Teaching optics and lasers in biomedical engineering

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Abstract

The development of a biomedical optics and laser curriculum at the University of Miami Department of Biomedical Engineering is presented. The objective of this curriculum is to provide students with a general knowledge of the principles of geometrical and physical optics, optical instrumentation, optical fibers and lasers, as well as a hands-on practical experience through laboratory sessions and individual projects. The ultimate goal is to give biomedical engineering students the ability to understand the principles of medical optical instruments and laser systems, and sufficient knowledge and practical experience to be able to design and operate basic optical and laser systems for biomedical applications.

1. Introduction and Objectives

Although light has been used in medicine and biology since ancient times, and optical instruments, such as microscopes and endoscopes, have been available for more than a century, biomedical optics has developed into a field of its own only in recent years, significantly spurred on by the development of lasers and optical fibers. Medicine was one of the first major applications of lasers, and today there is probably no field of medicine or biology which does not employ optics and lasers in some form. Biomedical optics is now an important and growing field of biomedical engineering. In the past 4 years, the creation of 2 dedicated peer-reviewed journals (*Journal of Biomedical Optics, Applied Optics - Optical Technology and Biomedical Optics*) in the US alone, attest to this. The growing market represented by the biomedical optics industry is also evidenced by the creation of new professional magazines, such as *Biophotonics International* in 1994.

Biomedical optics can be divided into two major sub-fields: diagnostics and therapy. Optical and laser diagnostic techniques include, for instance, microscopy, endoscopy and spectroscopy. Optical therapeutic techniques are mostly laser techniques related to surgery. Today lasers are used extensively for clinical interventions in many fields, including general surgery, plastic and reconstructive surgery, urology, dermatology, ophthalmology, cardiovascular surgery, oncology, gastro-enterology, ear nose and throat surgery, and gynecology. Optics and lasers are on the leading edge of minimally invasive therapy and diagnostics.

As optics and lasers play an increasingly important role in biomedical sciences, biomedical engineers and scientists will most likely have to use, maintain, and/or design optical and laser systems or instruments for modern medical practices on a day to day basis. In such a situation, a knowledge of optics and lasers will be not only an asset but also increasingly a requirement.

These considerations led us to the creation of a two-semester biomedical optics and laser course for undergraduate (junior and senior years) and graduate students at the Department of Biomedical Engineering, University of Miami, starting in the Fall of 1991.

The objective of these courses is to provide students with a general knowledge of the principles of geometrical and physical optics, optical instrumentation, optical fibers and lasers, as well as a hands-on practical experience, through laboratory sessions and individual projects. Medical applications and engineering aspects are emphasized both in the class and projects. The ultimate goal is to give biomedical engineering students the ability to understand the principles of medical optical instruments and laser systems, and sufficient knowledge and practical experience to be able to design and operate basic optical and laser systems for biomedical applications.

2. Description of the curriculum

From 1991 to 1995, the curriculum was divided into one semester of lectures, taught during the Fall, with practical design projects assigned to interested students in the Spring semester. Starting in the Fall of 1996, the class was expanded into two one-semester classes taught in the Fall and Spring semester to increase the number of topics covered and the depth of coverage, allow for more examples of medical applications, and increase the number of laboratory sessions. Evaluation of the curriculum (student placement, student evaluations, performance of graduating students) is currently ongoing.

2.1. Classes

Each of the two biomedical optics classes currently consists of approximately fifteen 75-minute lectures covering principles of geometrical optics, fiber optics, optical instruments, tissue optics, physical optics and lasers, and their direct medical application (fig. 1). Aspects of laser safety, design and surgical ease of use are also stressed, and practical aspects of current medical practice are illustrated with reference to procedures used in the University of Miami hospitals and clinics. Each class also includes six laboratory sessions that typically demonstrate principles taught in class or their practical application (fig. 2).

2.2. Design projects

Design projects are offered to students that have taken one of the two classes. These projects can be undergraduate Senior Design Projects (2 semester duration) , graduate Independent Studies, or Special Projects (BME 547). In these projects, the students conduct experiments or theoretical studies on specific aspects of biomedical optics, or design basic optical setups (Fig. 3). Each student is expected to write a report and present the results of his project during a full day symposium held annually on biomedical optics and related applications, organized specifically for this purpose at the University of Miami.

BME 545: **Biomedical optical instruments (Fall semester)**
Introduction to geometrical optics and fiber optics with emphasis on engineering and design aspects and medical applications. Visual optics. Medical optical instruments (microscopes, endoscopes, ophthalmic instruments). Laboratory.

BME 546: **Medical Applications of Lasers (Spring semester)**
Review of geometrical and fiber optics. Introduction to physical optics and laser physics and technology with an emphasis on engineering aspects. Medical laser systems. Tissue optics. Laser-tissue interactions. Applications of lasers in medicine. Laboratory.

BME 547: **Special Projects in Biomedical Optics and Lasers**
Individual design projects in biomedical optics and lasers. Design of biomedical optical instruments. Experimental and theoretical studies of laser-tissue interactions. Studies of the optics of the eye.

Figure 1: Biomedical Optics Course Listing (University of Miami)

BME 545 Laboratories

Geometrical optics

Mounting of optical components - Law of refraction - Total reflection
Image formation by a lens
Measurement of focal length- Measurement of transmission

Basic optical systems

Laser beam expansion and focusing - Beam steering

Fiber optics

Fiber cleaving and polishing - Laser to fiber coupling
Fiber-optic illumination system - Fiber optic delivery system
Measurement of fiber transmission

BME 546 Laboratories

Interference/Diffraction

Measurement of speed and displacement with a Michelson interferometer
Spatial filtering

Lasers

Measurement of laser beam divergence and intensity distribution
Laser delivery systems

Tissue optics - Laser interactions

Measurement of transmission and reflection with an integrating sphere
Measurement of collimated transmission - Laser tissue ablation

Figure 2: Example of basic laboratory experiments

Undergraduate design projects (2 semesters)

Measurement of the refractive index of biological tissue
Fiber-optic delivery system for high power lasers
Fiber optic delivery of an ophthalmic Q-switched Nd:YAG laser
Construction of a fiber-optic interferometer
Corneal thickness measurement by low-coherence interferometry
Measurement of laser ablation depth with a confocal optical system
Design of a diffusing optical fiber for medical laser delivery
Design of a miniature ophthalmic fiber-optic delivery probe using GRIN lenses
Evaluation of the Photon Inc. beam profiler

Graduate projects (1 semester)

Calculation of cell kill during laser thermal therapy of breast cancer
Measurement of pressure transients during in vitro laser litothripsy
Analytical model for subablative thermal laser tissue-interaction
Experimental diode laser hyperthermia with the MAMTAT system
Optical models of the eye using BEAM 4

Figure 3: Examples of typical student design projects (1993-1999)

2.3. Undergraduate laboratory

Even though the laboratory sessions included in the classes significantly enhance the students' understanding and provide an initial practical experience, an evaluation of the students enrolled in design projects after taking the classes demonstrates that the practical experience acquired in the laboratory sessions is not sufficient to allow the students to independently tackle optical systems or solve optical design problems in practice, which is an ultimate goal of the curriculum.

To improve the curriculum, we are currently developing an undergraduate laboratory in biomedical optics (NSF ILI grant #DUE-9751369). In addition to classical teaching experiments on optics, fiber optics and lasers, the laboratory will be used to teach undergraduate students how to solve representative design problems in medical optics and laser applications, with an emphasis on medical laser and light delivery systems and laser-tissue interactions.

The laboratory is currently used for design projects, to teach the practical sessions of the two optics classes, and also to provide a first experience of biomedical optics and lasers to freshmen students as part of an Introduction to Engineering class (BME 112), and to 11th and 12th grade students from the Dade County Laboratory Internship Program. A laboratory course on biomedical optics that will serve as a practical yet instructional introduction to optics, fiber optics, lasers and their application in the medical sciences is currently being developed.

3. Limitations and challenges

3.1. Background knowledge in optics and lasers

Currently, one of the main limitation of our curriculum, and biomedical optics curricula in general, is that most biomedical engineering students do not have a sufficient initial knowledge of optics or lasers to be able to understand even basic design considerations for a biomedical application. This can be compared, for instance, to having to teach biomechanics to advanced undergraduate biomedical engineering students that have no background knowledge of mechanics other than what is covered in undergraduate physics courses. Consequently, a significant section of the classes must be used to cover basic general principles of optics and lasers rather than topics and applications specific the biomedical sciences. This is necessary, so that applications in medicine, biology and surgery can be more fully understood.

It is expected that the undergraduate laboratory classes will provide for background knowledge and initial practical experience that many undergraduate students in biomedical engineering are currently missing. Transferring introductory lectures from the current classes to the proposed laboratory classes will enable us to cover a wider range of practical applications of optics and lasers in medicine. Alternatively, the necessary background knowledge in optics could also be provided by listing an undergraduate optics course as a pre-requisite. However, such a course is often not available, even in a physics department.

3.2. Broadness of topics

Another problem in designing a biomedical optics and laser curriculum, is that a large number of topics must be covered for the curriculum to be complete. The ideal curriculum on biomedical optics would cover at least the following topics in some detail:

1. Background
   Geometrical optics - Optical design - Wave optics - Emission/ Absorption / Spectroscopy - Lasers and Light sources - Light detectors - Fiber optics
2. Biomedical Optical Instruments
   Microscopy - Endoscopy - Other optical instruments
3. Optical diagnostics
   Tissue optics - Optical imaging - Tissue spectroscopy - Opto-chemical sensors - Biometrics
4. Laser surgery
   Laser-tissue interactions - Laser delivery systems - Clinical laser applications
5. Regulatory issues
   Safety - FDA regulations

Covering all these topics while providing sufficient depth and examples relevant to biology and medicine would probably require at least 4 semester-long classes, which is more than what can be integrated in a regular undergraduate biomedical engineering curriculum. Therefore, biomedical optics curricula typically focus on a limited number of topics, that are usually related to the research interests of the faculty teaching the courses (1). In our curriculum, a number of additional topics that are not discussed during regular class hours are covered in 5 to 10 minute long presentations that each student is required to make on a biomedical optics topic of his choice during the last lecture, or last two lectures of the semester.

3.3. Teaching materials

One of the problems that was encountered when the curriculum was initially developed, is that there is currently no single textbook available for teaching biomedical optics and lasers at an undergraduate or graduate level. General undergraduate and early graduate optics textbooks usually cover the basic principles of geometrical and physical optics, and sometimes mention optical fibers and lasers (2-4). More specialized and engineering-oriented textbooks usually cover only one specific field, such as optical design, laser theory and engineering, physical optics, or fiber optics (6-10) at an advanced level. As optics applications have also become increasingly important in electrical engineering, especially in telecommunications, a large proportion of the recent textbooks emphasize electro-optics, opto-electronics, and fiber optics, with little or no coverage of geometrical optics (10-12).

Many specialized monographs have been written on medical applications of lasers, or on specific topics of medical optics (13-19). However, these books are generally reviews or references aimed at physicians and researchers, physicists, or engineers in a specific field, rather than instructive texts for undergraduate students. In addition, optical instrumentation not based on laser sources is usually neglected. Some of these books may be used as textbooks for graduate classes (18, 19). To our knowledge, only one undergraduate level textbook on biomedical optics, focusing on optical fibers and laser applications, has been written (20). Instructional materials for laboratories or classes in biomedical optics are currently available on the World Wide Web (21). We are currently using class notes that were developed specifically for our two classes, or adapted from notes that were prepared by Dr. Rol for undergraduate and post-graduate engineering courses in Switzerland.

As optics and lasers have become important tools of biomedical engineering, a comprehensive undergraduate textbook of biomedical optics and lasers is needed.

4. Conclusion

Biomedical optics is an important and growing field of biomedical engineering. In this paper, the development of a Biomedical Optics Curriculum at the University of Miami is presented. An increasing number of biomedical engineering programs have recently developed, or are currently developing, similar courses in biomedical optics or laser medicine. Given the rapid development of medical laser applications and optical diagnostic and imaging techniques, as well as the trend toward minimally or non-invasive therapy and diagnostics, biomedical optics may soon become an integral part of many undergraduate biomedical engineering programs, much like optical communications or optoelectronics in electrical engineering curricula. However, biomedical optics covers a much wider range of topics and applications than optical communications, which is concerned mainly with optical systems using single mode optical fibers or optical waveguides, semi-conductor light sources and optical detectors. Developing an exhaustive curriculum and teaching materials for biomedical optics is therefore a much more challenging task.

5. Acknowledgments

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Duncan - Optics in Biomedical Engineering. an effective bias frequency of 50 kHz before it was passed to the processing electronics. The reason for matching the refractive index of the working fluid to that of the compliant cast is twofold.Â Light from a linearly pola-rized helium-neon laser was formed into a slit and passed transversely through the arterial cast at the sites of in-terest by means of a cylindericallens and beam-expander optics. The silhouette of the cast cross section was pro-jected onto the 512-element detector array. To put the images of the internal and external sides of the cast wall within the dynamic range of the camera, the light in-tensity was adjusted by changing the orientation of a pol-arizer placed immediately in front of the camera. The development of a biomedical optics and laser curriculum at the University of Miami Department of Biomedical Engineering is presented. The objective of this curriculum is to provide students with a general knowledge of the principles of geometrical and physical optics, optical instrumentation, optical fibers and lasers, as well as a hands-on practical experience through laboratory sessions and individual projects.Â Milne, P., & Rol, P., & Parel, J., & Mann, F. (2000, June), Teaching Optics And Lasers In Biomedical Engineering Paper presented at 2000 Annual Conference, St. Louis, Missouri. 10.18260/1-2--8858. Ã—. APA. 'Educators in Biomedical Optics and Biophotonics have been long awaiting a comprehensive text to accompany their teaching in this rapidly growing field and this is as good as it gets. Educators may have their own bias, but this text provides a balanced approach giving due weight to the topics within the field and covering them comprehensively for most undergraduate and graduate courses in the field â€¦Â Irving Bigio is Professor of Biomedical Engineering and Electrical Engineering at Boston University. His research activities address the interactions of light with cellular and tissue structures on the microscopic and mesoscopic scales. Applied Spectroscopy. Biomedical Optics Express. Chinese Optics Letters. Current Optics and Photonics.Â Laser-induced fluorescent visualization and photodynamic Feature Issues View All. Polarization and Orbital Angular Momentum of Light in Biomedical Applications (2021) Submission Opens: 1 October 2020; Submission Deadline: 31 March 2021 Igor Meglinski, Tatiana Novikova, and Kishan Dholakia. Translational Photoacoustic Imaging for Disease Diagnosis, Monitoring, and Surgical Guidance (2021) In Progress Jun Xia, Muyinatu Bell, Jan Laufer, and Junjie Yao. Biophotonics (2020) Published Rainer Leitgeb, David Sampson, Regine Choe, Kevin Eliceiri, Christine Hendon, and James Tunnell. Biomedical optics & imaging. Imaging tools to better understand the brain. The Akkin Lab develops non-contact optical imaging tools to study tissue structure and function, with an emphasis on better understanding the brain. Non-invasive or minimally invasive applications in medicine are possible, because the techniques use back-scattered light. Non-invasive imaging for cancer therapy. The Ashkenazi Lab develops high-resolution imaging devices and techniques that combine laser, fiber optics, and ultrasound technologies. The team developed a unique method for non-invasive imaging of tissue o