A Practical Study to Enhance Pressure Signal Quality in Mechanical Ventilators Using Moving Average Filtration: A Comparative Study

Husam Y. Al-Hetari (1,*)
Noman Q. Al-Naggar (1,*)
Abdu Alameri (1,*)
Mahmoud A. Al-Rumaima (1,*)
Muhammad Nomani Kabir (2,*)
Zaied Alhaj (3,*)

[1] Department of Biomedical Engineering, Faculty of Engineering, University of Science and Technology, Sana'a, Yemen

[2] United International University, Bangladesh

[3] Biomedical Engineering Department, İstanbul Üniversitesi-Cerrahpaşa, Türkiye

* Corresponding authors: husamalhetari@gmail.com, nnagar845@gmail.com, a.alameri2222@gmail.com, m.alromaima@gmail.com, dr.nomankabir@gmail.com, zaiedalhaj@gmail.com.

A Practical Study to Enhance Pressure Signal Quality in Mechanical Ventilators Using Moving Average Filtration: A Comparative Study

Abstract:

Undesirable noise and interference present a substantial obstacle in the process of obtaining biomedical signals for analysis and diagnosis. It is necessary to reduce the noise and enhance signal quality for many designs of medical devices such as Mechanical Ventilators (MV), patient monitors and overall biosignal processing. To contribute for addressing this problem, and for medical applications such as MV which are used for critical diseases such as pneumonia, COVID 19 etc. This paper, conducted comparative study to evaluate the performance of a 3-point Moving Average Filter (MAF) and a 5-point MAF in order to reducing noise and improving signal quality in MVs which are used in medical applications. MATLAB was utilized to perform filter approximation, realization and analysis. LabVIEW was employed for pressure signal data acquisition, implementation, and Signal-to-Noise Ratio (SNR) calculation. Experimental data, which needed for filters implementation, were obtained by running a MV connected to an artificial lung and a reference device which is used to measure pressure signal. In general, 3 point presented better SNR against 5 points MAF for pressure signal required in MVs. This approach can potentially enhance healthcare quality by providing better quality of biomedical signals which are used in medical devices.

Keywords: Moving Average Filter, Pressure Signal, Signal Quality, Medical Ventilator, MATLAB and LabVIEW.

https://doi.org/10.59222/ustjet.2.2.4

دراسة عملية لتحسين جودة إشارة الضغط في أجهزة التنفس الصناعي باستخدام الترشيح المتوسط المتحرك: دراسة مقارنة

الملخص:

تمثل الضوضاء والتداخل غير المرغوب فيه عقبة كبيرة في عملية الحصول على الإشارات الطبية الحيوية والتي تستخدم للتحليل والتشخيص. من المعلوم ضرورة تقليل الضوضاء وتحسين جودة الإشارة في العديد من تصاميم الأجهزة الطبية مثل أجهزة التنفس الصناعي، وأجهزة مراقبة المرضى ومعالجة الإشارات الحيوية بشكل عام. للمساهمة في معالجة هذه المشكلة، ومن اجل التطبيقات الطبية مثل التنفس الصناعي التي تستخدم للأمراض الخطيرة مثل الالتهاب الرئوي و19 COVID وغيرها، أجرت هذه الورقة دراسة مقارنة لتقييم أداء مرشح نوع Moving Average Filter ذو الثلاث نقاط مع المرشح ذو النقاط الخمس لتقليل الضوضاء وتحسين جودة الإشارة في أجهزة التنفس الصناعي المستخدمة في التطبيقات الطبية. تم استخدام برنامج الماتلاب MATLAB لإجراء تصور وتحليل وتحقق للمرشح. تم استخدام برنامج اللاب فيو LabVIEW للحصول على إشارة الضغط عمليا وتطبيق المرشحات المستخدمة وحساب نسبة الإشارة إلى الضوضاء (SNR). تم الحصول على البيانات التجريبية اللازمة لتطبيق المرشحات عن طريق تشغيل جهاز MV متصل برئة صناعية وجهاز مرجعي يستخدم لقياس إشارة الضغط. بشكل عام، قدم الفلتر ذو الثلاث نقاط نسبة اشارة الى الضوضاء (SNR) أفضل مقابل الفلتر ذو الخمس نقاط لإشارة الضغط التي يتم استخدامها في اجهزة التنفس الصناعي. يمكن لهذا العمل أن يعزز جودة الرعاية الصحية من خلال توفير جودة أفضل للإشارات الطبية الحيوية المستخدمة في الأجهزة الطبية.

الكلمات المفتاحية : مشرح المتوسط المتحرك، إشارة الضغط، جودة الإشارة، التنفس الصناعي، ماتلاب، لاب فيو.

https://doi.org/10.59222/ustjet.2.2.4

1. Introduction

In medical applications, such as Mechanical Ventilators (MV), spirometers, patient monitors etc., noise is considered a source of big concern and it usually influence sensors signals quality used in these applications. Pressure signal usually gained unwanted noise when acquired for medical applications [1]. MVs usually are used in ICU for emergency case for critical diseases such as pneumonia, COVID 19 etc. [2, 3]. In MVs, pressure signal monitoring is important to assess patient lung status, nevertheless this signal usually gains unwanted noise therefore it is necessary to study how to remove this noise to enhance signal quality for MV applications.

The Moving Average Filter (MAF) is widely used as a digital filter to remove undesirable noise which reduce signal quality [4, 5, 6]. MAF is perfect for many applications and it can reduce random noise while keeping excellent response [6, 7]. Recent works applied MAF and proved its ability to remove different types of noise in many applications [8-13]. Besides, MAF proved its ability to reduce noise in real time for biomedical signals [5].

This paper presents a study of 3 points MAF against 5 points MAF which are used to remove unwanted noise of pressure signals in MVs. Before applying the filters in real-time practice, filter analysis should be done, therefore, MATLAB software codes are used to study the filters characteristics which include its frequency response, poles and zeroes etc. LabVIEW is a good software for real time implementation and graphical monitoring [14], therefore, it is the best choice to implement the suggested filters in real-time and check filters efficiency. The performance for each filter was evaluated using Signal to Noise Ratio (SNR) metric which determines which filter is the best.

2. Methods

2.1 Block diagram of the study

In this section we implemented MAF in order to remove unwanted noise of pressure signal acquired from a MV. The digital filter design process can be done in four steps: filter approximation (filter specification), filter realization, performance analysis and finally implementation [15,16] these steps are illustrated in Figure 1.

https://doi.org/10.59222/ustjet.2.2.4

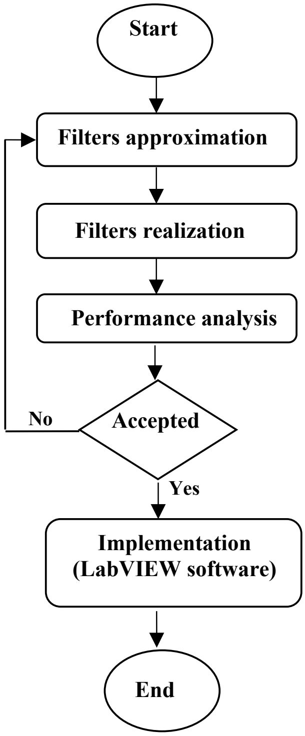


Figure 1: Filter Design Process

2.1.1 Filters approximation (filters specifications)

A transfer function is a relation between output and input of any filter, finding the transfer function is important to determine the filter response and its specifications, this process is called filter approximation. In this process also we can find poles and zeroes which are important to understand the filter behavior [15]. Filter specifications are approximated to eliminate pressure signal noise in MVs which are used in the medical filed, therefore, in this stage, we determined frequency response characteristics, which included passband, stopband and a maximum of the frequency response magnitude.

The general equation in the time domain for L points MAF is defined as:

$$y(n) = \frac{1}{L}\sum_{K=0}^{L-1} x(n-k) \qquad (1)$$

Where, y(n) is the filter output, x(n) is the filter input, L filter rank and k input delay.

Or equivalently in Z domain equation (1) can be written as:

$$H(Z) = \frac{Y(Z)}{X(Z)} = \frac{1}{L}\sum_{K=0}^{L-1} Z^{-k} \quad (2)$$

Where, H(Z) is a transfer function of the system

For this work, Equation 2 can be written as transfer function H(z) for 3 points MAF as the following:

$$H(Z) = \frac{1}{3}\sum_{K=0}^{2} Z^{-k} \quad (3)$$

Similarly, Equation 2 can be written as transfer function H(z) for 5 points MAF as the following:

$$H(Z) = \frac{1}{5}\sum_{k=0}^{4} Z^{-k} \quad (4)$$

- Impulse response of the 3 points MAF and the 5 points MAF

In time domain, the 3 points MAF impulse response h[n] = {1/3, 1/3, 1/3}, this means when impulse is applied to the filter as an input the output will be three equal values of 1/3. Therefore, the filter output will be the average of the recent input with the two previous inputs. Similarly, the impulse response of the 5 points MAF h[n] = {1/5, 1/5, 1/5, 1/5, 1/5}, Therefore the filter output will be the average of the recent input with the four previous inputs.

- Frequency response Analysis of the 3 points MAF and the 5 points MAF

As shown in Figure 2, notice that in both filters, the frequency response has characteristics of low pass filter. Then, the low frequencies in the input pass through the filter without attenuation, whereas the high frequencies will be attenuated. The factor of attenuation depends on the filter rank, therefore, the high frequencies will be attenuated by higher factor in the 5 points MAF than 3 points MAF.

MATLAB software is used to investigate the proposed MAFs specifications and performance. MATLAB codes implemented equations 3 and 4 for both filters to investigate filter specifications before implementation in real time practice.

https://doi.org/10.59222/ustjet.2.2.4

Therefore, frequency response characteristics are obtained for both filters as presented in Figure 2.

Zeroes are located at the edge of stopband and the poles are located at the origin point, both filters frequency response magnitude reached up to maximum at frequency equals zero (ω = 0), and the magnitude gradually decreased as frequency increase, the attenuation of magnitude reaches up to zero at filters zeroes 2π/3 (rad/s) or 0.333 (Hz) for 3 points MAF and π /3 (rad/s) or 0.166 (Hz) for 5 points MAF. These values of zeroes called normalized frequency (ω) and can be calculated from equation 5 , this frequency showed the estimated edge of the stopband of both filters as shown in Figure 2

$$\omega = 2\pi \frac{F}{fs} \qquad (5)$$

Where,

F is actual frequency (time domain frequency)

fs sampling frequency

2π/3 (rad/s) and π/3 (rad/s), called normalized frequency which refers to cutoff frequencies for the 3 points MAF and the 5 points MAF respectively, and by applying equation 5 we can obtain a cutoff frequency as actual frequency (time domain frequency) for both filters. That means the value of F/fs = 1/3 for 3 points MAF and F/fs = 0.5/3 for 5 points MAF. Therefore, in this case, at sampling frequency equals 3 Hz the actual frequency equals 1 Hz for 3 point MAF and 0.5 Hz for 5 points MAF. Accordingly, the frequency above 1 Hz will be attenuated by 3 points MAF and similarly, the frequency above 0.5 will be attenuated by 5 points MAF.

In general, 3 points MAF filers works as low pass filter with stopband edge (cutoff frequency) 0.333 Hz, similarly, 5 points MAF works as low pass filter with stopband edge at 0.166 Hz which means it has narrower pass band than 3 point MAF. Then, when we look at the right side of the frequency response magnitude, the area at the right of the zeroes is considered stopband of both filters, whereas the area at the left of the zeroes considered passband of both filters as presented in Figure 2.

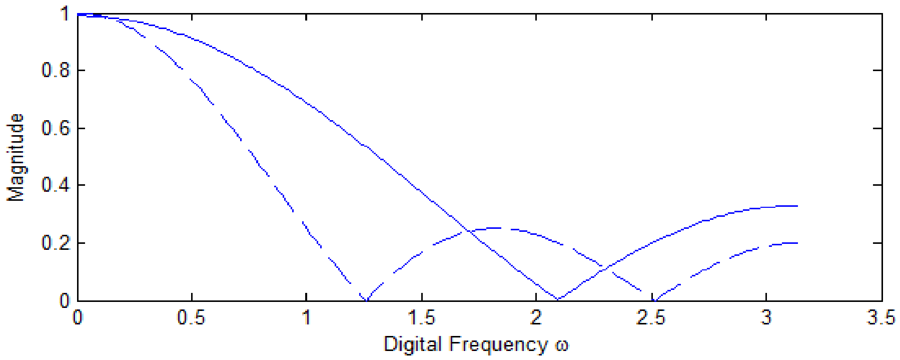


Figure 2: Frequency response of 3 points MAF (solid line) and 5 points MAF (dashed line)

2.1.2. Filters realization

Once the filter transfer function is obtained, it has to be synthized as block structure as shown in Figure 3, this type of form use numbers of adders and multipliers and delays functions.

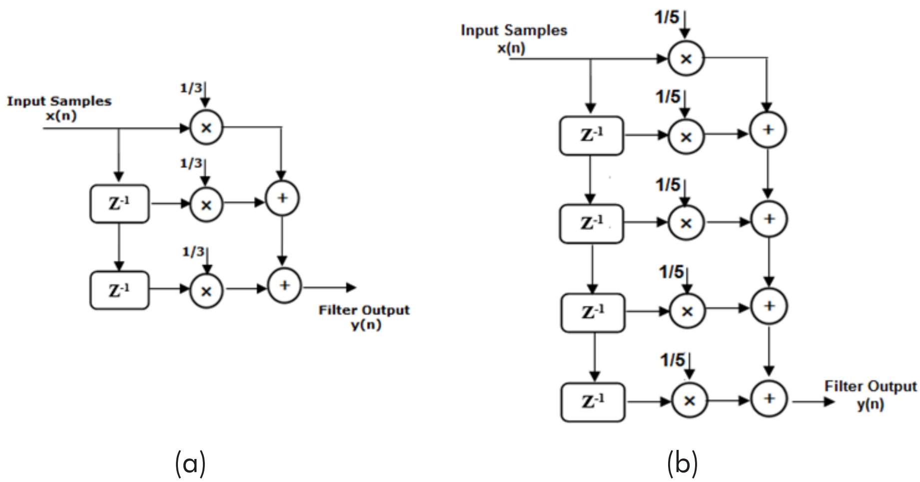


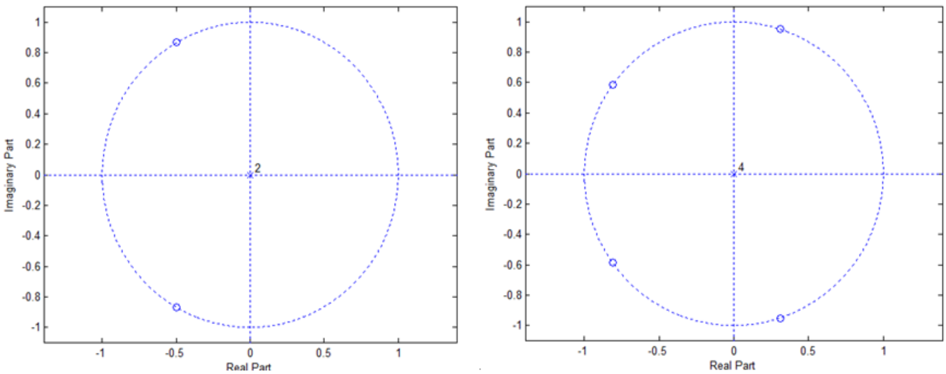
Figure 3: System realization of 3 points MAF (a) and 5 points MAF (b)

2.1.3 Filter performance analysis

Performance analysis is used to ensure that the filter is stable and the filter design doesn't have irregularity behaviors. In general, poles and zeroes locations analysis can predict its stability and performance [7]. In our design poles and zeroes located inside unit circle, which indicates that both filters are stable.

https://doi.org/10.59222/ustjet.2.2.4

The zeroes and poles in Z plane are presented in Figure 4 for both filters. Zeroes are marked by circles (○) and the poles (located in the centre of the unit cycle) marked by cross (×). 3 points MAF zeroes equal Z1= -0.5+0.87j and Z2 = -0.5-0.87j, similarly, the zeroes of 5 points MAF equal Z1= -0.809 + j0.5878, Z2= -0.809 - j0.5878, Z3= 0.309 + j0.9511 and Z4= 0.309 - j0.9511. It is clear that all zeroes for both filters are located inside unit cycle, thus this indicates that both filters are stable and effective if they implemented in real practice.



(a) (b)

Figure 4: Zeroes and poles in Z plane for 3 points MAF (a) and 5 points MAF (b)

2.1.4 Filters implementation for noisy pressure signal acquired from a MV

The proposed filters were implemented in real time; therefore, pressure signal was acquired in real time from pressure sensor of reference device [17]. This signal was taken and sent into LabVIEW software where 3 points MAF and 5 points MAF were constructed to remove unwanted noise. Figure 5 illustrates the block diagram of implementation process.

2.2 Experiment setting

MV setting for all experiments was Intermittent Positive Pressure Ventilation (IPPV), respiration rate (RR) was 16 breaths per minute (bpm) and I/E ratio was 1:2.75. In addition, reference device and artificial lung, which are accurate and reliable product, [17, 18] were used in the experiments as shown in Figure 5. Artificial lung was used to mimic two cases of lung, a healthy lung of 50 ml/cmH2O compliance and unhealthy lung of 20 ml/cmH2O compliance [19], for each case; 3 scenarios were conducted to change pressure values according to Vt setting 400 ml, 500 ml and 600 ml respectively.

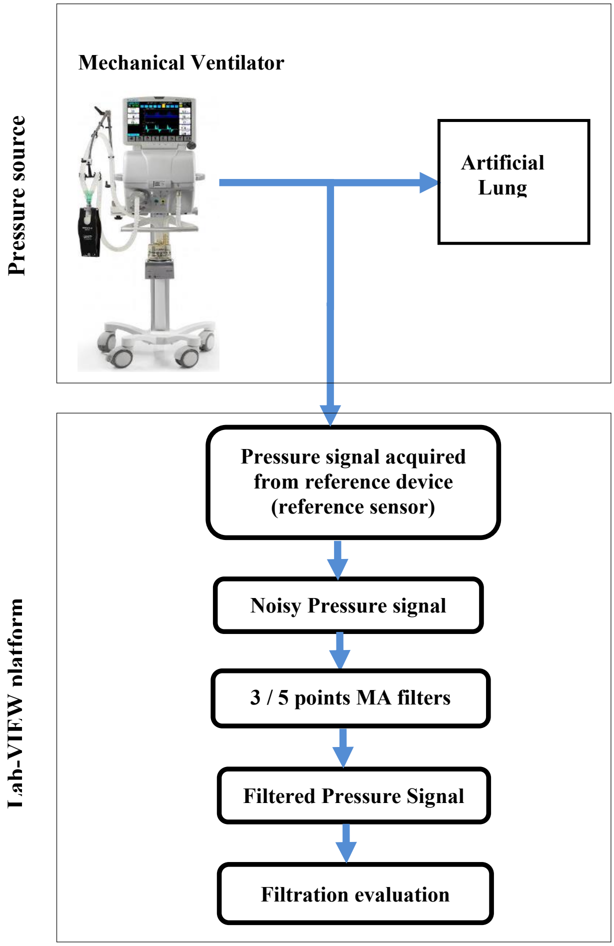


Figure 5: Block diagram of the implementation process

2.3 Evaluation process

Signal to Noise ratio (SNR), measured in dB unit, can be used to evaluate the filtration process. It can compute the filter efficiency by compute both signal smoothness and signal shift after filtration, therefore, The high SNR, the better filter performance. Equation 6 is used for SNR calculation [20].

https://doi.org/10.59222/ustjet.2.2.4

$$\mathrm{SNR} = 10\log\left[\frac{S}{N}\right]^2 \quad (6)$$

Where S is signal amplitude and N is noise amplitude

3. Results and Discussion

The 3 points MAF and 5 points MAF were analyzed. Experimental data, which needed for filters implementation, were obtained by running a MV connected to an artificial lung and a reference device. LabVIEW utilized experimental data to implement both filters, and SNR were calculated to determine which one is better for removing unwanted noise.

Firstly, we investigated the 2 filters using pressure signals acquired from reference device for a healthy lung which was inflated with 400 ml, 500 ml and 600 ml. These 3 scenarios recorded in real time. Figures 6, 7 and 8 showed the obtained results, which demonstrated that the 3 points MAF obtained total of a good curve filtration and less curve distortion than 5 points MAF, therefore, 3 points MAF achieved SNR average 20.992 dB compared to 5 points MAF which achieve average 16.044 dB as shown in Table 1.

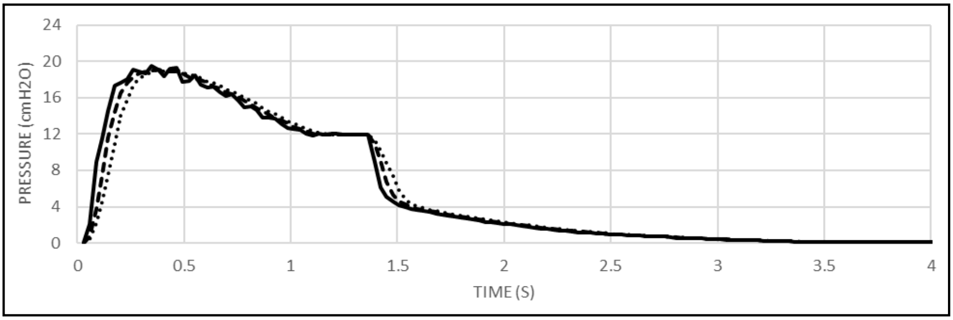


Figure 6: Filteration by 3 points MAF (dashed line) and 5 points MAF (dotted line) for nosiy presssure signal (solid line) at volume 600 ml for healthy lung

https://doi.org/10.59222/ustjet.2.2.4

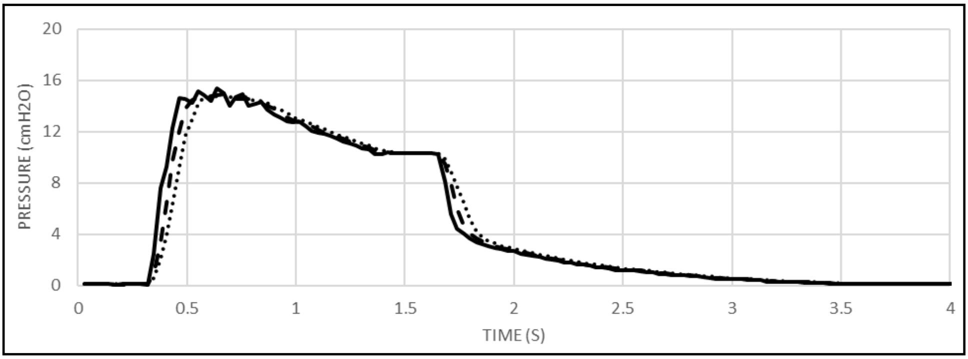


Figure 7: Filteration by by 3 points MAF (dashed line) and 5 points MAF (dotted line) for nosiy presssure signal (solid line) at volume 500 ml for healthy lung

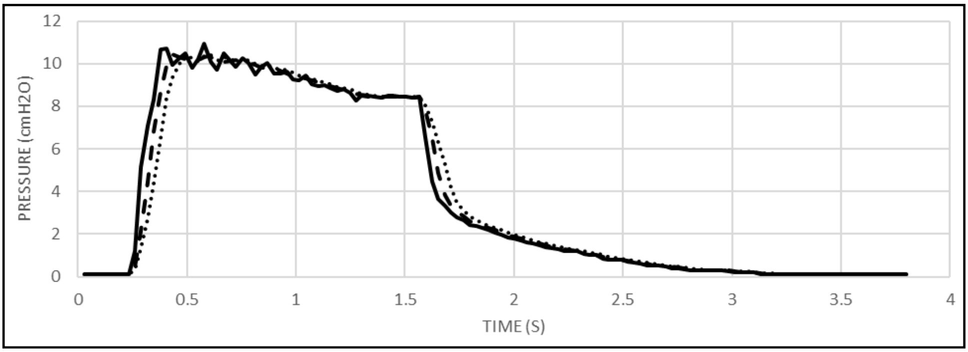


Figure 8: Filteration by 3 points MAF (dashed line) and 5 points MAF (dotted line) for nosiy presssure signal (solid line) at volume 400 ml for healthy lung

Table 1: SNR of 3 points MAF and 5 points MAF for healthy lung

Sensors / Scenarios	Reference Sensor	
	SNR for 3 points MAF (dB)	**SNR for 5 points MAF (dB)**
400 ml	20.84	16.061
500 ml	21.029	16.001
600 ml	21.106	16.069
Average	20.992	16.04

Secondly, we investigated the 2 filters using pressure signals acquired from reference sensor for an unhealthy lung which was inflated with 400 ml, 500 ml and 600 ml. Similarly, these 3 scenarios recorded in real time. Figures

https://doi.org/10.59222/ustjet.2.2.4

9, 10 and 11 showed the obtained results which explained that the 3 points MAF obtained total of a good curve filtration and less curve distortion than 5 points MAF, therefore 3 points MAF achieved SNR average 22.335 dB compared to 5 points MAF which achieved an average 17.31 dB as shown in Table 2.

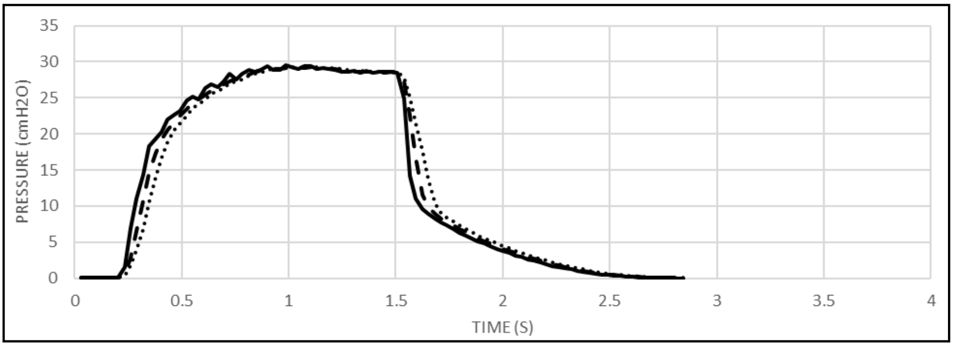


Figure 9: Filteration by 3 points MAF (dashed line) and 5 points MAF (dotted line) for nosiy presssure signal (solid line) at volume 600 ml for unhealthy lung

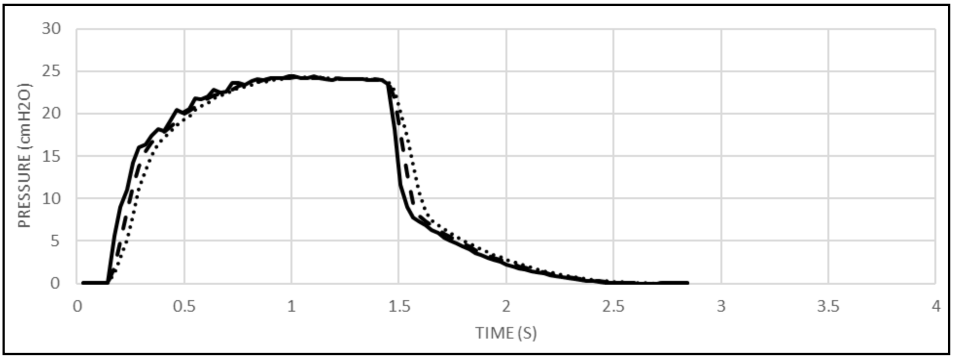


Figure 10: Filteration by 3 points MAF (dashed line) and 5 points MAF (dotted line) for nosiy presssure signal (solid line) at volume 500 ml for unhealthy lung

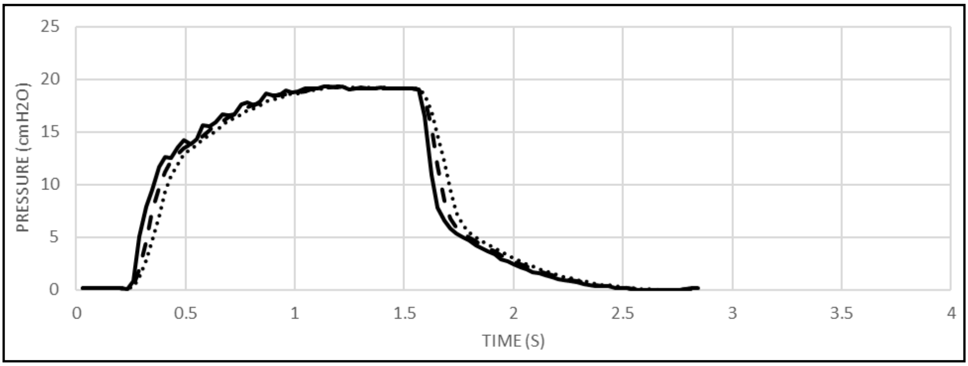


Figure 11: Filteration by 3 points MAF (dashed line) and 5 points MAF (dotted line) for nosiy presssure signal (solid line) at volume 400 ml for unhealthy lung

Table 2: SNR of 3 points MAF and 5 points MAF for unhealthy lung

Sensors / Scenarios	Reference Sensor	
	SNR for 3 points MAF (dB)	**SNR for 5 points MAF (dB)**
400 ml	22.43	17.359
500 ml	22.379	17.34
600 ml	22.195	17.233
Average	22.335	17.31

4. Conclusion

Unwanted noise is considered a problem for signal acquisition in biomedical applications. MAF was used in previous works as a good tool to remove noise. Understanding the trade-off between noise elimination and signal distortion is challenge and depends on filter length. Therefore, comparative study has been done to study 3-point MAF against 5-point MA filter, and determine which one is better to remove unwanted noise and improve signal quality in real time practice of MV. MATLAB program was used to analyzer the suggested filters and LabVIEW program was used for pressure signal acquisition, implementation process and SNR calculation. Experimental data, for both filters› implementation, were acquired in real time by running a MV connected to an artificial lung and a reference device. Signal filtration and signal shift was considered to prove which one gained better SNR. Thus, this investigation proved that 3 points MAF achieved better efficiency than 5 points MAF in order to remove the unwanted noise of pressure signals during mechanical ventilation process or similar practical biomedical applications. In spite of 3 points MAF demonstrated high SNR and best computational response, nevertheless, we still need to prove 3 points MAF efficiency for many practical pressure sensors. In future, this research can be significant for research works to acquire better pressure signal for MV simulation, modelling or implementation. In general, 3 points MAF can be used to reduce the noise and enhance signal quality for many applications such as design ventilators, research work, and overall biomedical applications, and this can improve health care quality.

Compliance with Ethical Standards

1. Authors› contributions

All authors jointly worked on the results and they read and approved the final manuscript. We confirm that all the Figures and Tables in the manuscript are ours.

2. Availability of data and material

The paper includes all the data and material used in this research.

3. Declaration of Competing Interest

The authors declare that they have no conflict of interest.

4. Human participants and animals

This article contains no studies with human participants or animals performed by any of the authors.

5. Funding statement

This research did not receive any specific grant.

References

[1] Akbarzadeh, S., Ghayvat, H., Chen, C., Zhao, X., Hosier, S., Yuan, W., ... & Chen, W. (2022). A simple fabrication, low noise, capacitive tactile sensor for use in inexpensive and smart healthcare systems. IEEE Sensors Journal, 22(9), 9069-9077. http://doi.org/10.1109/JSEN.2022.3159610

[2] Gattinoni, L., Caironi, P., Cressoni, M., Chiumello, D., Ranieri, V. M., Quintel, M., ... & Bugedo, G. (2006). Lung recruitment in patients with the acute respiratory distress syndrome. *New England Journal of Medicine, 354*(17), 1775-1786. http://doi.org/10.1097/CCM.0000000000000770

[3] Al-Hetari, H. Y., Kabir, M. N., Al-Rumaima, M. A., Al-Naggar, N. Q., Alginahi, Y. M., & Hasan, M. M. (2020, June). A Mathematical Model of Lung Functionality using Pressure Signal for Volume-Controlled Ventilation. In 2020 IEEE International Conference on Automatic Control and Intelligent Systems (I2CACIS) (pp. 135-140). IEEE. http://doi.org/10.1109/I2CACIS49202.2020.9140092

[4] Instruments, D. A. T. A. Q. (2005). A closer look at the advanced CODAS moving average algorithm. AT/MCA CODAS Application Note.

[5] Chen, Y., Li, D., Li, Y., Ma, X., & Wei, J. (2017). Use moving average filter to reduce noises in wearable PPG during continuous monitoring. In eHealth 360°: International Summit on eHealth, Budapest, Hungary, June 14-16, 2016, Revised Selected Papers (pp. 193-203). Springer International Publishing. http://doi.org/10.1007/978-3-319-49655-9_26

[6] Golestan, S., Ramezani, M., Guerrero, J. M., Freijedo, F. D., & Monfared, M. (2013). Moving average filter based phase-locked loops: Performance analysis and design guidelines. *IEEE transactions on power electronics, 29*(6), 2750-2763. http://doi.org/10.1109/TPEL.2013.2273461

[7] Bria, O. N. (1999). John G. Proakis and Dimitris G. Manolakis, Digital signal processing. Principles, algorithms, and aplications. J*ournal of Computer Science and Technology, 1*(1), 1.

[8] Liu, J., Gao, Z., Li, Y., Lv, S., Liu, J., & Yang, C. (2024). Ranging Offset Calibration and Moving Average Filter Enhanced Reliable UWB Positioning in Classic User Environments. *Remote Sensing, 16*(14), 2511. http://doi.org/10.3390/rs16142511

[9] Luo, W., & Wei, D. (2020). A frequency-adaptive improved moving-average-filter-based quasi-type-1 PLL for adverse grid conditions. *IEEE Access, 8*, 54145-54153. http://doi.org/10.1109/ACCESS.2020.2981426

[10] Liu, C., Jiang, J., Jiang, J., & Zhou, Z. (2019). Enhanced grid-connected phase-locked loop based on a moving average filter. *IEEE Access, 8*, 5308-5315. http://doi.org/10.1109/ACCESS.2019.2963362

[11] Rizhky, A. N. B., Wisana, I. D. G. H., & Das, S. (2023). QRS Detection On Heart Rate Variability Readings using Two Moving Average Methods. *Indonesian Journal of Electronics, Electromedical Engineering, and Medical Informatics, 5*(1). http://doi.org/10.35882/ijeeemi.v5i1.258

[12] Chatfield, C., & Xing, H. (2019). *The analysis of time series: an introduction with R*. Chapman and Hall/CRC.

[13] Huang, Q., & Rajashekara, K. (2017). An improved delayed signal cancellation PLL for fast grid synchronization under distorted and unbalanced grid condition. *IEEE Transactions on Industry Applications, 53*(5), 4985-4997. http://doi.org/10.1109/TIA.2017.2700282

[14] Lin, S. L., Guo, N. R., & Chiu, C. C. (2012). Modeling and simulation of respiratory control with LabVIEW. *Journal of Medical and Biological Engineering, 32*(1), 51-60. http://doi.org/10.5405/jmbe.829

[15] Practical Digital Signal Processing for Engineers and Technicians, Edmund Lai PhD, BEng; Lai and Associates, Singapore a book, Lai, E. (2003). Practical digital signal processing. Elsevier.

[16] Ifeachor, E. C., & Jervis, B. W. (2002). Digital signal processing: a practical approach. Pearson Education.

[17] Fluke Biomedical Corporation. (2009).VT PLUS Gas Flow Analyzer Operator›s Manual. PN 2137275.USA.

[18] Artificial Lung-ACCU-LUNG Precision - Fluke Biomedical – USA

[19] Training & Test Lung Operation Manual, www.michiganinstruments.com, REV: 2017-05

[20] https://www.collimator.ai/reference-guides/what-is-signal-to-noise-ratio