging into the clinical endoscopic screenings.

Multiscale Imaging and Spectroscopy, edited by Paul J. Campagnola, Kristen C. Maitland, Darren M. Roblyer, Proc. of SPIE Vol. 11216, 112160W · © 2020 SPIE
CCC code: 1605-7422/20/$21 · doi: 10.1117/12.2545201

Hyperspectral imaging captures a two-dimensional spatial image over a range of wavelengths creating a hyperspectral image cube with each pixel having a specific spectra to show component spectral signatures.[10] The idea is the reflectance and/or fluorescent hyperspectral images of normal and abnormal tissues will have distinct spectral differences due to changes such as vascularization or metabolic deficiencies.[11–15] If these changes can be detected and visualized in real time this could aid the clinician in diagnosis prior to biopsy and pathology. Thus far, we have produced a prototype proof-of-concept solid light guide LED-based spectral light source capable of electronically cycling through multiple wavelengths providing the speed necessary for real time hyperspectral imaging. However, the initial prototype of multi-branched light guide which collimates the LEDs to one output has high transmission losses (~98%). This created a trade-off between spatial resolution and temporal resolution creating low quality images at only a moderate framerate (~8 fps) or a higher quality image with a longer acquisition time.[16–19] The current work focuses on determining a solid light guide design to increase the optical transmission allowing for improved spatial and temporal (higher framerate) resolution. The remainder of this article discusses the requirements of light guide and light source design and the optical simulations to determine the next best design for real time fluorescence hyperspectral imaging for endoscopy and bronchoscopy.

2. METHODS

2.1 Requirements for Redesigning a Multi-Branched Lightpipe

We have previously described a proof-of-concept spectral light source using LED-based illumination to incorporate into endoscopy. Gastrointestinal endoscopic procedures were chosen for the readily available resources and the use of larger illumination fibers to transmit the spectral light source. That said, this technology should also transfer into pulmonology and bronchoscopy, where we are working to accommodate the smaller cavities (airways vs. colorectum) and smaller tools. The prototype is able to cycle through wavelengths electronically and limited in speed only by the on/off time of the LEDs and the acquisition time and readout speed of the camera. However, in our initial prototype the collimation source, a multi-furcated solid light guide, did not transmit sufficient light to the distal end to allow short acquisition times (minimal light hits the detector during the time the shutter is open for the specified wavelength) to create a higher spatial resolution image. Reviewing the overall system, each individual component with the exception of the light guide has the power and speed to accomplish real time fluorescence hyperspectral imaging. Hence, the remaining research has focused on developing a collimation source to transmit the maximum amount of optical power to the output of the light source to maintain the efficiency of the other components in the system. To accomplish this, we need to define requirements prior to the fabrication and testing of a new collimation component in the spectral light source. The collimation source (solid light guide) will be modeled in an optical ray tracing software (TracePro, Lambda Research Co.) for geometry feasibility and a verification metric for future physical system testing. The main requirements for modeling to reflect physical outcomes are as follows: 1) The optical output of the spectral light source shall be a minimum of 10 mW per wavelength. 2) The optical output of the spectral light source shall have a numerical aperture equal to or less than that of the endoscope or bronchoscope interface. 3) Uniform optical power output should be maintained while cycling through wavelengths to achieve video rate speeds.

These requirements were reviewed for each model tested in TracePro. The simulation process varies one or more independent variables (e.g. arc length or wavelength illuminated) through a parametric sensitivity study. Every model traced 100,000 rays for each value of the independent variable. Individual LED packages were modeled by importing their respective angular and wavelength distribution as well as the power output. The solid light guides were modeled as optical grade acrylic. An irradiance map was produced of the detection surfaces showing the surface distribution of incident rays as an intensity plot and calculating the % transmission. The irradiance maps were normalized to the emitted flux of the LED. This process was repeated for every value of the independent variable for the entire cycle. The following sections outline the process in producing each model for a new geometry multi-branched solid light guide.

2.2 Modeling Solid Light Guide Branch Combinations

We have previously reported on the first phase of ray tracing models by creating single lightpipe bends and curves with iterative increases in the arc length of pipe (arc length is a function of the circumscribed angle and radius of a theoretical circle that the curve is a section of).[19] The results demonstrated that bends in the pipe provided insufficient transmission while pipe curvature provided a maximum of 50% transmission when the arc length was 100 mm or larger. Here, the data from Phase 1 was used to guide creation of the models for this Phase 2 study by merging two branches to a single output of the lightpipes. The two models produced were: a straight lightpipe merged with a curved lightpipe and a curved lightpipe merged with another curved lightpipe projected in the opposite direction (Figure 1).

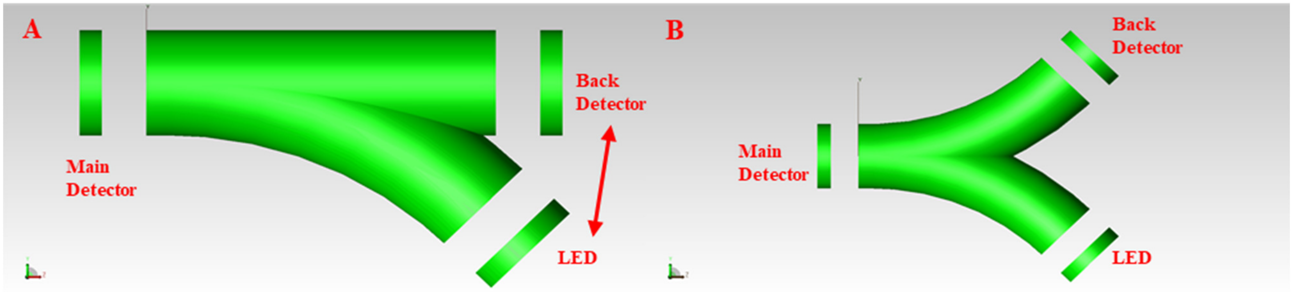

Figure 1: TracePro viewing window of the models used in simulation to observe the transmission of light through the merging of two lightpipes: (A) one with a straight lightpipe and curved lightpipe and (B) one with two curved lightpipes projected in opposite directions.

Each pipe diameter remained at 5 mm for consistency and for these models the arc length of the previously stated testing (Phase 1) was used in Phase 2. If merged with a straight pipe then the linear length was set equal to the arc length for the specified iteration and if both branches were curved, then the arc lengths were set equal, but in opposite directions. The percentage of light transmitted was measured at the output after the two pipes merged to become one and at the input of the branch not illuminated with the LED for light loss back through the light guide on a secondary detector.

2.3 Simulating a Multi-Furcated Solid Light Guide

Phase 3 of the ray trace model for the multi-branched solid light guide used the information from Phase 1 (single lightpipe curvature) and Phase 2 (merging two lightpipes together) to create a fully developed multi-furcated solid light guide. By the end of Phase 3 testing there were 8 versions of 3 different geometries of a multi-furcated solid light guide but for this reporting we will focus on one of the tests: a symmetrical light guide. The independent variables for these models were which branch of the light guide the LED was illuminating and what wavelength the LED was projecting. Branch one was always denoted as the bottom branch of the viewing window with the branch number increasing with every branch above. The LEDs were evaluated in order of increasing wavelength from 365nm to 980 nm. Optical properties were extracted and manufacturer datasheets and imported to TracePro as mentioned above. While similar, there were small variations in angular output of the irradiance patterns of the LEDs. This was to observe any changes in % transmission between branches and what wavelengths had better transmission. The wavelength iterations were not to "down-select" LEDs but to determine if one LED better transmits a wavelength through the material (optical acrylic) better than another.

The symmetrical design closely resembles the light guide produced for our proof-of-concept light source to see if an altered original design is feasible. This model collimates 16 branches with 4 merge points. The model was tested for transmission throughput after each of these major merge points to monitor the light loss with each addition of branching.

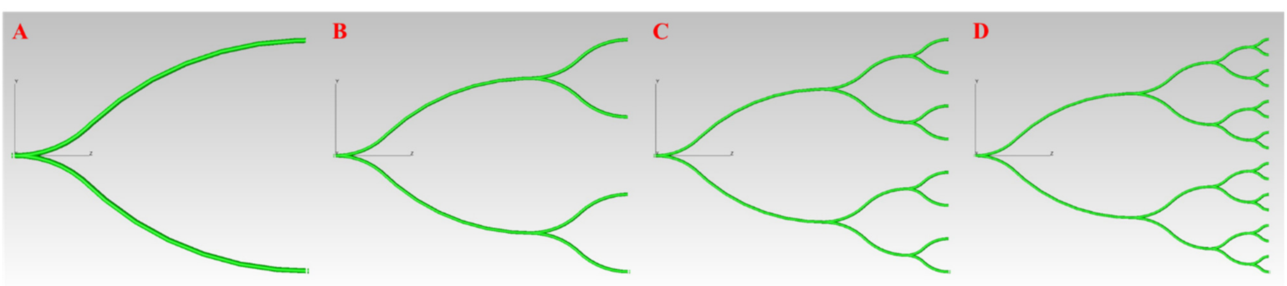

Figure 2: TracePro viewing window of the models used in simulation to observe the transmission of light through a multi-branched solid light guide. The change in transmission was monitored at (A) two branches, (B) four branches, (C) eight branches and (D) sixteen branches for light loss through merging branches.

3. RESULTS AND DISCUSSION

3.1 Phase 2 Ray Trace Modeling

Phase 2 modeling focused on the merging of two branches. One version merged a straight lightpipe with a curved light pipe (Figure 3.A-D) and the other merged to curved lightpipes projected in opposite directions (Figure 3.E-F). The ray trace data collected was the % transmission of through the merging of both branches to the output and detector. The straight and curved lightpipe merge illuminated both branches to see the difference where both curved lightpipes illuminated one because the second is mirrored and the results would be redundant. The % transmission was also collected on the opposite branch illuminated to measure the light loss. Figure 3 below shows the results for the main and back detector (% transmitted) for each of the three models.

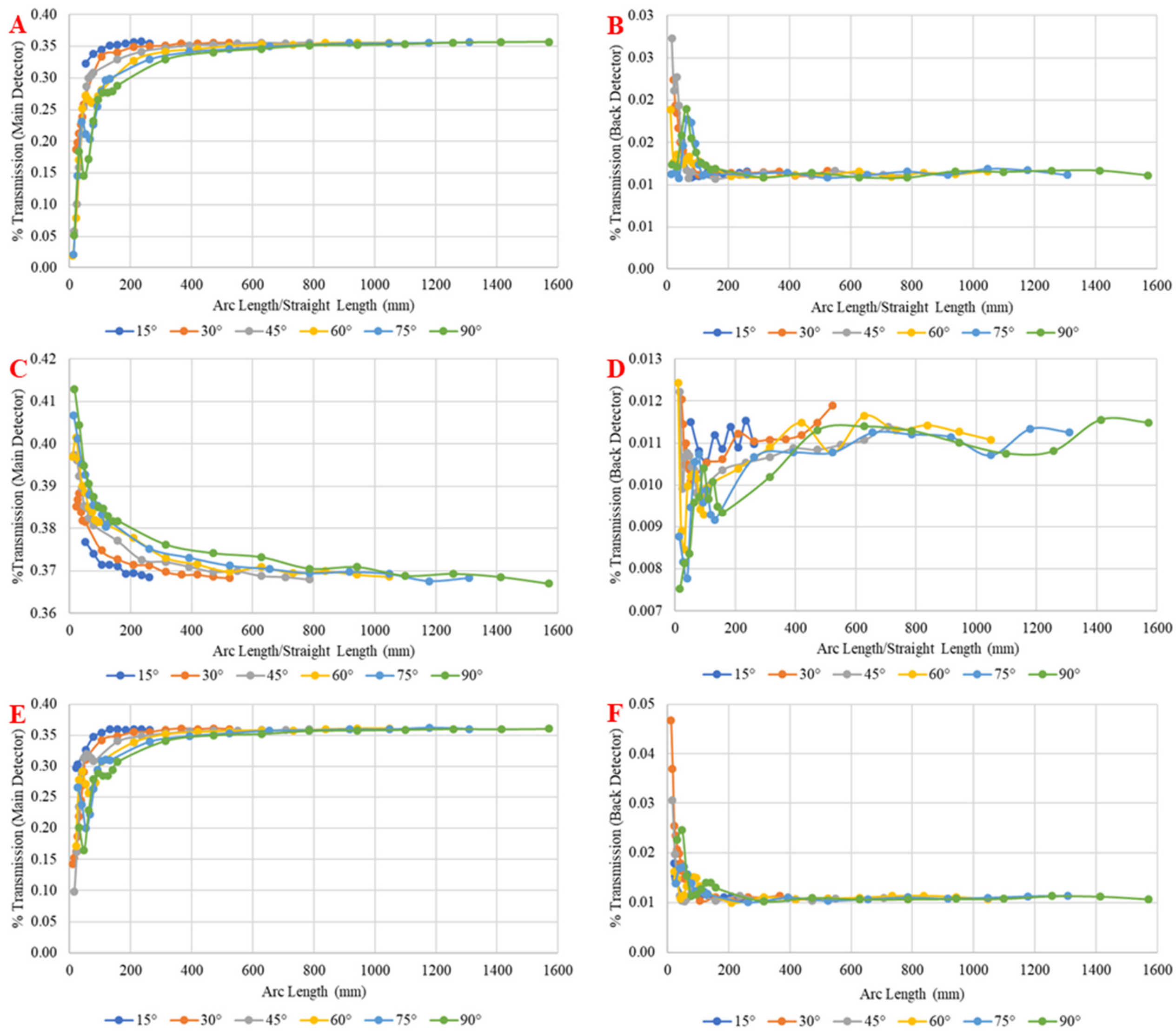

Figure 3: Comparison of the optical lightpipes: one straight-one curved and both curved in opposite direction models showing optical transmission as a function of % transmission vs. arc/total pipe length. (A) Results of the main detector of the one straight-one curved lightpipe with the LED on the curved branch over the range of arc lengths for each angle iteration and (B) the back detector. (C) Results of the main detector of the one straight-one curved lightpipe with the LED on the straight branch over the range of arc lengths for each angle iteration and (D) the back detector. (E) Results of the main detector of the both curved lightpipe with the LED on a curved branch over the range of arc lengths for each angle iteration and (F) the back detector.

The transmitted light through the merging of two branches resulted in an average of 10-40% transmission averaging 35% for the majority of the iterations. The higher transmission comes from illuminating the straight branch which stands to reason as it has the smallest change in geometry. Illuminating the straight lightpipe also has an inverse shape resulting in higher transmission with smaller arc lengths and illuminating the curved lightpipe transmits better with larger arc lengths. The light that transmits down the opposite branch shows minimal loss (1%), therefore, most of the loss comes from light refracting at the merging point. Overall, 35% transmission would be sufficient for our imaging applications, given a typical high-powered LED output of >200 mW. This knowledge along with the knowledge of curving a single lightpipe in two different directions (this places the input and the output in the same direction of the same plane[19]) provided the initial ideas for the multi-branched light guides of section 2.3 and the following sections.

3.2 Phase 3 Ray Trace Modeling

The symmetrical models were similar in design to our original prototype solid light guide.[19] This design would have the least amount of change from the original allowing for minimal redesign of the overall light source. Figure 4 below shows the results of the symmetrical design (Figure 2). The measurements were acquired at every merge point.

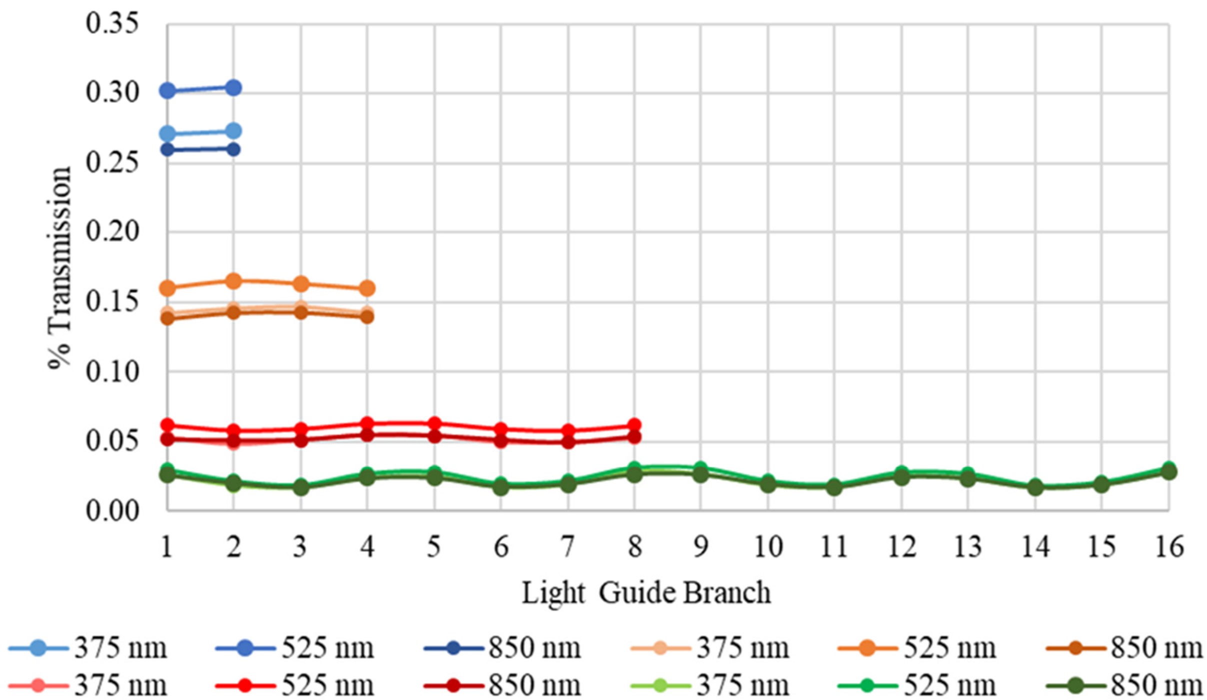

Figure 4: Symmetrical light guide showing optical transmission as a function of % transmission vs. branch illuminated. Results of transmitted LED light per branch for a 2, 4, 8 and 16 branch model over the range of LEDs. A UV, visible and IR wavelength LED were evaluated to show any optical transmission changes as a result of wavelength.

Figure 2 with merges at 2, 4, 8 and 16, demonstrated that doubling the number of branches reduced the transmitted light throughput by approximately 50%. The 2 and 4 branch models are the only ones to meet the optical power requirements with 15% and 30% transmission but these geometries do not provide sufficient spectral resolution for our hyperspectral method. We believe this is due so some of the branches merging with a large angle refracting the light. This could be overcome with larger, smoother curves but calculating the overall size was unrealistically large (1.2 m x 1.8 m). This inspired other geometries for a multi-branched solid light guide to potentially meet the requirements expressed above for achieving fluorescence hyperspectral imaging at video rate speeds.

4. FUTURE WORK

The majority of optical ray trace modeling is complete (not all documented here). We have developed 2 other collimating designs (3 in total) that are viable options to achieve real time fluorescence hyperspectral imaging.[20,21] For the completion of designing the multi-furcated solid light guide we will work with the current designs to evaluate which design has an optimal optical transmission. These tests will include evaluation of a lens for LED collimation prior to the light guide, modifying the light guide entrance geometry for better total internal reflection angles and changing the branch diameter to collect more light while remaining cognizant of numerical aperture requirements. These are future modeling studies to optimize one key component of the whole system. By integrating all optimized components, we will have an optimized spectral light source where we will begin testing for real time fluorescence hyperspectral imaging using LEDs. Testing will include system optical throughput, trade-off analysis in resolution (temporal, spatial and spectral) and hyperspectral data visualization and analysis to provide results in real time. These are the immediate steps in developing an endoscopic system that provides improved definition of lesions, and increased contrast in higher defined, higher contrasted screening solutions to aid clinicians in visualizing colorectal or lung cancer.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge support from the NASA/Alabama Space Grant Consortium, NASA Grant #NNX15AJ18H, NIH grant numbers UL1 TR001417, P01 HL066299, NSF grant number 1725937, the Abraham Mitchell Cancer Research Fund, the University of Alabama at Birmingham Center for Clinical and Translational Science (CCTS), and the Economic Development Partnership of Alabama. Drs. Leavesley and Rich disclose financial interest in a start-up company, SpectraCyte LLC, founded to commercialize spectral imaging technologies.

REFERENCES

[1] Siegel, R.L., Miller, K.D., and Jemal, A., "Cancer statistics, 2017," CA: A Cancer Journal for Clinicians 67(1), 7–30 (2017).

[2] Siegel, R.L., Miller, K.D., and Jemal, A., "Cancer statistics, 2019," CA: a cancer journal for clinicians 69(1), 7–34 (2019).

[3] Higashi, R., Uraoka, T., Kato, J., Kuwaki, K., Ishikawa, S., Saito, Y., Matsuda, T., Ikematsu, H., Sano, Y., et al., "Diagnostic accuracy of narrow-band imaging and pit pattern analysis significantly improved for less-experienced endoscopists after an expanded training program," Gastrointestinal Endoscopy 72(1), 127–135 (2010).

[4] Ignjatovic, A., Thomas-Gibson, S., East, J.E., Haycock, A., Bassett, P., Bhandari, P., Man, R., Suzuki, N., and Saunders, B.P., "Development and validation of a training module on the use of narrow-band imaging in differentiation of small adenomas from hyperplastic colorectal polyps," Gastrointestinal Endoscopy 73(1), 128–133 (2011).

[5] Andolfi, M., Potenza, R., Capozzi, R., Liparulo, V., Puma, F., and Yasufuku, K., "The role of bronchoscopy in the diagnosis of early lung cancer: a review," Journal of thoracic disease 8(11), 3329 (2016).

[6] Chen, W., Gao, X., Tian, Q., and Chen, L., "A comparison of autofluorescence bronchoscopy and white light bronchoscopy in detection of lung cancer and preneoplastic lesions: a meta-analysis," Lung Cancer 73(2), 183–188 (2011).

[7] Ignjatovic, A., East, J., Guenther, T., Hoare, J., Morris, J., Ragunath, K., Shonde, A., Simmons, J., Suzuki, N., et al., "What is the most reliable imaging modality for small colonic polyp characterization? Study of white-light, autofluorescence, and narrow-band imaging.," Endoscopy 43(2), 94–99 (2011).

[8] Chiu, H.-M., Chang, C.-Y., Chen, C.-C., Lee, Y.-C., Wu, M.-S., Lin, J.-T., Shun, C.-T., and Wang, H.-P., "A prospective comparative study of narrow-band imaging, chromoendoscopy, and conventional colonoscopy in the diagnosis of colorectal neoplasia," Gut 56(3), 373–379 (2007).

[9] Asano, F., "Advanced bronchoscopy for the diagnosis of peripheral pulmonary lesions," Respiratory investigation 54(4), 224–229 (2016).

[10] Leavesley, S.J., Annamdevula, N., Boni, J., Stocker, S., Grant, K., Troyanovsky, B., Rich, T.C., and Alvarez, D.F., "Hyperspectral imaging microscopy for identification and quantitative analysis of

fluorescently-labeled cells in highly autofluorescent tissue," Journal of biophotonics 5(1), 67–84 (2012).

[11] Favreau, P.F., Deal, J.A., Weber, D.A., Rich, T.C., and Leavesley, S.J., "Assessment of autofluorescent signatures in multiple tissue types with novel excitationscanning hyperspectral imaging," The FASEB Journal 30(1 Supplement), 51–1 (2016).

[12] Favreau, P.F., Hernandez, C., Heaster, T., Alvarez, D.F., Rich, T.C., Prabhat, P., and Leavesley, S.J., "Excitation-scanning hyperspectral imaging microscope," Journal of biomedical optics 19(4), 046010–046010 (2014).

[13] Deal, J.A., Favreau, P., Weber, D., Rich, T., and Leavesley, S., "Potential of Hyperspectral Imaging for Label-free Tissue and Pathology Classification," The FASEB Journal 30(1 Supplement), 51–2 (2016).

[14] Deal, J., Mayes, S., Browning, C., Hill, S., Rider, P., Boudreaux, C., Rich, T.C., and Leavesley, S.J., "Identifying molecular contributors to autofluorescence of neoplastic and normal colon sections using excitation-scanning hyperspectral imaging," Journal of Biomedical Optics 24(2), 021207 (2018).

[15] Leavesley, S.J., Walters, M., Lopez, C., Baker, T., Favreau, P.F., Rich, T.C., Rider, P.F., and Boudreaux, C.W., "Hyperspectral imaging fluorescence excitation scanning for colon cancer detection," Journal of Biomedical Optics 21(10), 104003–104003 (2016).

[16] Browning, C.M., Mayes, S., Favreau, P., Rich, T.C., and Leavesley, S.J., "LED-based endoscopic light source for spectral imaging," presented at SPIE BiOS, 2016, 97031I-97031I.

[17] Browning, C.M., Mayes, S., Rich, T.C., and Leavesley, S.J., "Design of a modified endoscope illuminator for spectral imaging of colorectal tissues," presented at Proc. of SPIE Vol, 2017, 1006015–1.

[18] Browning, C.M., Mayes, S., Rich, T.C., and Leavesley, S.J., "Endoscopic hyperspectral imaging: light guide optimization for spectral light source," presented at Multimodal Biomedical Imaging XIII, 2018, 104870H.

[19] Browning, C.M., Mayes, S., Deal, J., Arshad, A., Mayes, S.G., Parker, M., Rich, T.C., and Leavesley, S.J., "Sensitivity analysis of a multibranched light guide for real time hyperspectral imaging systems," presented at Multimodal Biomedical Imaging XIV, 2019, 1087107.

[20] Parker, M., Browning, C.M., Rich, T.C., and Leavesley, S.J., "Optimization of light transmission through an excitation-scan hyperspectral mirror array system," presented at Imaging, Manipulation, and Analysis of Biomolecules, Cells, and Tissues XVII, 2019, 108810O.

[21] Mayes, S.G., Mayes, S.A., Browning, C., Parker, M., Rich, T.C., and Leavesley, S.J., "A spherical mirror-based illumination system for fluorescence excitation-scanning hyperspectral imaging," presented at Imaging, Manipulation, and Analysis of Biomolecules, Cells, and Tissues XVII, 2019, 108810N.