Doppler Ultrasound Monitoring for Feline Surgery

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Abstract -

This paper presents the utilization of Doppler ultrasonography for the real-time monitoring of heart rate and blood pressure (BP) in feline surgery. The implementation of Doppler ultrasonography in this context aims to enhance perioperative care and improve surgical outcomes by providing continuous and accurate assessments of cardiovascular parameters.

Doppler ultrasonography stands out for its ability to offer a detailed and reliable method for the assessment of heart rate and BP without necessitating direct vascular access, mitigating the risks associated with invasive monitoring techniques. It operates on the principle of detecting and analyzing the Doppler shift in ultrasound waves that are reflected off moving blood cells within the vascular system. This capability allows for the quantification of blood flow velocity, from which heart rate (HR) and systolic BP can be derived.

I. INTRODUCTION

The safety and effectiveness of surgical procedures on small animals are of paramount importance in veterinary medicine. Anesthesia plays a critical role in these procedures, ensuring pain management and immobilization. The fundamental aspects of anesthetic monitoring are circulation, ventilation, and body temperature, as shown in Figure 1. However, anesthetic properties may relax the heart muscle to the extent that not enough blood is pushed through the body, which may lead to cellular death from the lack of oxygen and nutrients. This paper will focus on designing a solution for the feline (cat) - a common, small household mammal. The small size of cats poses significant challenges in monitoring their vital signs during anesthesia, necessitating innovative solutions. Due to weaker electrical signals stemming from the heart compared to humans, it is much harder to use an electrocardiogram on small animals as it may obtain inaccurate results. This report delves into the use of Doppler ultrasound technology as a non-invasive method to monitor heart rate and systolic blood pressure, which are critical parameters in the anesthetic management of feline surgeries.

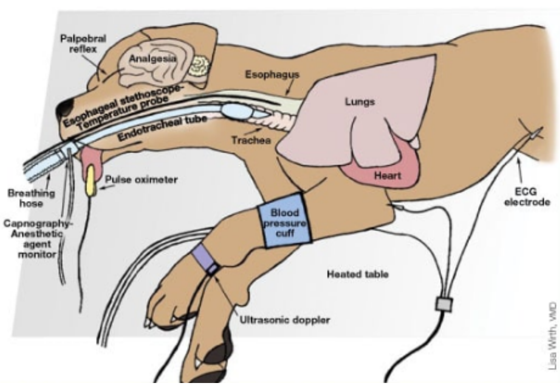

Figure 1. General Surgical Setup for Small Animals

Proposed Solution -

Our design aims to obtain heart rate and systolic blood pressure data to then notify the surgeon of any abnormalities during surgery. The operation of the system involves emitting ultrasound waves towards the brachial artery of the left arm, receiving the reflected waves, and processing these signals to determine the heart rate and systolic blood pressure.

The brachial artery is a major artery in the front limb of cats, similar to humans' brachial artery in the arm. By occluding this artery temporarily with a blood pressure cuff and then gradually releasing the pressure, veterinary surgeons can determine the blood pressure of the cat during the surgical procedure. A blood pressure cuff is used to constrict the blood vessel 10-15mmHg past the typical systolic blood pressure of a cat, so when the pressure decreases below the systolic blood pressure, at the interval of 2mmHg/sec, there will be a sudden increase in the voltage signal associated with the jump in blood velocity. The pressure cuff will be inflated every minute during surgery to continuously monitor the feline patient. Critical thresholds are set based on veterinary standards to trigger alerts when values fall outside safe ranges, ensuring that the surgeon will be able to intervene when needed as shown in Figure 2. In the whole scale of the surgical monitoring system, the Doppler ultrasound monitoring will be one of the components that the veterinarian can monitor through the display screen and decide if a change in the dosage of anesthesia is necessary during surgery.

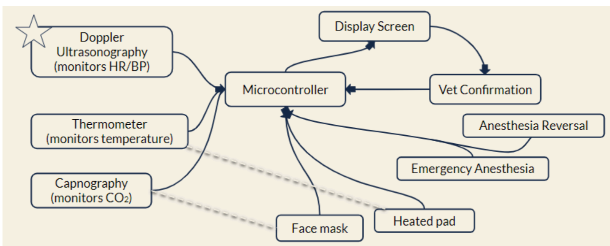

Figure 2. Proposed Surgical Monitoring System for Felines Under Anesthesia

While gas exchange and temperature are important parameters for anesthesia monitoring, this paper will focus on HR/BP monitoring with Doppler ultrasonography. For the purpose of this study, several assumptions regarding the health status and pre-surgical condition of the cat patients were made so the blood flow velocity, blood pressure, and heart rate values used can be applicable:

- Age range: 6 months to 10 years.
- Weight range: 2 to 12 lbs.
- No pre-existing cardiovascular or respiratory conditions.
- Calm and unstressed before anesthesia administration.

I. METHODS

System Design Overview -

The proposed Doppler ultrasound system integrates a microcontroller with an ultrasonic emitter and receiver, coupled with a blood pressure cuff, oscillator, and mixer. This design facilitates real-time acquisition of blood velocity, which is analyzed to output heart rate and blood pressure data.

Doppler Ultrasound Frequency Mixer -

The Doppler effect illustrates the phenomenon where a moving wave source approaches and passes an observer with varying perceptions of the source based on relative speed and location. When the source travels toward the observer, the frequency wave is compressed, resulting in a higher frequency. The wave is stretched when the source travels away from the observer, resulting in a lower frequency. This concept is applied to the Doppler ultrasound monitoring device design in Figure 3 below.

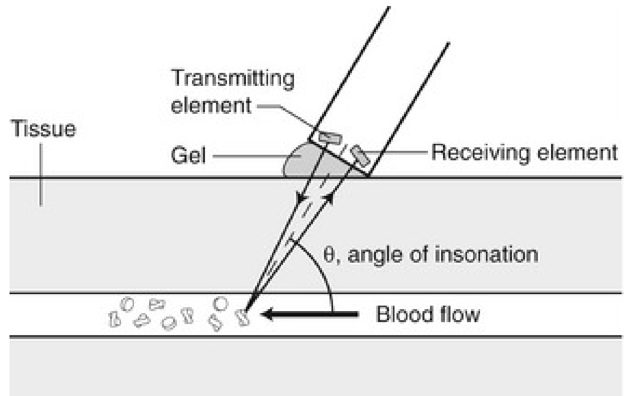

Figure 3. Doppler ultrasound arrangement of the emitter and receiver placed at an angle relative to the direction of blood flow

Using a continuous wave Doppler, the device has an emitter and receiver of signal frequencies, usually made of piezoelectric elements. The emitter sends a frequency signal (Ft) towards the blood vessel and the back-scattered echoes (Fr) reflecting off of the red blood cells are then perceived by the receiver. The received and emitted frequencies are then compared to find the frequency shift. This is known as the Doppler shifted signal, which is the difference between (Fr) and (Ft). The greater the frequency shift, the higher the blood velocity, as the blood cells have moved fast enough that the frequency they reflect is significantly smaller than what was emitted. Additionally, the smaller the angle between the Doppler beam and blood vessel, the larger the Doppler shifted signal. Very small signals are produced as the Doppler beam angle approaches a 90° angle. Since blood flows towards the distal end of the paw in the brachial artery, it is assumed that the Doppler transducer in the surgical cuff will be placed facing incoming blood flow.

The following equation models the relationship between the Doppler shifted signal (Fd) and the blood flow velocity (V):

$$F_d = \frac{2F_t V cos\theta}{c}$$

Here, c is the propagation speed of ultrasound in soft tissue, which is ~$1540ms^{-1}$[5]. The average blood flow velocity range in the artery of a cat (diameter $\geq 150\mu m$) is also found to be $59.9 \pm 5.3 \frac{mm}{s}$ at the average blood pressure of 129.8 ± 5.8 mmHg [8]. Doppler ultrasound emitters usually send high-frequency sound waves of around 2M-20MHz at an ideal angle of 45∘ from the blood vessel with the blood flowing towards the transducer. Using these parameters, the estimated Doppler shifted signal should be between ~500-600 Hz when $F_t = 10MHz$.

To integrate this into our designed circuit, an oscillator is connected to the emitter to serve as the AC source, and both the emitter and receiver are connected to a passive frequency mixer that finds the Doppler shifted signal. The output of the mixer should serve as an AC source for the circuit that measures systolic blood pressure and heart rate.

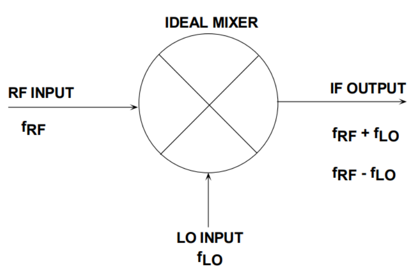

Figure 4. Diagram of a frequency mixer that integrates the Radio Frequency (RF) input and Local Oscillator (LO) input to create the Intermediate Frequency (IF) output

The LO input would be the emitter frequency from the oscillator and the RF input would be the receiver frequency input (Fig.4). The IF output gives the sum and difference of both inputs. Therefore, we will be using a bandpass filter to select the frequency subtraction result, as we have calculated the Doppler shifted signal.

Systolic Blood Pressure -

Following the frequency mixer output would be two different circuit pathways that process the information - one of them for systolic blood pressure. The output of the frequency mixer would be inputted into a lowpass filter to attenuate any higher frequency noise than the cutoff frequency, which is calculated with the following equation:

$$f_c = \frac{1}{2\pi RC}$$

where R and C are the corresponding values of the resistor and capacitor, respectively. A non-inverting amplifier is then used to amplify the signal by a controllable gain value, which is calculated with the equation below:

$$Gain = 1 + \frac{R_1}{R_2}$$

Where R1 and R2 are the voltage dividing resistors at the negative voltage input. The voltage output from the amplifier is then given to the microcontroller for analysis.

Since the pressure in the surgical cuff is increased past the systolic blood pressure, the blood flow velocity should be minimal. As soon as the pressure in the cuff decreases below the systolic pressure, there should be a sudden increase in blood flow velocity. The microcontroller would find the corresponding pressure at the beginning of the spike in voltage using appropriate Laplace transform calculations. If the obtained value is outside of the normal range (Table 1), the system will display a warning for the veterinarian as shown in Figure 2.

Heart Rate	*120-160 beats per minute*
Systolic Blood Pressure	*90-140 mmHg*

Table 1. Normal heart rate and systolic blood pressure values for felines under anesthesia

Heart Rate -

Similar to the processing of systolic blood pressure values, the circuit calculating the heart rate also takes the output of the frequency mixer as the input. First, an inverting hysteretic comparator switches its output state when the input signal crosses a higher and lower threshold, which helps with noise and stability.

When the input voltage exceeds the higher threshold, the output would result in an immediate decline from the +3V maximum voltage to the -3V minimum voltage. As soon as the input voltage decreases below the lower threshold, the output voltage will immediately increase back to the +3V value. The higher and lower threshold of the comparator is calculated by:

$$V_{ref}^{\pm} = \frac{R_1}{R_1+R_2}(\pm V_{supply})$$

where R1 is the resistor connected to the ground in the voltage divider. The output of the hysteretic comparator is then used as input into a monostable single-shot 555 timer. Triggered by a falling edge, the 555 timer generates a single positive square-wave pulse output of a specified duration (T) in response, which is calculated by:

$$T = ln(3) * RC$$

where R and C are the resistor and capacitor values adjacent to the discharge and trigger nodes on the 555. The output of the 555 timer is then converted to a DC signal through a lowpass filter that has a significantly lower cutoff frequency than the heart rate. The output would then be approximated as the average of the input, which equates to half of the amplitude of the 555 timer square waveform. In addition, the voltage output of the lowpass filter is equivalent to the following:

$$V_{LP\ output} = T * HR * (+V_{supply})$$

Lastly, the output is then amplified using a non-inverting amplifier that increases the DC signal by a gain value that is calculated similarly to that of the systolic blood pressure circuit. The output of the amplifier, which is the value of the DC signal, is then obtained by the microcontroller to be converted to a heart rate value to be displayed on the screen for the veterinarian. The heart rate of the cat (in Hz) can be calculated using the equation above.

II. RESULTS

The circuit design solution for the Doppler ultrasound monitoring system is shown in Figure 5. The voltage source for the amplifiers is ±3 V. One side of the hysteretic comparator is grounded, the other is 3 V. We assume the input voltage into the circuit is in the range of 0-6 mV.

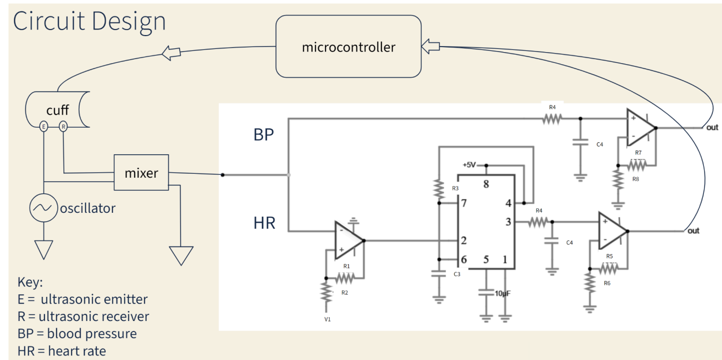

Figure 5. Circuit design of the Doppler ultrasound monitoring device

Component	Value
R1	100 kΩ
R2	100 kΩ
V1	2 mV
R3	200 kΩ
C3	1 µF
R4	10 MΩ
C4	10 µF
R5	200 kΩ
R6	300 kΩ
R7	6 MΩ
R8	10 kΩ

Table 2. Values on the circuit (see appendix)

Values of the circuit resistors and capacitors are found by analyzing each of the components separately. On the heart rate side of the circuit, the comparator was set with targets of V_{ref}^{-} and V_{ref}^{+} of 1 and 3 mV, respectively. The monostable single-shot was set to have a τ of 0.22 seconds, fulfilling the condition of $\tau < 0.25$s for a maximum heart rate of 240 bpm. Values for the low pass filter were chosen to keep $f_c << 1$ Hz. The amplifier for heart rate set A = 1.67, and for BP was set to A = 600. This kept the output voltage for heart rate in the range of 2.16 - 2.93 V, corresponding to a heart rate of 120 - 160 bpm. Any voltage higher or lower will cause the microcontroller to display a warning. The output voltage range for blood pressure is 0.6 to 2.4 V, with sharp changes in voltage signifying the shift from above systolic pressure to below.

The following figures (6, 7, 8) are the resulting waveforms proceeding each circuit element for both the systolic blood pressure and heart rate processing. Figure 6 shows the filtering out of noise from the mixer input and amplifying the signal before submitting to the microcontroller.

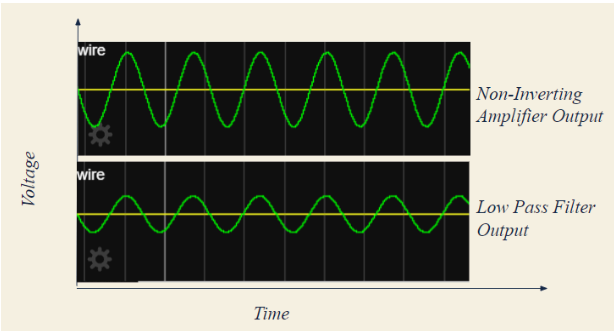

Figure 6. Systolic blood pressure circuit outputs

Figure 8 below shows the magnified square waveform output from the hysteretic comparator at the top of Figure 7. The 555 timer positive square waveform corresponds to the downfalling edges of the hysteretic comparator output. The lowpass filter output is the average of the 555 timer output, and the amplifier increased the magnitude of the DC voltage. This DC signal value corresponds to the calculated heart rate in the microcontroller and is displayed on the screen.

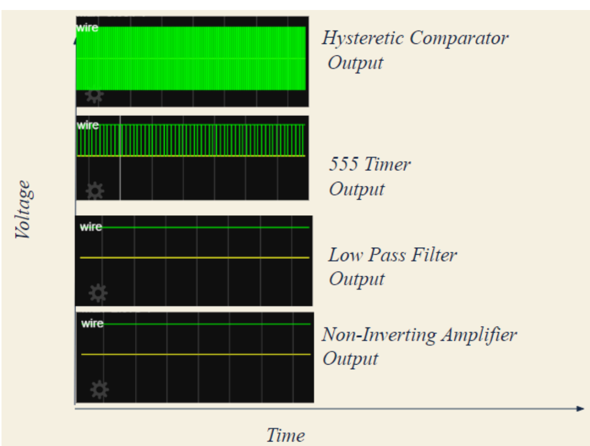

Figure 7. Heart rate circuit outputs

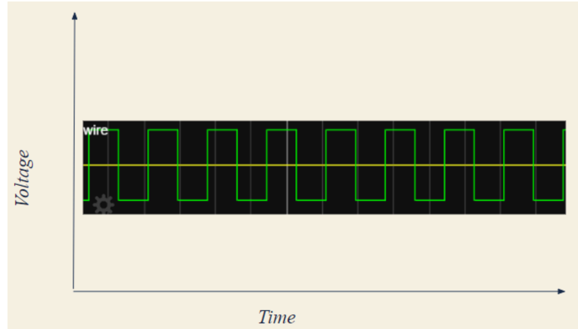

Figure 8. Magnified Voltage vs. Time graph for the hysteretic comparator in Figure 7

III. DISCUSSION

Advantages -

1. Non-Invasiveness

One of the primary benefits of Doppler ultrasound technology is its non-invasive nature. Unlike some traditional methods that may require invasive procedures to monitor vital signs, Doppler ultrasound can assess blood flow and pressure externally, reducing the risk of infection and minimizing stress for the animal. This aspect is particularly beneficial for monitoring patients with conditions that contraindicate invasive monitoring methods.

2. Applicability to Small Animals

Small animals such as cats present unique challenges for monitoring due to size and physiological differences from larger animals. Traditional ECG and blood pressure monitors may not always be effective due to the small size of blood vessels and the lower electrical activity of the heart. Doppler ultrasound is better suited for use in small animals, providing reliable data irrespective of the patient's size.

3. Improved Surgical Outcomes

By providing accurate and real-time data, Doppler ultrasound technology contributes to improved surgical outcomes. The early detection of potential issues allows for timely corrective actions, ensuring that the animal remains stable during the operation. This approach to patient care can lead to quicker recoveries, shorter hospital stays, and overall better health outcomes for the animal.

4. Versatility and Cost-effectiveness

Doppler ultrasound equipment is versatile and can be used for a variety of applications beyond monitoring during anesthesia, including diagnostic imaging and evaluating vascular health. This makes it a cost-effective option for many veterinary practices, providing added value beyond its initial investment. Additionally, the technology's adaptability to different sizes and species of animals enhances its utility in many veterinary practices.

Limitations -

The study acknowledges its limitations, including the reliance on specific health assumptions and the focus solely on systolic blood pressure. Future research could expand the system's capabilities to include diastolic pressure measurements and other vital parameters such as temperature and CO2 levels. Adjustments for broader applicability to different animal sizes and species undergoing anesthesia are also considered.

This method also does not measure diastolic blood pressure, which means issues affecting only diastolic blood pressure and not systolic blood pressure may go unnoticed. Doppler ultrasonography would not be able to detect arrhythmias as a traditional ECG would. While this is a concern in rare cases, arrhythmia is a fairly uncommon issue.

However, the greatest limitation of this study is the lack of data on the blood flow velocities of different arterial pathways in cats. Most data found have focused on the feline pial artery, which is a branch of the internal carotid artery, and one of the major arteries supplying blood to the brain. The radius of the pial artery is smaller than the brachial artery, which according to Poiseuille's Law, the blood flow velocity can be slower in the brachial artery by the power of 4.

IV. CONCLUSION

Incorporating Doppler ultrasound into veterinary anesthetic monitoring practices offers many advantages, from non-invasiveness and increased accuracy to its suitability for small animals and real-time monitoring capabilities. This allows for monitoring of heart rate and systolic blood pressure during anesthesia, keeping watch on crucial parameters related to circulation, with an alert if any of the values fall out of standard ranges. These benefits definitively improve the safety and effectiveness of surgical procedures by letting veterinarians keep constant watch on their patients. As veterinary medicine continues to advance, the adoption of technologies like Doppler ultrasound represents a step forward in providing better quality care for animal patients.

Acknowledging the limitations and the focused scope of this study, future research should aim to broaden the applicability of Doppler ultrasound technology across different small animal species and surgical conditions. This includes studying the integration of additional vital parameter monitoring to provide a more comprehensive scope of patient status during anesthesia. Expanding Doppler ultrasonography use within this context could further enhance veterinary diagnostic and monitoring capabilities, contributing to the goal of improving animal healthcare outcomes.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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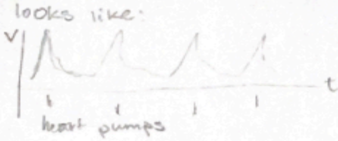
VII. APPENDIX

V_{in}: 0 - 6 mV

looks like:



HR

- inverting hysteretic comparator

  $V_{ref}^{-} = \frac{R_1}{R_1+R_2} \cdot V_1$

  target: $V_{ref}^{-} = 1$ mV, $V_{ref}^{+} = 3$ mV

  ↳ $V_1 = 2$ mV

  $\frac{R_1}{R_1+R_2} = 0.5$, $R_1 = R_2$

  Let $R_1 = R_2 = 100$ kΩ

- Monostable Single-shot

  $T = \ln(3) R_3 C_3$ ($\ln(3) \approx 1.1$)

  let max HR = 240 bpm,

  so $T < 0.25$ s.

  let $R_3 C_3 = 0.2$

  ↳ $C_3 = 1$ μF

  $R_3 = 200$ kΩ

- Low pass filter

  $f_c = \frac{1}{2\pi R_4 C_4} \ll 1$ Hz

  let $R_4 = 10$ MΩ

  $C_4 = 10$ μF

  V_{out} from low pass filter:

  HR range 120 - 160

  V_{out} range 1.3 - 1.76 V

- Non-Inverting Amplifier

  $A = 1 + \frac{R_5}{R_6}$

  target $\frac{R_5}{R_6} = \frac{2}{3}$

  Let $R_5 = 200$ kΩ, $R6 = 300$ kΩ

  V_{out}: 2.16 - 2.93 V

  lower or higher, alert

  HR above 160 will not be differentiated

BP

- low pass filter

  same values

  Expected V_{out}: 1 - 4 mV

- non-inverting amplifier

  $A = 1 + \frac{R_7}{R_8}$ ⟶ target ~600

  Let $R_7 = 6$ MΩ

  $R_8 = 10$ kΩ

  Expected V_{out}: 0.6 - 2.4 V