CHAPTER 7

CONCLUSION
AND
FUTURE WORK

7.1 Conclusion:

This thesis proposes a new technique named as modulated ultrasound combined with infrared light-based technique for *in-vitro* measurement of blood glucose concentration in optically active tissue phantoms. The significant conclusions of the present work are as follows:

- The *in-vitro* examination by modulated ultrasound and infrared light-based technique of different human blood samples mixed with Intralipid^{TM} phantom samples provides clinically significant and acceptable results.
- The light transmission phenomenon gets influenced by the concentration of blood glucose levels in *in-vitro* samples. It identifies that with increase in glucose levels in dextrose (glucose) mixed Intralipid^{TM} phantom sample causes least scattering effects, consequently shorter optical path lengths and this phenomenon decrease the absorption properties, which thus causes increased light transmission effects and vice-versa. In our *in-vitro* investigations, the correlated effect has-been-observed in FFT domain signal analysis. The peak amplitude in FFT domain varies in correspondence to the glucose concentration in *in-vitro* phantom samples.
- The peak amplitude variations in FFT domain is the functional indicator for analysis of blood glucose level encoded information and it is very useful to analyze the real blood glucose levels in different human blood mixed Intralipid^{TM} phantom samples. Henceforth, this characteristic facilitates us in performing the calibration and preparation of look-up table for conversion of the peak amplitude in FFT domain to its corresponding Blood Glucose Levels.
- Our modulated ultrasound and infrared light-based technique has been capable to measure changes in glucose levels during the different investigation stages such as fasting, postprandial, random stage respectively. This technique additionally recognizes glucose dose induced alteration in blood glucose levels in the subject samples as revealed during our *in-vitro* examinations.
- In this present work, *in-vitro* experimental work proves the suitability of 40 kHz frequency based ultrasound transmitter and the infrared light emitting diode of 940 nm for significant determination of glucose concentration in *in-vitro* samples.

- Total *in-vitro* examination as reported in previous chapter (5) of this present thesis includes examination over 187 (male = 138 and female = 49; in which normal healthy subjects = 93 and diabetic subjects = 94) adult study subjects, that acquired total 520 data pairs of reference and predicted blood glucose levels. Further, in paired data set of 520, the corresponding reference blood-glucose range has been 60-300 mg/dl.
- The *in-vitro* examination of different types of human blood samples with our indigenously developed technique over healthy normal and diabetic subjects for blood glucose estimation yielded promising results. Our developed prototype detection levels of blood glucose from 60 mg/dl to 260 mg/dl, which is acceptable for clinically significant level.
- *In-vitro* examinations depicted that in different phantom mediums utilized such as water, commercialized milk, chicken breast tissue and whole blood sample, the peak amplitude varies in accordance with sample glucose-concentration levels.
- Different statistical performance assessment including Pearson Correlation Coefficient (R-Value), Standard Error of Prediction, Mean Absolute Error, Median Absolute Error, Root Mean Squared Error, Percentage of Mean Relative Absolute Error, and Percentage of Median Relative Absolute Error thoroughly revealed that our modulated ultrasound and infrared light-based technique is better than or comparable with other developing blood glucose measuring techniques for noninvasive blood glucose monitoring. Further, the results akin with published data ranges of other developing glucose monitoring technique. Further, to investigate the results accuracy more-statistical analysis were-performed. The parameters including Deming Regression analysis, Paired sample t-tests, CUSUM test for linearity, Mountain Plot, Bland-Altman Plot, Clarke and Parkes Error Grid analysis thoroughly revealed that our modulated ultrasound and infrared light-based technique based blood glucose estimations are statistically significant.
- The experimental study presented in this thesis provides a new methodology using Intralipid^{TM} based tissue phantom for development of noninvasive blood glucose measurement using amplitude modulated ultrasound and infrared light based techniques. Promising *in-vitro* results have-been-obtained using the

developed system. Further for improving accuracy, the other factors like skin pigmentation, melanin content of skin, tissue and skin contours, pressure dependent variation in blood flow, finger positioning alignment schemes are also needed to be considered for design and development of Intralipid^{TM} based finger phantoms. Investigation and experimentation related to these points will-be-considered in our future research work.

7.2 Recommendations for future work:

This present thesis work provides the experimental results obtained by modulated ultrasound and infrared light based technique. The present thesis performs *in-vitro* investigation using modulated ultrasound and infrared light to measure blood-glucose levels in *in-vitro* phantom mixed samples. The results are promising; however, certain future works needs to be-incorporated for further developments in this field. Such improvements are as follows:

- For the specificity and sensitivity factors of the prototype, large number of calibration to prediction *in-vitro* experiments needed to be-performed. Hence there is need for conducting large number of *in-vitro* experimental studies using different human blood samples (including blood plasma, blood serum and whole blood) mixed with Intralipid^{TM} phantom samples for developing the noninvasive blood glucose-measurement technique.
- In present work *in-vitro* experimentation has been carried out using Intralipid^{TM} phantom mixed blood samples in the range of 60 mg/dl to 300 mg/dl of glucose levels, for evaluating the performance of the proposed technique, further studies for level 300 mg/dl and above are needed to be done.
- In this present work, all the results are-based on peak-to-peak amplitude change in FFT domain according to the blood glucose levels present in the human blood mixed with Intralipid^{TM} phantom samples respectively. Further, in future experiments, time and frequency domain based parameter estimations can also be investigated.
- Other phantom medium such as gelatin, agar and polyester can also be tried and test for measuring blood glucose levels *in-vitro* samples.
- Application of our proposed technique can also be carried out for other blood component and parameter analysis.

Our results indicates that amplitude modulated ultrasound and infrared light based technique has been efficient in measuring blood glucose concentration in *in-vitro* samples of blood plasma, blood serum, whole blood respectively.

Further, our technique proves to be efficient in determining glucose concentrations in different types of tissue optical phantoms that include dextrose mixed water samples, dextrose mixed commercialized milk samples, chicken breast tissue dipped in dextrose solution, and dextrose mixed whole blood samples respectively.

Hence, modulated ultrasound and infrared light-based technique will prove to be a potential methodology for noninvasive blood glucose monitoring in the near future.