BROAD-SPECTRUM OPTICAL BLOOD MONITORING

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ABSTRACT:

The goal of this project is to design, build, and calibrate a robust spectroscopy-based non-invasive arterial blood monitoring system (ABMS) and to evaluate its performance for concept validation. Commercially available units evaluate dual-wavelength transmission in determining oxygen saturation; the proposed use of a white light source and spectrophotometer will expand the implementation of optical techniques to a many-wavelength system capable of simultaneously monitoring several blood constituents, such as carboxyhemoglobin, bilirubin and glucose. Software tools will be implemented in: 1) interfacing with the spectrometer; 2) performing digital filtering in real-time; and 3) analyzing the data mathematically and visually. The project will build on previous work in the department done by Corinne Bright ’98, Mark Tong ’99, and Jonathan Lee ‘03 [1],[2], [3].

Keywords: oximetry, broad-spectrum spectroscopy, optical, noninvasive methods, glucose, bilirubin, carboxyhemoglobin

ABBREVIATIONS

ABMS – Arterial Blood Monitoring System
COHb – carboxyhemoglobin
HbO_2 – oxygenated hemoglobin; oxyhemoglobin
LED – light-emitting diode
PaO_2 – Partial pressure of oxygen
PLS – partial least squares
PPG – photoplethysmogram
RHb – deoxyhemoglobin; reduced hemoglobin
R/IR – red-to-infrared signal ratio
SaO_2 – oxygen saturation
VIS-NIR – Visible-near infrared light

TERMS

bilirubin – reddish yellow water insoluble pigment occurring in bile and blood and causing jaundice if accumulated in excess
carboxyhemoglobin (COHb) – formed when CO bonds to hemoglobin. Elevated COHb saturation results in carbon monoxide poisoning.
deoxygemoglobin (RHb) - hemoglobin with no bound oxygen; reduced hemoglobin
dyshemoglobins – hemoglobins where molecules other than oxygen have bonded to the heme carrying groups; dysfunctional hemoglobins; dysfunctional hemoglobins
in vivo – within the human body
in vitro – outside the human body, in an artificial environment
glucose – optically active sugar, composed of aldehylic carbonyl group, accounting for assimilation of carbohydrate in animals. Glucose blood levels must be monitored carefully for patients of diabetes.
hemoglobin – iron-containing respiratory pigment in red blood cells consisting of a globin composed of four subunits, each linked to a heme submolecule, that functions in oxygen and carbon dioxide transport after conversions between deoxyhemoglobin and oxyhemoglobin in the lungs
hypoxia – condition of inadequate oxygen supply to tissues to maintain metabolic activity
oximetry – determination of blood/tissue oxygen content, generally through optical means
oxyhemoglobin (HbO_2) – hemoglobin with bound oxygen; oxygenated hemoglobin
oxygenated hemoblogin (HbO_2) – see *oxyhemoglobin*
pulse oximetry – determination of oxygen saturation of pulsatile arterial blood by radiometric measurement of tissue optical absorbance curves
reduced hemoglobin (RHb) – see *deoxyhemoglobin*

1. INTRODUCTION

Prevailing methods in blood monitoring require the invasive procurement of blood samples using a needle or skin-prick for *in vitro* analysis. Beyond inherent patient discomfort, the inconvenience and processing time requirements of such procedures constitute the primary drawbacks of existing technology. This in turn inhibits continuous real-time monitoring and results in barriers to enhanced control of critical blood constituents. For example, a closed-loop system for monitoring glucose levels and automated insulin delivery for diabetes patients has long been envisioned, but the invasive nature of glucose monitoring precludes realization of any such system. Dependence on invasive techniques, with its many drawbacks, inhibits the efficient and tight control of this and other blood constituents.

The basic approach behind optical noninvasive methods is to pass light through a vascular region of the body. Blood constituent concentrations can then be extracted from the spectral information of the transmitted beam. Given its completely noninvasive nature and the aforementioned drawbacks of current methods, and with rapid advancements in biomedical technology, the noted potential of optical methods for accurate and continuous determination of micronutrient concentration in real-time continues to invite considerable interest, and the successful development of non-invasive micronutrient monitors would represent a major advancement in the treatment and management of such conditions.

Most commercially available optical blood monitoring systems measure the transmission of narrow-band LED and laser diode emissions optimized at specific wavelengths for oximetry analysis. The specialization of these systems consequently limits their application to oxygen saturation. Utilization of a broad-spectrum VIS-NIR light source and spectroscopy-based analysis, however, would expand these capabilities to include the simultaneous analysis of a wider set of frequencies, and thus, a larger set of blood constituents. Research geared towards the detection of carboxyhemoglobin, bilirubin and glucose for carbon monoxide poisoning, infant jaundice and diabetes mellitus applications, respectively, receives the most attention from the private sector due to the considerable social demand for such tools [4]. The purpose of this project is to design and build a robust, broad-spectrum, spectroscopy-based noninvasive system for the optical monitoring of multiple blood constituents. The proposed system would combine the multiple appeals of noninvasive *in vivo* blood monitoring with multifunctional convenience and cost efficiency.

The project will include the complete design process, from product research to prototype development and documentation, of an Arterial Blood Monitoring System (ABMS). I will need to select a light source capable of transmitting light across the visible and near-infrared regions with a roughly flat power spectrum, program a computer-spectrometer interface capable of taking scans at about 20 Hz, design a sensor array for capturing the transmission spectrum, and design and implement digital filtering, signal processing, and mathematical algorithms for extracting micronutrient concentrations from the transmission spectrum. An additional goal is to ensure robustness in facilitating future development, thus necessitating that the final design will need to be well documented. The final product will be a fully functional and thoroughly tested prototype with complete documentation.

A technical discussion including realistic constraint considerations (§1), project plan (§3), and a discussion of qualifications and costs (§4 and §5) follow this introduction.

2. TECHNICAL DISCUSSION

2.1 Transmission pulse oximetry: principles

The appeal and widespread implementation of pulse oximetry lies in its completely noninvasive nature, its continuous and real-time application, and its ease of use. Development of oximetry-based methods requires theoretical and practical knowledge in a variety of fields. Assessment of expansion to broad-spectrum, spectroscopy-based applications should begin with a discussion of existing oximetry techniques, which serve as the baseline for design, and inherent limitations.

• Basic physical and biological principles

The foundation of pulse oximetry relies on two primary principles: 1) that light absorbance of oxygenated hemoglobin (HbO_2) differs from that of reduced (oxygen-deprived) hemoglobin (RHb) at red and infrared wavelengths, and 2) that absorbance at both wavelengths includes an AC component reflecting fluctuations in arterial blood volume between the light source and the transmission detector. Pulse oximetry techniques and design follow from these two facts [5].

Hemoglobin is a porphyrin ring containing four subunit oxygen carrying proteins. The loading and unloading of oxygen from hemoglobin changes the coordination number of the iron compound and alters the electron distribution. This redistribution results in different light absorption in the two states, which can be noted visually through observable color differences between the oxygen-deprived deoxyhemoglobin (RHb) and oxygen-rich oxyhemoglobin (HbO_2). HbO_2 will absorb short wavelengths and appear bright red, whereas RHb will absorb longer wavelengths and appear a darker red [2]. This discrepancy in light absorption serves as the basis for the first principle behind optical detection of oxygen saturation through the transmission of two wavelengths: red (?=600 nm) and near-infrared (?=940 nm). The ratio between the concentrations of deoxygenated blood and oxygenated blood is proportional to the ratio of red light absorption to near-infrared light absorption, and Lambert-Beer's Law can be used to extract absorbance information from transmission spectra. This proportionality is then used to compute arterial oxygen saturation.

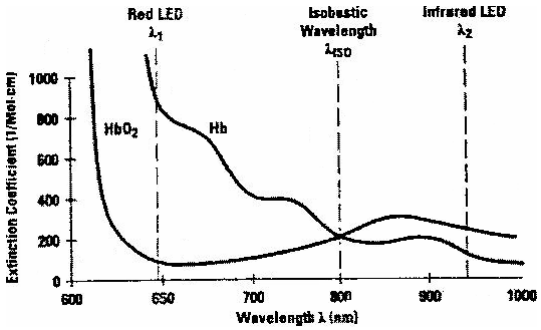


Figure 1: Extinction coefficients (E) for oxygen-rich (HbO_2) and oxygen-deprived (RHb) hemoglobin. Since $E \mu A$, the graph gives a proportionate representation of the absorption spectra for oxyhemoglobin and deoxyhemoglibin.[6]

• ***Lambert-Beer's Law and oxygen saturation in hemoglobin***

Light of intensity of I_0 passing through an absorbing medium emerges with intensity I. Ignoring scattering and reflecting of light from surfaces, the Beer-Lambert Law states that the relationship between the two, at a given wavelength, will follow the relationship:

$$I = I_0 e^{-ecd}, \qquad \text{(EQ. 1)}$$

where e is the molar absorptivity, or molar extinction coefficient (L/mol-cm), d is the distance traveled by the light (cm), and c is the concentration of the absorbing medium (mol/L). The expression can be re-written in the form

$$ecd = \ln(\frac{I_0}{I}) = -\ln(\frac{I}{I_0}) = A \qquad \text{(EQ. 2)}$$

where A is the absorbance, a dimensionless quantity defined as the natural logarithm of the ratio with the transmitted intensity over the incident intensity. A spectrophotometer can be used to obtain spectra as plots of absorbance versus wavelength. For a specific molecule or ion, this plot gives the characteristic spectrum of that particular molecule or ion [7]. For a mixture, however, Lambert-Beer's Law then states that the total absorbance of a mixture of elements with varying absorbencies is the sum of the individual absorbencies. Therefore, total absorbance at wavelength ? can be expressed as

$$A_l = e_{l1}c_{l1}d_{l1} + e_{l2}c_{l2}d_{l2} + \cdots + e_{ln}c_{ln}d_{ln}, \qquad \text{(EQ. 3)}$$

where each ecd term corresponds to the absorbance contribution of each element. For the specific case of pulse oximetry, there are three relevant elements: 1) oxyhemoglobin, 2) deoxyhemoglobin, and 3) all other elements at two wavelengths: 1) red, and 2) infrared. Equation 3 can be written for this specific application as:

$$A_l = e_{ld}c_{ld}d_{ld} + e_{lo}c_{lo}d_{lo} + e_{lx}c_{lx}d_{lx} + A_{lc}, \qquad \text{(EQ. 4)}$$

with d representing the contribution from deoxyhemoglobin, o representing the oxyhemoglobin contribution, x representing the contribution from all other elements, and the c term as the emitter/detector constant. As the last two terms can be assumed to remain constant, time derivatives written as the ratio between the rates of change for absorbencies of red and NIR light reduce as follows:

$$ratio(\frac{R}{IR}) = \frac{dA_{l(R)}}{dA_{l(IR)}} = \frac{-d\ln(\frac{I_R}{I_0})/dt)}{-d\ln(\frac{I_{IR}}{I_0})/dt} = \frac{\Delta I_R / I_{IR}}{\Delta I_{IR} / I_{IR}} = \frac{e_{R_0}c_o + e_{R_d}c_d}{e_{IR_0}c_o + e_{IR_d}c_d} \qquad \text{(EQ. 5)}$$

The saturation of oxygen can then be determined using this ratio and a calibration curve. Oxygen saturation (SaO_2) is defined as the percentage of oxyhemoglobin to the sum of oxyhemoglobin and deoxyhemoglobin (note that any hypothetical presence of dyshemoglobins such as carboxyhemoglobin,

methemoglobin and sulfhemoglobin are neglected in this expression). This can be written in terms of the equations defined in the Beer-Lambert Law as

$$SaO_2 = \frac{c_0}{c_0 + c_d}, \qquad \text{(EQ. 6)}$$

which in turn can be written in terms of the R/IR ratio as

$$SaO_2 = \frac{e_{R_d} - e_{IR_d}(R/IR)}{\left(e_{R_d} - e_{R_0}\right) - \left(e_{IR_d} - e_{IR_0}\right)} \qquad \text{(EQ. 7)}$$

This expression serves as the basis for deriving oxygen saturation from the ratio of red to infrared transmission intensities.

Software tools developed by Catherine Choi and Corrinne Bright simplified Equation 7 in terms of AC and DC light intensities for determining SaO_2. Normalizing AC components by DC components, the software tools implemented the empirical equation:

$$\frac{R}{IR} = \frac{I_{R_{AC}} / I_{R_{DC}}}{I_{IR_{AC}} / I_{IR_{DC}}} \qquad \text{(EQ. 8)}$$

From this, oxygen saturation can be determined by applying a standard linear calibration curve of the function $SaO_2 = (a-bR)/(c=dR)$, where a-bR and c-dR are of the standard linear equation y=mx+b and m=R. The calibration curve used by Corinne Bright is shown below.

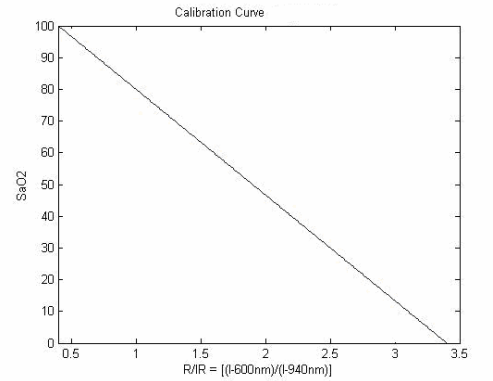


Figure 2: Calibration Curve for converting R/IR ratio into SaO_2 [1]

• Arterial pulse considerations

The second principal driving modern pulse oximetry techniques incorporates considerations necessary due the nature of the signal from an arterial pulse. Pulse oximetry makes use of the fractional change in light transmission during an arterial pulse at the red and IR wavelengths. Spectrometer data across a finger will incorporate an AC component, attributed to variations in artery size during arterial wall contraction, and a DC component, which results from interaction with other

material through which the light passes, such as skin and tissue. Also, the magnitude of these signals will vary from user to user.

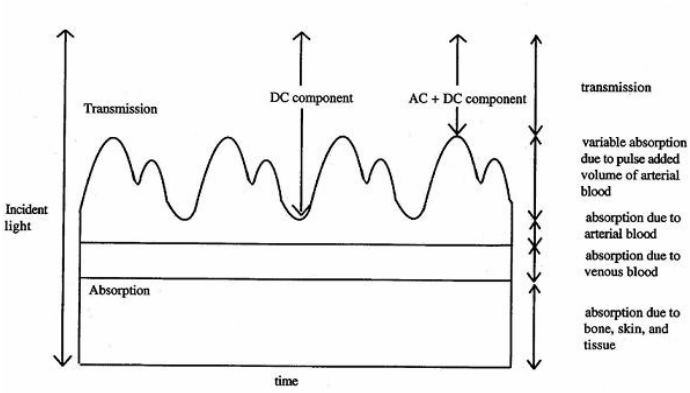


Figure 3: Light transmission in a vascular bed. The AC component is the arterial pulse signal (roughly 1 Hz) and is used to determine SaO_2.[1]

While hemoglobin is the strongest absorbing molecule in the blood, most of the total attenuation is due to light scattering and the opacity of the human finger. Pulse oximetry makes use of the graphical display of red and infrared signals, or photoplethysmogram (PPG) to calculate oxygen saturation. The pulsatile arteries in the vascular bed, through constant contraction and expansion, modulate the light absorbance and produce a characteristic PPG waveform. While the amplitude and pulsatile component of the two waveforms differ, they share an almost identical shape which can therefore be used for the determination of oxygen saturation.

2.3 Known limitations of pulse oximetry

While noninvasive optical analysis represents a noteworthy advance in patient monitoring, the inherent limitations of pulse oximetry should be reviewed before extending the application to simultaneous multi-constituent monitoring due to the reliance that may be placed on information derived from an ABMS.

1. *Dyshemoglobin interference.* The primary functional weakness of the two-wavelength design lies in its limitation to the discrimination of only two species. High concentrations of other constituents with similar absorption properties presents a source for inaccuracy. Of particular concern are dyshemoglobins such as carboxyhemoglobin (COHb) and methemoglobin (MetHb), whose structural relation to RHb and HbO_2 result in similar light absorbance at oximetery wavelengths. Such interference causes readings to remain high even when the patient is hypoxic [8].

2. *Poor performance for low perfusion.* A normal pulse waveform is necessary for good pulse oximetry performance. However, situations such as hypothermia, hypotension, or the administration of vasoconstrictor drugs alter the arterial pulse characteristics and interfere with oximeter performance [9]. Patients with a history of vascular disease may also receive less accurate readings from pulse oximetry.

3. *Motion artifacts*. Disruption to the collection of PPG due to motion will result in inaccuracies in SaO_2 analysis. Care must therefore be taken to ensure that the probe is securely fastened to the skin and motion is minimized.

4. *Nonlinearity of the hemoglobin-oxygen dissociation curve*. The typical adult hemoglobin-oxygen dissociation curve is both nonlinear with decreasing slope and in virtually flat for high values of PaO_2 (see Figure 4). This characteristic shape suggests that attempts to relate SaO_2 with PaO_2 by linear regression, as is often the case in patient monitoring, meet serious difficulty in this range [5]. This implies that the pulse oximeter will generally fail to provide early warning of falling PaO_2 in contexts such as the operating room.

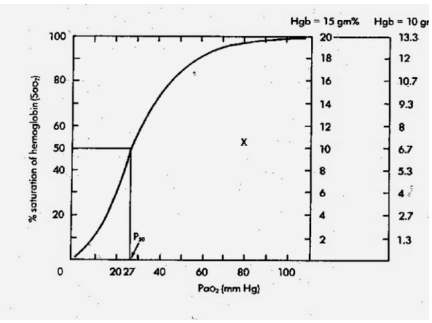


Figure 4: Typical adult hemoglobin-oxygen dissociation curve: arterial saturation plotted against oxygen partial pressure (PO_2).

2.4 Extension to simultaneous evaluation of multiple blood constituents

The next theoretical consideration is the feasibility of non-invasive optical monitoring methods in the determination of arterial carboxyhemoglobin, bilirubin and glucose. Extensive investigation of available literature is planned, pending the arrival of additional materials requested through inter-library loan (ILL).

• Carboxyhemoglobin

Carboxyhemoglobin monitoring, or CO-oximetry, represents the most natural extension of pulse oximetry. The COHb dyshemoglobin occurs when carbon monoxide instead of oxygen binds to the hemoglobin subunits, thus reducing the arterial oxygen transport and resulting in carbon monoxide poisoning. The similarities in molecular structure and absorption spectra are often cited as possible causes for error in pulse oximetry. However, these characteristics also purport that an extension of pulse oximetry to a three-wavelength module may feasibly be implemented in simultaneous determination of RHb, HbO_2, and COHb.

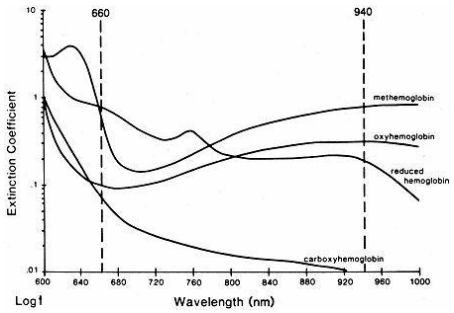


Figure 5: Absorbance spectra for oxyhemoglobin; deoxyhemoglobin; carboxyhemoglobin; and metHb. The vertical dotted lines indicate the wavelengths used in pulse oximetry.[10]

• Bilirubin

Absorption spectroscopy methods for determining bilirubin levels have been developed for the treatment of bilirubinemia [11]. Hyperbilirubinemia, common in neonates, is the accumulation of bilirubin because the liver has not yet developed enzymes for oxidizing bilirubin. Increased levels of cutaneous bilirubi case jaundice, or in extreme cases, will result in bilirubin precipitation into the brain, causing kernicterus, or permanent brain damage.

Commercial systems are currently manufactured by SpectRx, Inc and Minolta [12]. One method for measuring cutaneous bilirubin levels depends on measuring the reflectance of light off skin. The reflectance spectrum is then used to determine the absorption coefficient, which is proportional to bilirubin concentration [13]. Thus, given a white light source, a spectrophotometer, and reflectance sensors, the system can be expanded to include a bilirubin determination module.

• Glucose

Noninvasive methods for monitoring glucose saturation, essential in the treatment of diabetes, include absorption spectroscopy, polarimetry, raman spectroscopy, and fluorescence monitoring [4]. Attempts to monitor arterial glucose concentrations *in vivo* using absorption spectroscopy have met considerable difficulty, and the analytical feasibility of glucose determination remains ambiguous [14]. However, a number of promising analytical tools have been developed in the *in vivo* measurement of glucose by near-infrared (NIR) spectroscopy through partial least squares (PLS) regression and Fourier filtering [15], [16]. These concepts will also be explored with greater rigor pending the arrival of materials requested through ILL.

2.5 Design process

The next step in the project involves the design of the Arterial Blood Monitoring System involves investigation of system components (light sources, spectrometers, optical fiber, and optical sensors) relative to known constraints and defined design goals. Broadly defined, the primary design goals include:

1. *Accuracy and Proof of Concept.* The ABMS should output constituent concentrations within an acceptable range of error. Oxygen saturation readings can

be easily compared with the commercial oximeter available in the lab. Methods for validating glucose and bilirubin levels will need to be developed.

2. *Robustness*. Given the interest the project both within and beyond the department, and the growing demand for noninvasive biotechnologies, a design facilitating future research would enhance the long-term potential and outlook for the project and is thus highly desirable.

3. *Ease of use.* In addition to increasing the longevity from the research standpoint through a robust design, the outlook for development would be enhanced through considerable ease of use on the part of the user. As a critical component of the design goals for any eventual product, we well retain this goal even within the formative context of the project.

A more refined understanding of recent work in noninvasive monitoring is essential to the design process. I have been researching relevant literature, and will focus on determining parameters for component selection including spectrometer wavelength range and resolution, light source spectrum characteristics, attenuation of optical fiber, and sensitivity of optical sensors. Cost and time constraints must also be considered. Primary issues and areas of knowledge central to the design process include:

1. *Spectrophotometer properties.* Selection and configuration of a spectrophotometer will be subject to careful consideration of design needs. Current models offered by Ocean Optics being considered will need to be configured for grating (which affects groove density, spectral range, and resolution) and entrance aperture size, and the need for additional components such as a collimating lens, will be evaluated according to design goals. The Ocean Optics models offer portability and preexisting high-speed sampling capabilities[17]. Another option being considered is the potential use of the CVI Digikrom 240 monochrometer in the Optics and Photonics Laboratory, which would offer a better range than the Ocean Optics models, but would not be portable and would have to be evaluated in terms of the feasibility of high-speed sampling.

2. *Light source properties*. A light source will also need to be selected after careful consideration of design needs. The light source will need to cover the visible and near-infrared areas of the electromagnetic spectrum, with as close to a flat spectrum as possible. This is the primary concern, as light sources are rarely designed with frequency spectrum in mind, and even less often through visible and infrared regions. In addition, the light source will need to be of ample power to deliver enough photons to the finger so that the transmitted intensity may be quickly evaluated by the spectrometer while being careful not to expose the user to unnecessary radiation. Attenuation through the finger was found to be on the order of 10^3, thus providing a rough benchmark for light source power requirements.

3. *Software considerations*. Central to the design of the prototype system is knowledge of the Ocean Optics operating software and signal processing tools such as MatLab and LabVIEW, as software development will provide the means for data acquisition and concentration determination. Software is also the main design area

where robustness must be constantly considered, as it is the area with the greatest potential for further research and expansion.

4. Signal to noise (S/N) ratio. Transmission signals, and the importance of accuracy and precision in collecting spectrum, are essential to the viability of pulse oximetry. In addition, generally weak IR signals in broad-spectrum light sources enhance the importance of S/N ratio considerations for the proposed project.

5. ***Trade-offs between configuration and design parameters.*** Trade-offs among important design parameters such as spectrometer frequency range versus resolution, light intensity versus required power input, quality of components versus cost, and speed versus accuracy will be an essential portion of the design process.

2.6 Preliminary Design

The primary design considerations lie in the selection of a light source and any necessary circuirtry, the design of a photodetector array and sensor circuitry, which includes amplification, filtering, and demultiplexing, and software development in LabVIEW. The first step in design will be to attempt to reproduce prior documented designs and to evaluate their performance.

• Broad-spectrum light sources

The primary concerns are sufficient power for rapid spectrophotometer readings and that a relatively flat spectrum across the VIS-NIR section.

While much of the hardware and software design will initiate with reproduction and assessment of previous work, lesser prior success in the search for an appropriate which source necessitates more thorough research into the various options available. Below are the primary sources currently under consideration:

2.5.1a. Quartz Halogen Lamp

The Optics and Photonics Lab houses a Dolan-Jenner quartz halogen lamp (Fiber Lite 3100). The lamp is strong at the visible spectrum but weak at infrared wavelengths. Its spectrum appears below:

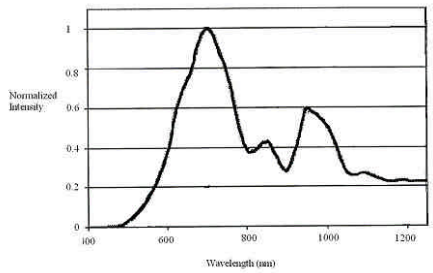


Figure 6: Frequency Spectrum for Fiber-Lite 3100 (quartz halogen) lamp. Adapted from Tong, 1999.

2.5.1b. Deuterium Tungsten Halogen Lamp

Deuteriem Tungsten Halogen lamps combine the continuous spectra of Duterium and Tungsten Halogen light sources. Such sources provide ample fower across the VIS-NIR spectrom (roughly 500-1000 nm) and are available commercially from Ocean Optics but come at a considerable cost.

The following is the frequency spectrym for an Ocean Optics Deuterium-Tungsten-Halogen lamp:

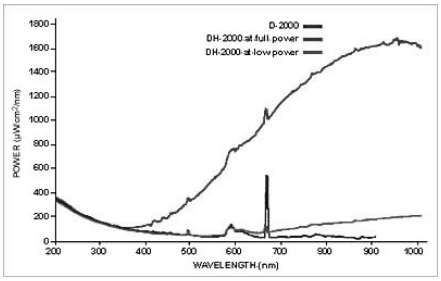


Figure 7: Frequency Spectrum for Ocean Optics DH2000 (Deuterium-Tungsten-Halogen) lamp. [18]

2.5.1c. Light-Emitting Diode

The use of red and infrared LED sources in pulse oximetry applications has been previously explored within the department [3]. Several forms of white LED are commercially available. One form is made of a composite RGB chip and has a frequency distribution with three sharp peaks at 450 nm, 530 nm, and 640 nm. The serious fluctuation in power across the spectrum thus renders this type of LED of little interest.

A second variety, invented by the Nichia Corporation, uses a blue LED (typically InGaN) coated with YAG phosphors. The blue emission excites the phosphors which then produce a broad yellow light, and the two combine to form a white light. An extended variety, produced by Lumileds, double coats the blue LED. The spectra of the two appear below:

Single coating

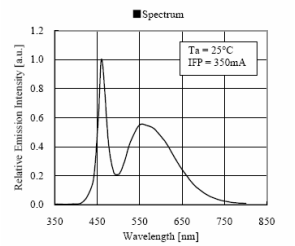


Figure 8a: Spectrum for Nichia NCCW022T (Chip Type White LED) [19].

Double coating

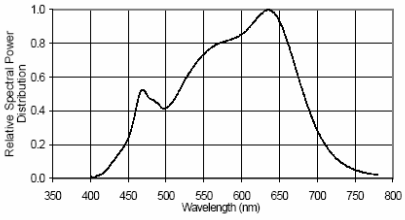


Figure 8b: Spectrum for Lumileds Luxeon Star (power source "bright white" LED) [20]

While the spectrum for the LED appears broad, they are designed for power efficiency across the visible range (400 nm to 800 nm) and do not emit in the IR range. Potentially, a second LED could be used in conjunction to provide the full range.

2.5.1d. Xenon Flash Lamp

Xenon flash lamps are often used in spectrophotometers and in *in vitro* diagnostics as they produce instant high-power white light. While they do not provide continuous illumination and instead pulsate at a controllable, they do provide a continuous spectrum across the UV-VIS-IR spectrum (roughly 200 nm – 2000 nm).

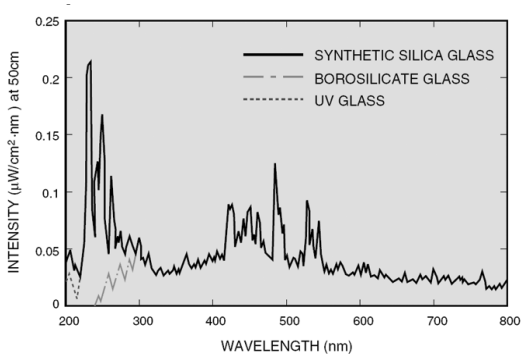


Figure 9: Spectrum for Hamamatsu L2187 Xenon Flash Lamp (UV-VIS region only) [21].

• Photodetector/sensor and signal processing circuitry

Necessary for the implementation of a full prototype is the design of amplification and filtering circuitry for the photodetector. Any use of a pulse design will also necessitate timing, pulsing and dempltiplexing circuitry. Design will generally be approached first through the evaluation of past designs. After producing working duplicates of past departmental designs, the designs will be modified to meet the specific needs of the current application.

• Software development

As with the necessary electronic circuitry, in-house oximetry software will be first examined and the modified for compatibility with the new spectrometer and its operating software and with any LabVIEW upgrades. The filtering capabilities of current in-house code will also be examined and enhanced. Finally, these software tools will be expanded to include other modules beyond pulse oximetry.

2.7 Design constraints and practical considerations

An analysis of inventory and impact addressed the following realistic design constraints and practical considerations:

1. *Economic.* Despite the considerable cost of system components, such as the Ocean Optics S-bench spectrometer and white light sources, cost demands will not exceed economic constraints placed upon the project.

2. *Manufacturability.* All materials will be either purchased off the shelf or made in the machine shop at Swarthmore. Thus, given the low fabrication requirements, ABMS assembly from component parts should be relatively straightforward and of minimal time and cost.

3. *Environmental.* The overall goals of concept proof do not involve fabrication, combustion or significant waste disposal and therefore pose no environmental threat. Furthermore, the system prototype presents no pollutant or radiation threat to its surroundings. The ABMS, within its current conceptual context as well as in future development, pose no significant environmental sustainability concerns.

4. *Sustainability.* Given the relatively short time frame involved, there will likely be no equipment retirement due to ageing for the duration of this particular project.

A hypothetical life cycle analysis of the design, development, operation and disposal of the ABMS, with components selected, will forecast the use of materials over the course of the project. Initial costs include a PC workstation, a diffraction grating spectrometer, a broad-spectrum light source, fiber-optic cables, a Teflon cuff, an A/D conversion board and software development tools, and the life-cycle of these components and the cost of replacement dictates sustainability concerns of an eventual product. A final product would have a life-cycle determined by the life of the white light source and the fiber-optic light source.

5. *Ethical.* There are no foreseeable unethical applications of the product. Widespread and uncontroversial use of commercial oximeters, and the similarity of the ABMS in function and application, supports this claim.

6. *Health and safety.* The current context of the ABMS remains that of concept proof and validation. Following further development, any future commercial production for use in medical practice must follow extensive and rigorous validation testing beyond the scope of that which will be performed here. Also, the limitations of optical noninvasive monitoring (§2.3) must be considered when making medical decisions based on oximetry data.

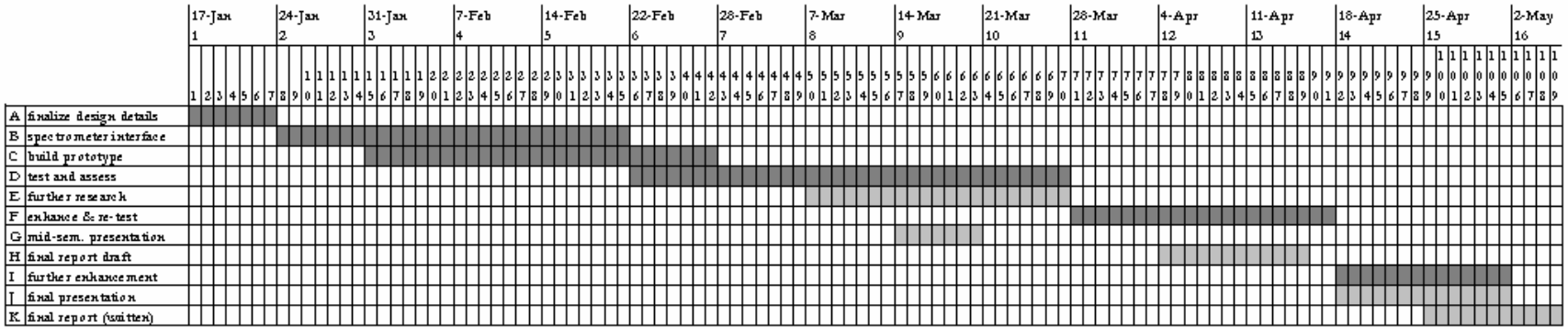
7. *Socio-political.* The considerable costs of various system components (§5) raises concern regarding per-unit cost and overall healthcare expenses. The multifunctional inclusion of several constituent saturation determination modules, however, and the social benefits of noninvasive blood analysis in patient comfort, safety, and prospects for development of closed-loop control offsets such concerns.

3. PROJECT PLAN

Task areas are summarized below:

Task areas	***Objective***	***Approach***	***Output***
Research and design	To come up with a model that is relatively simple to build, yet satisfies the general design goals	Research glucose and bilirubin techniques, determine necessary data processing algorithms	An ABMS design that satisfies general design goals
Choosing primary components	To choose appropriate light source and spectrometer.	Selection of components based on properties, availability and price.	Selection of materials that meet practical needs yet make for a robust design
Obtaining components	Obtain necessary materials in time, preferably at low cost	Compile relevant department inventory; determine feasible means of obtaining all additional and necessary components.	Materials
Build computer-spectrometer interface	Communication between computer and spectrometer at a speed of roughly 20 Hz	Determine communication interface of spectrometer, adjust protocol for high-speed sampling.	Control of spectrometer from PC, high-speed data transfer from spectrometer to PC
Build first prototype	Functional ABMS based on design specifications	Determine order of assembly and workspace requirements, and build component by component	A working prototype
Prototype testing and assessment; further research	Verifying design parameters and potential applications	Take data and assess results,	Results and plan for improvement
Modifying the prototype	To improve the prototype	Modify design: re-configure old components or design and build new ones	An improved prototype
Re-test	To observe and justify improvements	Test ABMS	Understanding operation of the ABMS
Write report and presentation	To document the project	Write report (include weekly progress reports) and prepare a talk	A report and a presentation

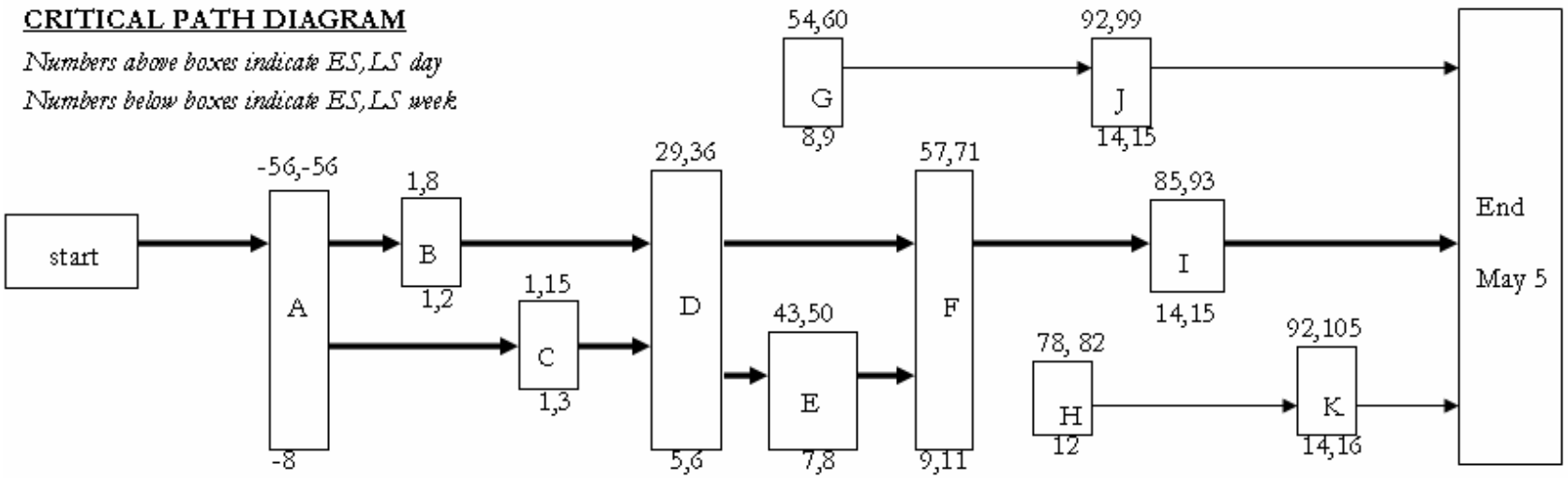
MILESTONE CHART



CRITICAL PATH DIAGRAM

Numbers above boxes indicate ES,LS day

Numbers below boxes indicate ES,LS week



4. PROJECT QUALIFICATIONS

Completed coursework and continued research in the specific application area will provide the necessary analytical and design tools for the completion of this project. Relevant coursework includes E15, E71, E72, E75, and E78. Completion of a directed reading in optics, and continued personal interest in optics and optoelectronic communication systems, will add to these qualifications.

5. PROJECT COSTS

The primary costs associated with the project will be the system components. These definitely include a light source, optical fiber, and optical sensors, and possibly include a new commercial spectrometer and a new finger cuff. A projected itemized expense report appears below, with upper bounds of estimated costs, appears below:

Item	Description	Amount
White Light Source	Broad-spectrum light source containing visible to near-infrared frequencies for transmission of light through finger cuff	$500
Ocean Optics USB2000 User-Configured Spectrometer *	Portable, pre-configured spectrometer with efficiency > 30% at 300-1100 nm range for collection of light transmission data	$2,500
Finger Cuff	Teflon cuff to stabilize finger position during light transmission and data collection	TBD
Optical Fiber	Fiber for delivery of white light from source to Teflon cuff	TBD
Optical Sensors	Sensors for collection of transmitted light intensity data	TBD

The necessary technical assistance required will be sought from Grant 'Smitty' Smith, the department's machinist, Professor Erik A. Cheever, Ph. D., and Professor Lynne A. Molter, Sc.D. Time requirements for assistance will include weekly consultation. There are no financial costs associated with their assistance, as they are respective faculty and staff members within the department.

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