Summer Internship Project

on

VOLUME FLOW ANALYSIS USING DOPPLER ULTRASOUND SCAN

Submitted by

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ABSTRACT

Doppler Ultrasound is a non-invasive method used to image tissue and obtain information about blood flow. Perforator flaps are used in reconstructive surgeries and the healthiest tissues are preferred. Such tissues can be identified by studying the blood flow in the region of interest. Spectral information from Doppler Ultrasound can be used to estimate the velocity of the blood flow. The healthiest perforator is identified from the volumetric flow to have the largest diameter, and it can be estimated by studying the energy of the Doppler shift audio from the Continuous Wave Doppler Ultrasound.

CONTENTS

1. INTRODUCTION

Arterial perforators are the branching patterns from the arteries which supplies muscle and the overlying skin. Types of perforators are musculocutaneous, sept cutaneous and cutaneous. For this purpose, acoustic dopplers are being used in preoperative, intraoperative and postoperative procedures. Over the past several decades, a variety of technological advancements have provided surgeons with tools that have facilitated the ability to perform autologous reconstruction. The very first tool was acoustic doppler ultrasound. The acoustic doppler enabled surgeons to understand the vascular anatomy relevant to a reconstructive procedure. The handled acoustic doppler can be used as a sole modality for preoperative, intraoperative and post-operative assessment of perforators in flap reconstruction.

A Doppler ultrasound is a test that uses high-frequency sound waves to measure the volumetric blood flow through arteries and veins of a person. Many conditions are commonly diagnosed using Doppler Ultrasound. Such conditions include aneurysms, blood clots, heart valve defects, narrowing of the arteries, health issues of an unborn fetus, and more. The Doppler Ultrasound utilizes the concept of the Doppler Effect. In a typical ultrasound, millions of pulses and echoes are sent and received each second. The Doppler shift is observed on the receiving end and is mapped on a frequency spectrum.

Doppler Ultrasound is a preferred method since it is a non-invasive technique to provide information about blood flow including flow rate and velocity. Color Doppler scanners are devices that have their own processors and displays that process and show the necessary results, but these devices are expensive and bulky and cannot be used in places like the operating theatre all the time. Handheld Dopplers are good alternatives in such cases. Handheld Dopplers are portable and inexpensive. However these hand held dopplers can produce only sounds generated by the perforators and indicates only the presence or absence of the perforators and it does not give sufficient information as in color doppler. Velocity can be obtained from the spectral information. The data that is provided by the Handheld Doppler can be studied and used to determine the location of a healthy perforator. To find such healthy perforators, the spectral information, velocity and energy of the signal are analyzed.

2. BASIC PRINCIPLES AND PHYSICS OF DOPPLER EFFECT

The Doppler effect describes a phenomenon in which a change in the frequency of sound emitted from a source is perceived by an observer when the source or the observer is moving or both are moving. The reason for the perceived frequency change for a moving source and a stationary observer is illustrated in Figure 2.1. In Figure 2.1(a) , the sound source S, is stationary and producing a uniform spherical spreading of the wave and the frequency of the sound perceived by an observer is f = c/λ, where c is the velocity of sound in the medium and λ is the wavelength.

In diagram (b), the sound source is moving to the right at a velocity v. The source motion changes the distance between the crests, increasing frequency and decreasing the wavelength to the right and decreasing the frequency and increasing the wavelength to the left. The frequency perceived by an observer on the right is

$$f' = \frac{c}{\lambda'} = \frac{c}{\lambda - vT} = \frac{c}{(c-v)T} = \frac{c}{c-v} f$$

and the frequency seen by an observer on the left is

$$f' = \frac{c}{c+v} f$$

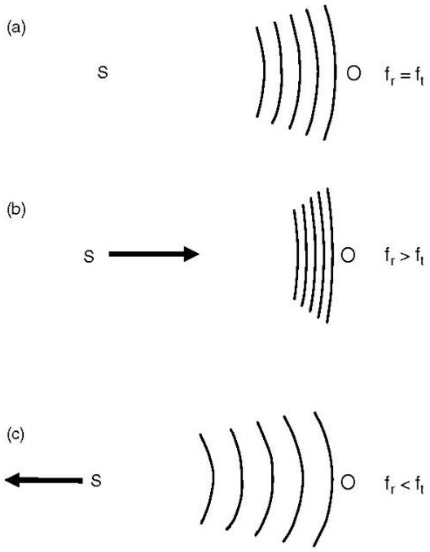


Figure 2.1: *Doppler Effect*

The difference between the actual frequency of the source, f, and the perceived frequency, f ′, is called the Doppler frequency, fd. A similar relationship can also be obtained for a moving observer. When combining these relationships, for a source moving with a velocity v and an observer with velocity v′, the Doppler frequency can be found to be given by:

$$f_d = f' - f = \left(\frac{c+v'}{c-v} - 1 \right) f \qquad (2.1)$$

If the source and the observer are moving at the same velocity, v, assuming that c >> v, then Equation (2.1) can be reduced to:

$$f_d = \frac{2vf}{c} \qquad (2.2)$$

For the situation in which the velocity is making an angle of θ relative to the direction of sound propagation, as shown in Figure 2.1(b), v in Equation (2.2) should be replaced by v*cosθ:

$$f_d = \frac{2v(\cos\theta)f}{c} \qquad (2.3)$$

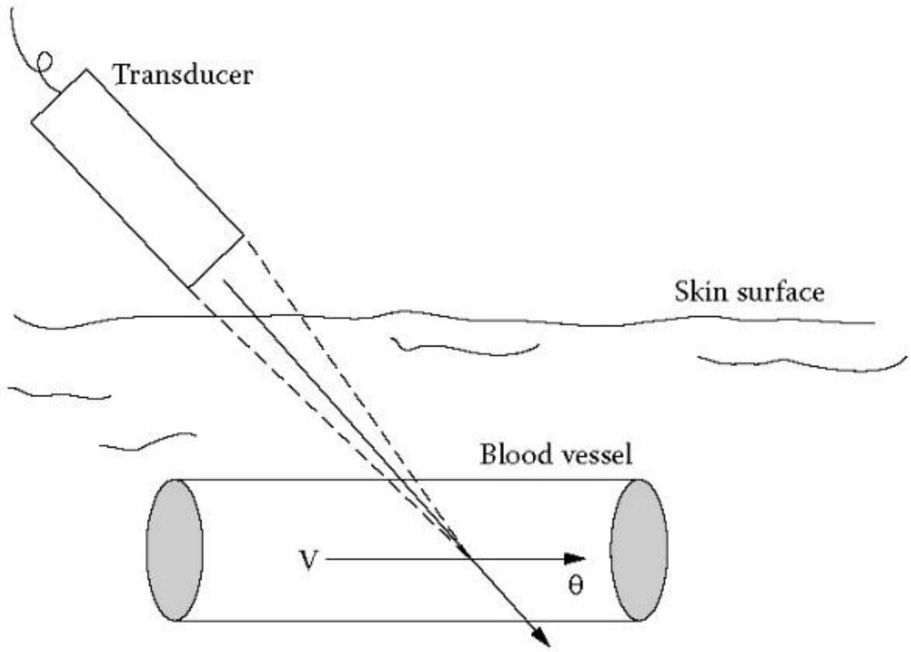
3. DOPPLER ULTRASOUND INSTRUMENTATION

The Doppler effect provides a unique capability for ultrasound to measure blood flow. Upon insonification by an ultrasound beam, the echoes scattered by blood carry information about the velocity of blood flow. Blood flow measurements are frequently performed in a clinical environment to assess the state of blood vessels and functions of an organ. Ultrasonic Doppler instruments allow a measurement of instantaneous blood flow velocity. Combined with pulse–echo instruments, instantaneous flow rate in a blood vessel as a function of time and cardiac output can be measured noninvasively with ultrasound.

Figure 3.1 shows an ultrasound beam of frequency ***f*** insonifying a blood vessel making an angle of θ relative to the velocity, ***v***. Here it is assumed that blood flows in a vessel with a uniform velocity '*v'*. The returned echoes are Doppler shifted. The Doppler shift frequency, ***fd***, is related to the ultrasound frequency, '*f'*, by Equation:

$$\boldsymbol{fd} = \frac{\boldsymbol{2v(cos\theta)}}{\mathbf{c}}\,\boldsymbol{f}$$

where *c* is the sound velocity in blood and may be assumed to be 1540 cm/s. The Doppler-shifted frequencies happen to be in the audio range for blood flow velocities in the human body



for an ultrasound frequency between 1 MHz and 15 MHz.

Figure 3.1: *An ultrasound beam is incident upon a blood vessel and makes an angle of θ relative to the direction of blood flow.*

Ultrasonic imaging is a very wide field in biomedical imaging. Besides the visualization of anatomical structures, which can be seen in A-mode, B-mode, C-mode or M-mode images, the Doppler mode exploits the Doppler effect in order to detect the motion of blood and tissue.

There are different Doppler modes and each one gives different information:

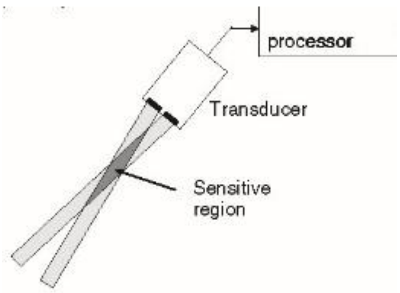
- Color Doppler or Color ow imaging, where velocity information is displayed as a color code overlying on a B-mode echo graphic image.
- Continuous wave Doppler (CW), where the transducer emits and receives the ultrasound beam continuously. Because of the continuity in emission and reception of the signal, two separate piezoelectric elements are needed in the probe, one emitting and one receiving. Doppler information comes from a line through the body, and all the velocities found by the beam are shown at every time point.
- Pulsed wave Doppler (PW), where the velocity information comes only from a small sample volume at a known depth. The transducer emits ultrasound beams in pulses and the probe needs only one element to emit and receive.
- Duplex, where PW (or CW) Doppler is displayed together with 2D images (B-mode) or Color Doppler images.

Both CW Doppler and PW Doppler techniques are called spectral Doppler because of the way of displaying the information: the spectrum of ow velocities on the y axis and time on the x axis, while the grey scale indicates the fraction of targets moving at that particular velocity.

3.1 CONTINUOUS WAVE (CW) DOPPLER :

CW system is shown in **Figure 3.2**. A probe consisting of two piezoelectric elements, one for transmitting the ultrasound signal and one for receiving echoes returned from blood, is excited by an oscillator. The Doppler-shifted echoes are amplified, demodulated, and band-pass filtered to remove the carrier frequency and other spurious signals. Suppose that the ultrasound signal generated by the oscillator is given by Acos(ωt), where A denotes signal amplitude and ω, the angular frequency, = 2πf. The demodulated signal would be

$$g_d(\omega,\omega_d) = A\cos(\omega t)B\cos[(\omega+\omega_d)t] = \frac{1}{2}AB\{\cos[(2\omega+\omega_d)t]+\cos(\omega_d t)\}$$



CWD Transducer

where the echoes are represented by Bcos[(ω + ωd)t] and ωd = 2πfd. The magnitude of constant B is determined by the scattering strength of blood.

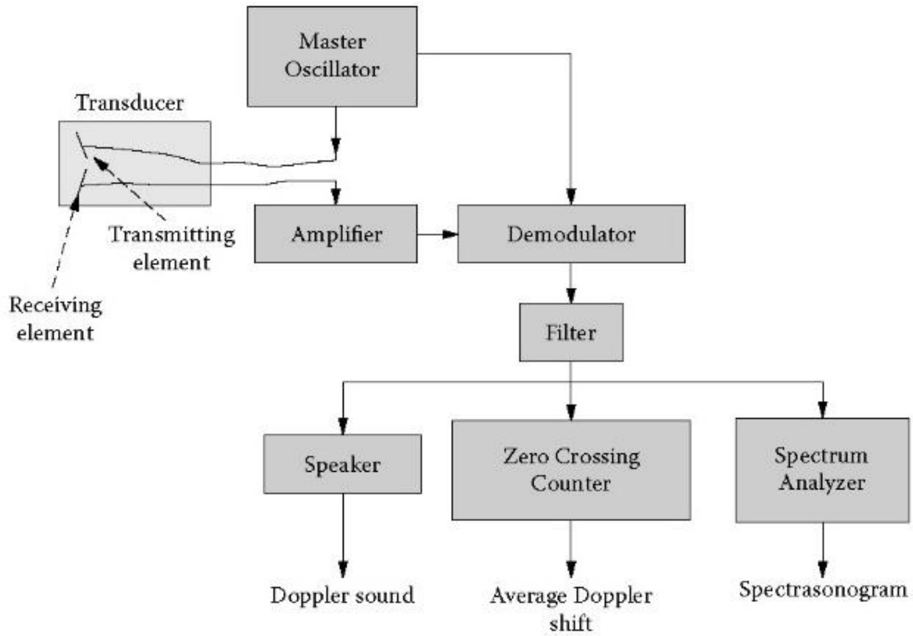


Figure 3.2: *Block diagram of a CW Doppler flow meter.*

The output of the demodulator contains the ultrasound carrier frequency and the Doppler shift, as illustrated in **Figure 3.3**. The carrier signal can be readily removed by band-pass filtering by setting the cut-off frequency of the band-pass filter at the high end to be much lower than the carrier frequency.

A problem in ultrasonic Doppler blood flow measurement is that the blood vessels that produce large reflected echoes are slow moving as well. In Doppler terminology, these large, slow-moving echoes are called clutter signals. The cut-off frequency of the band-pass filter at the low end must be designed to minimize the interference of these clutter signals. The design of this band-pass filter in the low-frequency region that performs the function of a high-pass (also called clutter rejection) filter has been problematic because the magnitude of clutter signals is several orders higher than those from blood and may mask those from slow moving blood. The signal after band-pass filtering can be processed in different ways. It may be heard with a speaker because the Doppler shift is in the audible range. Alternatively, a zero-crossing counter can be used to estimate the mean Doppler frequency, or a spectrum analyzer can be used to display the spectrum.

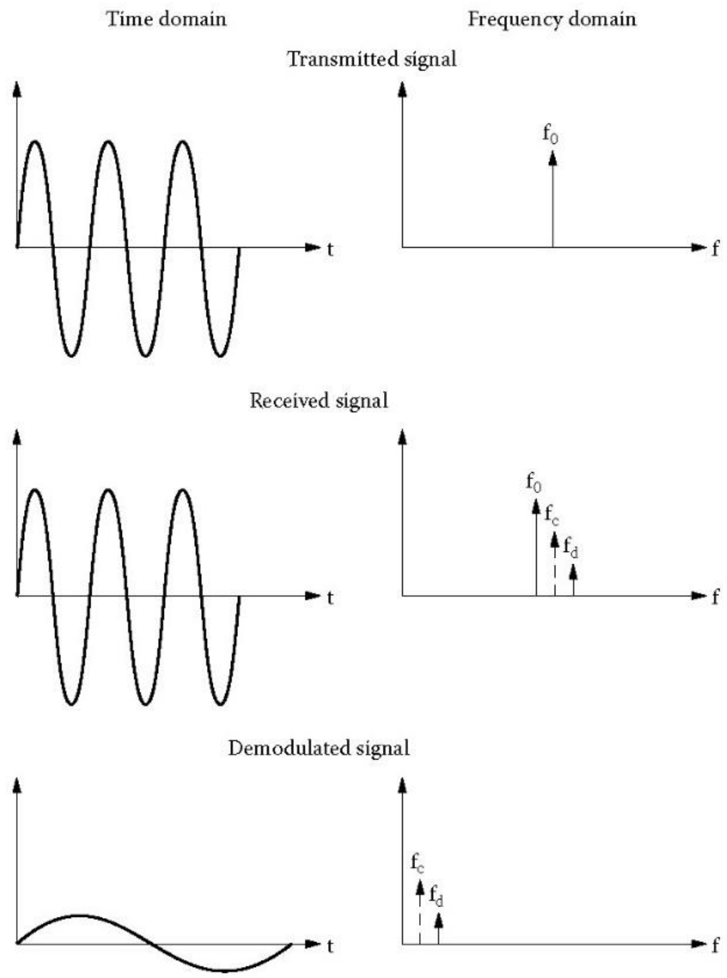
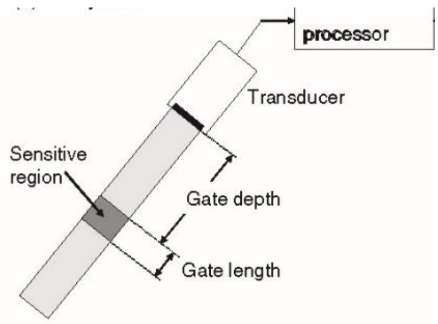


Figure 3.3: *Doppler signals in the time and frequency domain showing the effect of demodulation.*

3.2 PULSED WAVE (PW) DOPPLER :

A problem with a CW Doppler is its inability to differentiate the origins of the Doppler signals produced within the ultrasound beam. Signals coming from blood flowing in two blood vessels in the same vicinity, e.g., an artery and a vein, may overlap. To alleviate this problem, a pulsed wave Doppler may be used. Ultrasound bursts of relatively long duration consisting of many cycles are used to excite the probe. The returned echoes received by the same transducer are amplified and demodulated.



PWD Transducer

The demodulated signal is then sampled and held by a sample-and-hold circuit, which is triggered by the delayed pulses. The time-delayed pulses allow the selection of the location where the Doppler shift frequency is monitored.

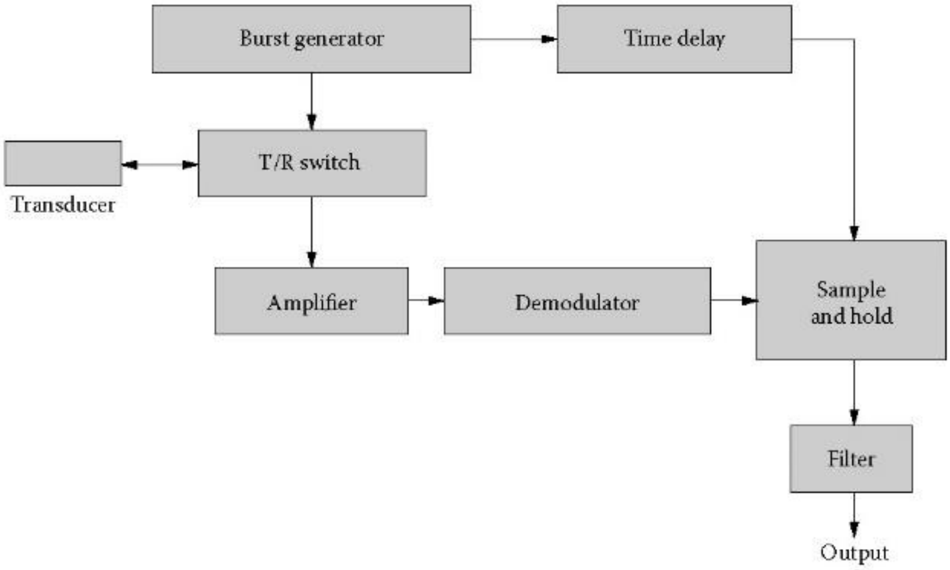


Figure 3.4: *Block diagram of Pulsed Wave Doppler (PWD)*

Figure 3.5 illustrates the principle behind pulsed Doppler flow meters. Each waveform in the left panel represents the echo waveform received by the transducer after a burst is transmitted. The waveforms are separated by the pulse repetition period (PRP). The time delay is set to allow the sampling of the waveform at points a, b, c, d, and e. The sample-and-hold circuit samples the waveforms at these points and holds the voltage at the sampled level until the next sampling time, as illustrated in the right-hand panel. Following band-pass filtering, the Doppler signal can be displayed or heard as the CW Doppler.

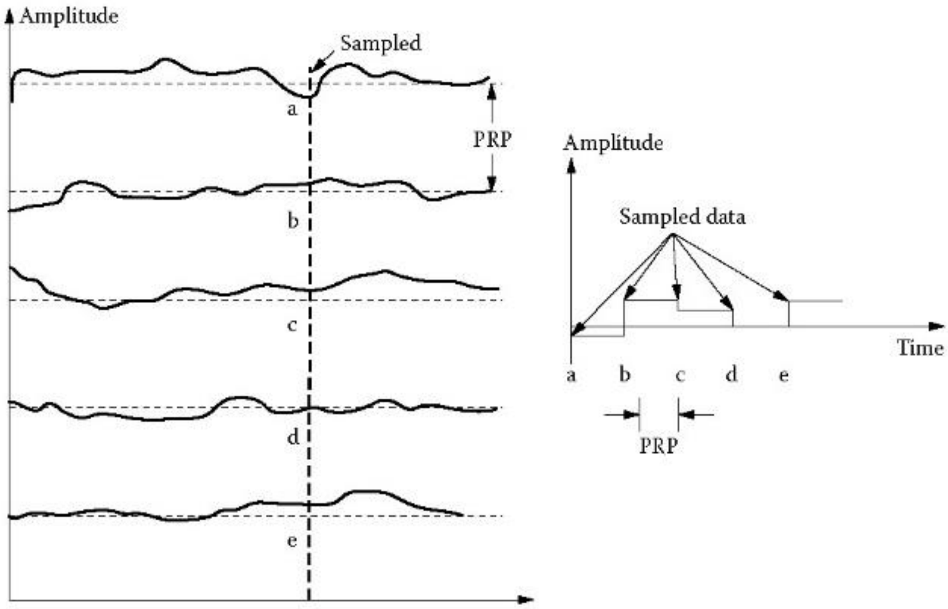


Figure 3.5: *Principle used by pulsed Doppler to acquire Doppler signals.*

A drawback of the pulsed Doppler is the limit of the highest Doppler frequency or maximal velocity that it can measure. This is determined by the pulse repetition frequency (PRF) of the device, which must be at least twice as large as the maximal Doppler frequency. This may pose a problem when measuring high velocities in the body, e.g., outflow tracts of

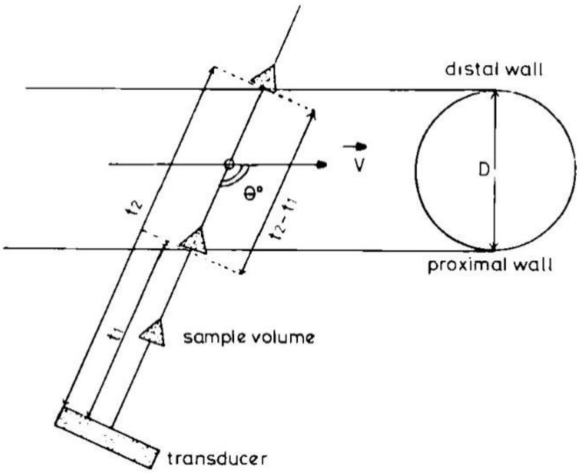


Figure 3.6: *Locations of the sample volume close to the vessel walls. The t_1 and t_2 values represent the time delays of the sample volume corresponding respectively to the first and the last Doppler signals obtained at entering and leaving the vessel lumen. The D value is the internal diameter of the vessel*

cardiac valves and stenosis in a blood vessel. To avoid aliasing, the PRF of the pulsed Doppler device must be

$$PRF > 2 * f_{max}$$

where *fmax* is the maximal Doppler shift frequency.

3.3 COLOR DOPPLER :

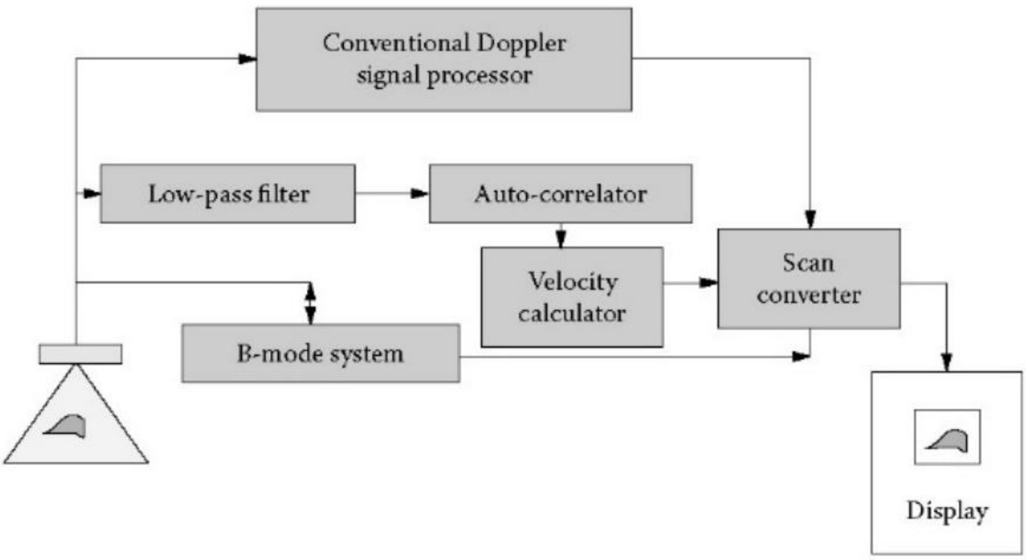


Figure 3.7: *Block diagram of Color Doppler*

Ultrasonic B-mode real-time imaging can be combined with Doppler in a scanner so that the scanner is capable of providing not only anatomical information but also blood flow data. Both sets of information are displayed simultaneously. A cursor line is typically superimposed on the B-mode image to indicate the direction of the Doppler beam.

Various Transducer Probes

An FFT algorithm is used to compute the Doppler spectrum that is displayed in real time. This type of scanner is called a “duplex scanner”.

Color Doppler flow imaging systems are duplex scanners capable of displaying B-mode and Doppler blood flow data simultaneously in real time. The Doppler information is encoded in color. Conventionally, the color red is assigned to indicate flow toward the transducer, and blue is assigned to indicate flow away from the transducer. The magnitude of the velocity is represented by different shades of the color. Typically, the lighter the color, the higher the velocity. The color Doppler image is superimposed on the gray-scale B-mode image.

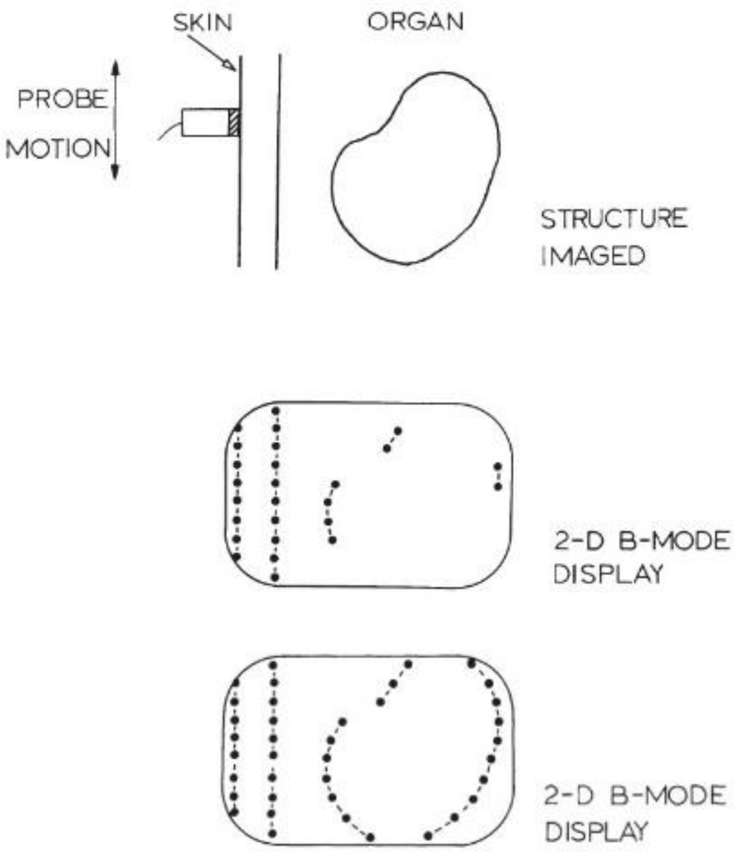


Figure 3.8: *The production linear B-mode image involves slowly moving the probe in straight line over the skin.*

The basic concept of the color Doppler is similar to that of the Pulsed Wave Doppler instruments that extract the mean Doppler shift frequency from a sample volume defined by the beam width and the gate width. The only exception is that the color Doppler instruments are capable of estimating the mean Doppler shifts of many sample volumes along a scan line.

4. DOPPLER AUDIO PROCESSING

As we know that the obtained Doppler signal from the Continuous Wave Doppler (CWD) after pre-processing it is then processed in different ways. In Handheld device the signal is given to the speaker because the Doppler shift is in the audible range. The audio signal is then recorded and saved in the storage for the doctors to listen or for further processing. On listening, certain features of the audio can be observed. There is also a lot of unnecessary background noise from the equipment. The sharp loudness can be attributed to the Systole cycles of vascular flow.

The audio signal is saved in storage as ‘ .wav’ extension file and is used for further processing to find the velocity and volume flow information. The Doppler frequency is directly related to the velocity as equation (2.2), since the other parameters are known. The incident frequency is known from the device setting. Angle is noted during the ultrasound procedure. Speed of sound in tissues is constant at 1540m/s. Hence a linear relation is established between the Doppler Frequency that is to be extracted from the audio signal and the velocity of blood flow.

To find the frequency we first filter the signal to remove the background noise using Wiener Filter.

4.1 WIENER FILTER :

Wiener filtering is a technique consisting of a Fourier filter in the frequency domain, where the original Fourier coefficients are rescaled according to the ratio between the desired and actual signal spectrum. First, a windowing function is segmented and convolved with the signal to produce a smoothly segmented signal as the output which retains the same features as the original audio signal. The signal is subjected to the Fast Fourier Transform to convert it into its frequency domain. A mean of power spectrum is calculated as the magnitude of noise frequencies of initial silence part of the signal which is assumed to have only noise. A mean variance value is also initialized. Both these values will be used to estimate the signal to noise ratio (SNR) which is essential in the noise elimination process. The a-priori SNR estimation via the decision directed approach (DDA) is a signal enhancement system based on spectral subtraction. It is implemented to calculate a suitable gain function. A weighting factor is used in the smoothing of the function. The gain function is multiplied with the signal segments to reduce the SNR to an acceptable value thereby eliminating the noise.

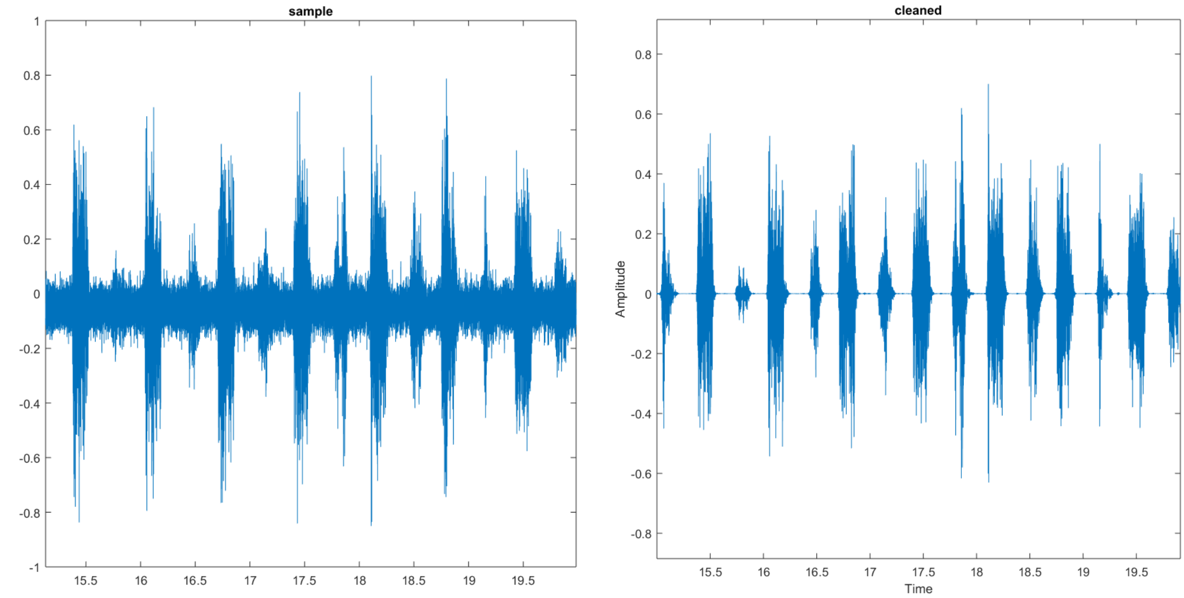


Figure 4.1: *(a) Section of the signal before filtering. (b) Same section after filtering.*

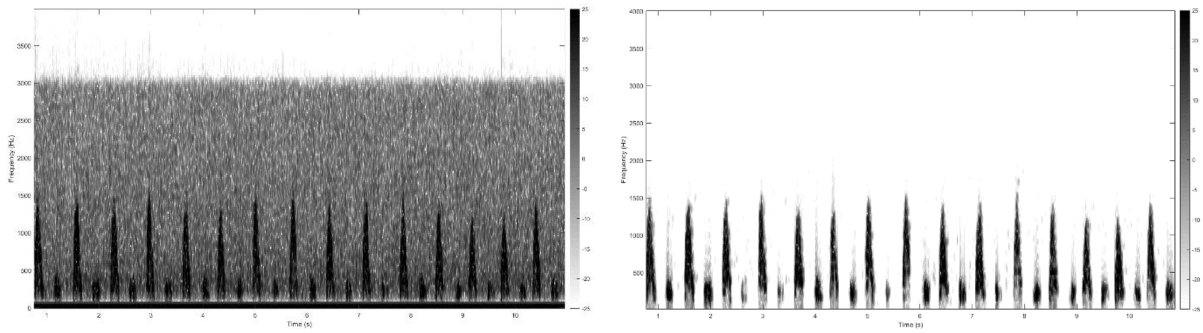


Figure 4.2: *(a) Spectrogram of section of the signal before filtering.*
(b) Spectrogram of same section after filtering.

The signal is reconstructed with the removed noise. The cleaned signal is saved and used for the frequency estimation. A short-term Fourier Transform is performed on the signal to observe the frequency peaks with respect to time in a spectrogram and also to obtain velocity profile. To obtain the velocity of blood flow, the fundamental frequency for the time frames must be obtained. This is done using either spectrogram analysis or autocorrelation method.

4.2 SPECTROGRAM ANALYSIS :

The obtained cleaned signal is then subjected to Short-time Fourier Transform (STFT) to estimate Doppler shift frequencies and thus velocity profile. In STFT, the audio sample is segmented into number of frames of windows size 20 ms. We used hanning window for spectrogram analysis. Then each window frames are subjected to FFT. The complex result is added to a matrix, which records magnitude and phase for each point in time and frequency. Further the magnitude of STFT values are plotted against time and frequency axis in MATLAB. The obtained plot is shown in Figure 4.3. From the plot we can easily identify the systolic and diastolic parts which corresponds to the Doppler shift frequencies. Since Doppler shift frequency is directly proportional to the blood flow velocity, we get velocity profile of blood flow. By keeping threshold, we can estimate average systolic peak velocity.

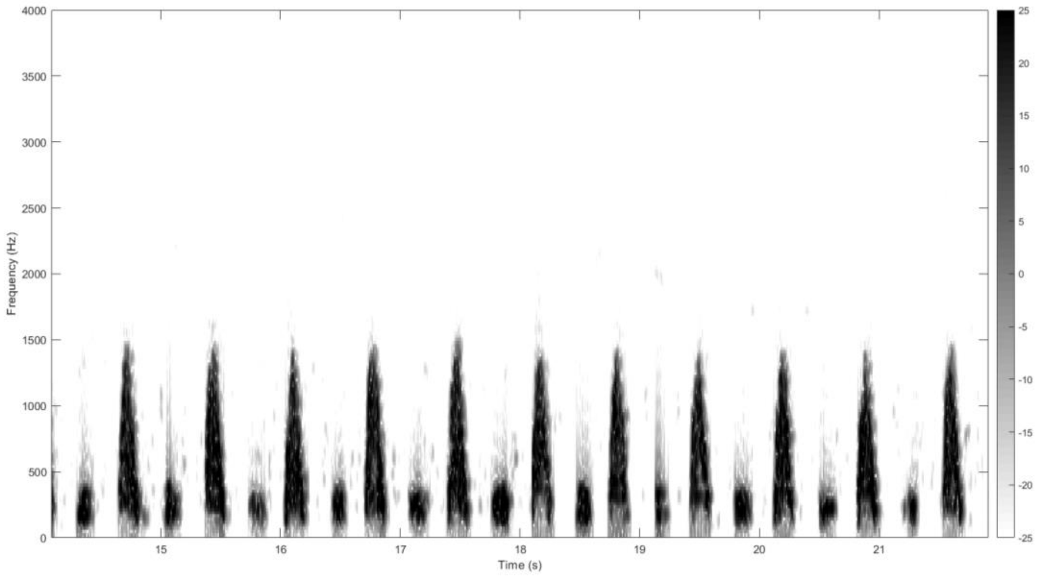


Figure 4.3: *Spectrogram of Doppler Audio sample showing Doppler shift frequencies*

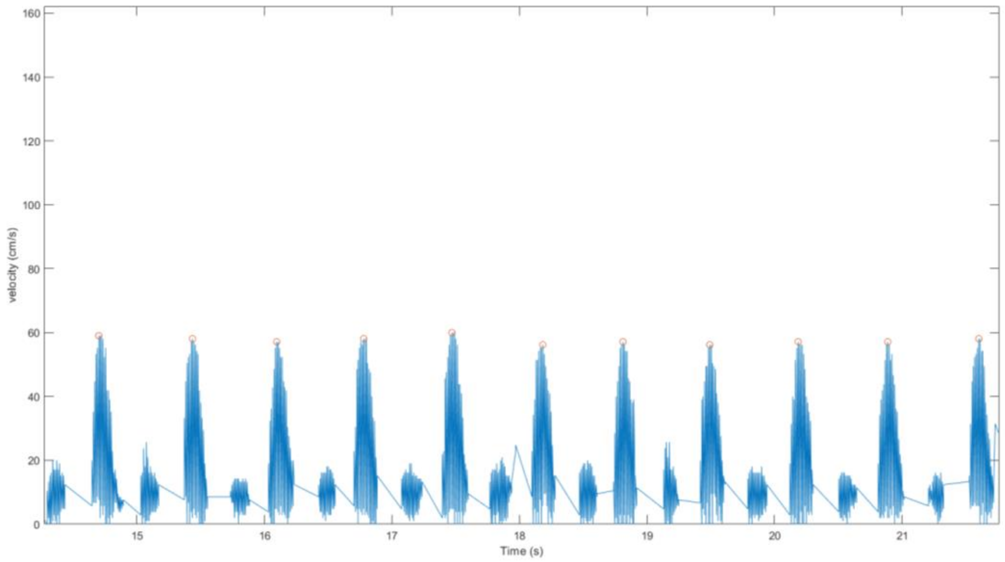


Figure 4.4: *Velocity profile of blood flow indicating peak systolic velocities.*

4.3 AUTOCORRELATION ANALYSIS :

It is the correlation of a signal with a delayed copy of itself as a function of delay. In other words, it is the similarity between observations as a function of the time lag between them. The signal is segmented into windows with overlapping frames. When a frame undergoes autocorrelation, a plot is returned which has repeated peaks with the center peak with the highest value to signify at this point the signal is perfectly in symmetry with itself. The distance between the center peak and the adjacent peak gives the period of the frame. This period is used to find the fundamental frequency of the frame. Each frame is passed through a thresholding function which discards frequencies with lower amplitudes. The threshold is set dynamically by obtaining the instantaneous amplitude using Hilbert Transforms, finding the mean envelope for a certain time duration. The remaining fundamental frequencies are used to calculate the velocity from equation (2.3). The velocity is obtained for each frame and is plotted against the corresponding window. By keeping threshold, average systolic peak velocity is calculated.

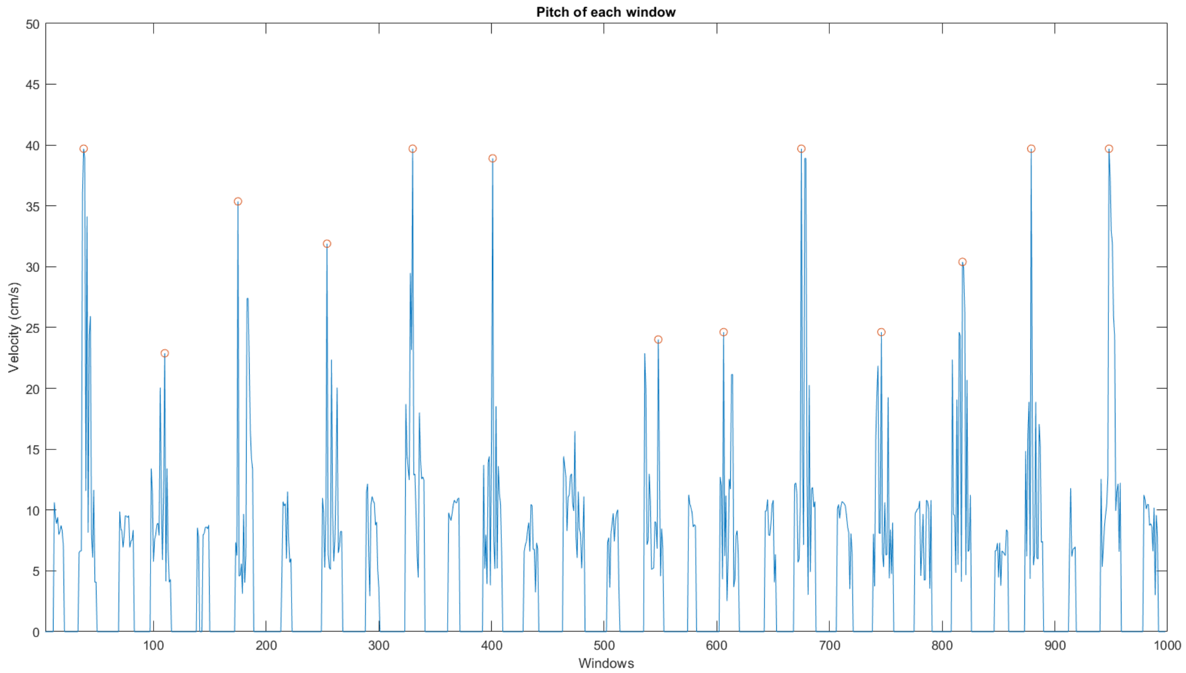


Figure 4.5: *Velocity plot corresponding to each window*

5. VOLUME FLOW ANALYSIS

The diameter of the blood vessel is determined using the time-delay in PW Dopplers. As we know the Handheld Doppler devices are CW Dopplers. With just the audio signal to use, the diameter cannot be determined. Experienced doctors are able to estimate a healthy perforator just by listening closely to the audio. Therefore, the energy of the signal at the systole part is observed at different frequency bands to find a relation to the diameter of the vessel.

We have manually selected systolic parts of two samples having different perforator diameter of same person for three persons and energy of systolic part is calculated. We have found that systolic part having greater perforator diameter has higher energy than the other. Hence many samples with a higher diameter tend to have high energies in systolic part of certain frequency bands.

6. CONCLUSION

The Doppler Ultrasound is a useful method to image tissues using the Color Doppler. However, the Handheld Doppler returns just an audio recording which can be used by experienced doctors to approximate healthy perforator, but in processing we can use it to estimate the velocity of blood flow in the perforator. The diameter can be compared by comparing the energies of the systoles in certain frequency bands. This information can be used to predict the healthiest perforator by having the highest energy of those frequency bands correspond to a larger diameter. Hence with these two parameters of velocity and diameter, volumetric flow and the healthy perforator can be estimated.

APPENDIX A

DOPPLER AUDIO SAMPLES DATA

NAME	AGE & SEX	PULSE RATE bpm	B.P mmHg	BMI	LOCATION OF PERFORATOR	DIAMETER OF PERFORATOR	DEPTH FROM SKIN (mm)	ANGLE OF INSONATION	VELOCITY	VOLUME FLOW
aditya1	*19y/m*	*84*	*116/78*	*29.03*	*lt*	*1*	*14*	*60*	***48***	***0.38***
aditya2	*19y/m*	*84*	*116/78*	*29.03*	*lt*	*1.8*	*25*	*60*	***45***	***1.15***
aditya3	19y/m	84	116/78	29.03	rt	1.6	16	60	**44**	**0.88**
jasir1	25y/m	80	120/90	23.7	rt	1.6	18	60	**30**	**0.60**
jasir2	25y/m	80	120/90	23.7	rt	2	20	60	**20**	**0.63**
jasir3	25y/m	80	120/90	23.7	lt	1.5	8	60	**20**	**0.35**
jasir4	25y/m	80	120/90	23.7	lt	1.4	11	60	**20**	**0.31**
jose1	26y/m	59	122/80	23.44	lt	1.82	10	60	**36**	**0.94**
noel1	*19/m*	*80*	*126/78*	*25.2*	*rt*	*1.2*	*13*	*60*	***50***	***0.57***
noel2	*19y/m*	*80*	*126/78*	*25.2*	*rt*	*1.54*	*8*	*60*	***55***	***1.02***
noel3	19y/m	80	126/78	25.2	lt	1.7	16	60	**65**	**1.48**
noel4	19y/m	80	126/78	25.2	lt	1.4	15	60	**57**	**0.88**
praveen1	18y/m	64	122/78	21.28	lt	1.78	8	60	**11**	**0.27**
praveen2	18y/m	64	122/78	21.28	lt	1.48	15	60	**9**	**0.15**
praveen3	18y/m	64	122/78	21.28	lt	1.36	13	60	**11**	**0.16**
praveen4	18y/m	64	122/78	21.28	rt	1	8	60	**9.3**	**0.07**
praveen5	18y/m	64	122/78	21.28	rt	1.26	15	60	**13**	**0.16**
rakshith1	18y/m	72	118/78	25.76	lt	2	11.2	60	**40**	**1.26**
rakshith2	18y/m	72	118/78	25.76	lt	3	18	60	**19.4**	**1.37**
rakshith3	18y/m	72	118/78	25.76	lt	2.5	17.6	60	**14.9**	**0.73**
rakshith4	18y/m	72	118/78	25.76	rt	1	19	60	**10**	**0.08**
rakshith5	18y/m	72	118/78	25.76	rt	2	19	60	**22**	**0.69**
sairam1	26y/m	70	110/70	26	lt	2	16.5	60	**67**	**2.10**
vinod1	*19y/m*	*76*	*120/80*	*22.95*	*lt*	*2.7*	*16*	*60*	***39.5***	***2.26***
vinod2	19y/m	76	120/80	22.95	rt	1.5	14.2	60	**83**	**1.47**

APPENDIX B

USAGE OF MATLAB CODE

1. **Move all the MATLAB code, named below, in a single folder**

   (a) Wiener.m

   It is a function file, which does noise reduction to enhance audio using 'Wiener Filter' algorithm.

   (b) envelop_hilbert.m

   It is a function file, which does 'Voice Activity Detection (VAD)' using Hilbert transform algorithm.

   (c) plot_doppler_samples.m

   It is a script file, used to plot (time domain), play and does noise reduction of Doppler audio samples.

   (d) spectrogram_analysis.m

   It is script file, used to do spectrogram analysis of Doppler audio samples.

   (e) pitch_detection.m

   It is a script file, used to estimate Doppler shift frequency in a Doppler audio sample using Autocorrelation algorithm.

2. **To obtain time domain plot, to play and to do the noise reduction of Doppler sample,**
   - Open **plot_doppler_samples.m** in MATLAB.
   - To play audio, put the value of **audio** as **1** otherwise **0** in the **line 5**.
   - To do the noise reduction, put the value of **filter** as **1** otherwise **0** in the **line 6**.
   - Then RUN the file.
   - File selection dialog box will open, then select the Doppler audio sample.
   - OUTPUT: i) Time domain plot.

ii) Audio will play if play option selected.

iii) Noise reduced audio, if filter option selected and it will ask to save the filtered audio in a folder specified by the user.

3. **To do spectrogram analysis and to get velocity profile of Doppler audio sample,**
   - Open **spectrogram_analysis.m** in MATLAB.
   - Enter the parameters of the **equation (2.3)** in the **line 7, 8 and 9.**
     Default value of 'Transmission frequency' **ft** is **3.8 MHz** and 'Doppler angle' **theta** is **60^0**.
   - To get 'Doppler shift frequency profile' of the audio sample, put **type** as **'freq'** and To get 'Blood Flow Velocity profile' of the audio sample, put **type** as **'Velocity'** in the **line 13.**
   - To get 'maximum' and 'average' systolic peak velocity, put value of **velocity** as **1** otherwise **0** in the **line 11.**
   - The RUN the file.
   - File selection dialog box will open, then select the Doppler audio sample.
   - OUTPUT: i) Spectrogram plot, with frequency or velocity on y-axis as user selected.

     ii) Maximum and average systolic peak velocity will be displayed on the command window.

4. **To get Doppler shift frequency and thus blood flow velocity using autocorrelation method,**
   - Open **pitch_detection.m** in MATLAB
   - Enter the parameters of the **equation (2.3)** in the **line 11, 12 and 13.**
     Default value of 'Transmission frequency' **ft** is **3.8 MHz** and 'Doppler angle' **theta** is **60^0**.
   - The RUN the file.
   - File selection dialog box will open, then select the Doppler audio sample.
   - OUTPUT: i) Blood flow velocity profile

     ii) Maximum and average systolic peak velocity will be displayed on the command window.

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