Journal of the Australasian Society of Aerospace Medicine (JASAM) No.14 (2025) 19-26
10.2478/asam-2025-0002

# THE UTILITY OF HEART RATE VARIABILITY IN AVIATION AND SPACE MEDICINE

**Corresponding Author**
**Dr Karen Lindsay BSc (Hons) Biomedical Science, MbChB, FRACP**
Department of Clinical Immunology and Allergy
Level 6 Support Building
Auckland City Hospital
Grafton Road, Auckland, New Zealand
Email: klindsay@adhb.govt.nz

Co-Author
Erik Van den Top MHSC ( University of Auckland )
Transformative Insights Limited
27 Ewen Alison Avenue
Devonport, Auckland 0624, New Zealand
Email: erik@transformative-insight.com

**KEYWORDS:**

ANS: Autonomic nervous system; PNS: Parasympathetic nervous system; SNS: Sympathetic nervous system; RR: Time between R-R intervals (ms) on an ECG lead; RSA: Respiratory sinus arrhythmia is heart rate variability in synchrony with respiration, by which the R-R interval on an ECG is shortened during inspiration and prolonged during expiration; SDNN: Standard deviation of all normal-to-normal RR intervals (ms); RMSSD: Root Mean Square of successive RR interval differences (ms); pNN50: The percentage of intervals > 50 ms different from preceding interval; ULF-HRV: Magnitude of variance in the frequency band 0.15-0.40 ; LF-HRV: Magnitude of variance in the frequency band 0.04–0.15 Hz; HF-HRV: Magnitude of variance in the frequency band 0.15-0.40; LF/HF: ratio Low Frequency (LFn) (ms2)/ High Frequency (HFn) (ms2)

## ABSTRACT

Heart rate variability, with modern technology detects the differences between each electro cardiac signal of the heartbeat, and is being utilized across a broad number of fields in aviation and space medicine, such as simulation training, assessment of performance and improvement in safety and wellbeing and has potential in the prediction of incapacitation in Civil Aviation Medicine, from both physical and mental health problems, and monitoring of astronauts in space flight. HRV has seen increasing utility across aviation and aerospace medicine but also has potential as a marker of -chronological aging, stress, cognitive load, recovery and optimal performance. Data needs to be gathered on the population being studied at baseline, and under physiological stress and recovery in the long term and potentially in the occupational role. Aviation Medical examiners need to be skilled at critical analysis of HRV data in predicting incapacity particularly in the aging pilot where there may be many cofounders. HRV biofeedback may enhance aviation medical wellbeing interventions. Aviation Medical Examiners would benefit from understanding the current use and potential of Heart rate variability data.

## INTRODUCTION

### What is heart rate variability

Heart rate variability (HRV) simply put, is a measure of the variation in time between heartbeats (1). The single lead electrocardiogram (ECG) provides information about differences in RR interval length in the QRS complex. Heart rate is determined by intrinsic activity of the sinoatrial node, supplemented by innervation from the vagus nerve which reflects the activity of the parasympathetic part of the autonomic nervous system (ANS). The sympathetic nervous system (SNS) part of the ANS leads to a reduction in HRV through the release of adrenaline and noradrenaline in the blood stream, which impact the sinoatrial node and heart muscle over a period of minutes, while the two (vagal) nerves of the parasympathetic part (PNS) leads to an increase in HRV through the release of acetylcholine from nerves, within seconds (2). HRV is also influenced by respiration. On inspiration the SNS dominates, and on expiration the PNS dominates, creating a respiratory sinus arrythmia (RSA). At rest and during mild exertion, the parasympathetic (vagal) control outweighs the sympathetic effect. In the paradigm of homeostasis of a healthy person, the interaction of the SNS and PNS leads to changes in heart rate variability (3).

A shift in paradigm to systems and chaos theory meant that HRV became understood as an emergent property of interdependent regulatory systems that help humans' adaptation to environmental and psychological challenges (2). Up to 80% of vagal fibres are afferent, providing vital information to the brain about the state of the visceral organs. HRV is a window into the synchronization of brain and heart oscillations (4), and low frequency diurnal variation reflects hypothalamic and endocrine function. Figure 1 shows the broad range of function of the ANS (5). The number and variety of HRV studies has increased exponentially into many different research areas and HRV is increasingly being used alongside Artificial intelligence (AI) (6), and in Occupational Medicine, to evaluate the internal physiological response to changes in temperature, air pressure, oxygenation and pollution and workload (7, 8).

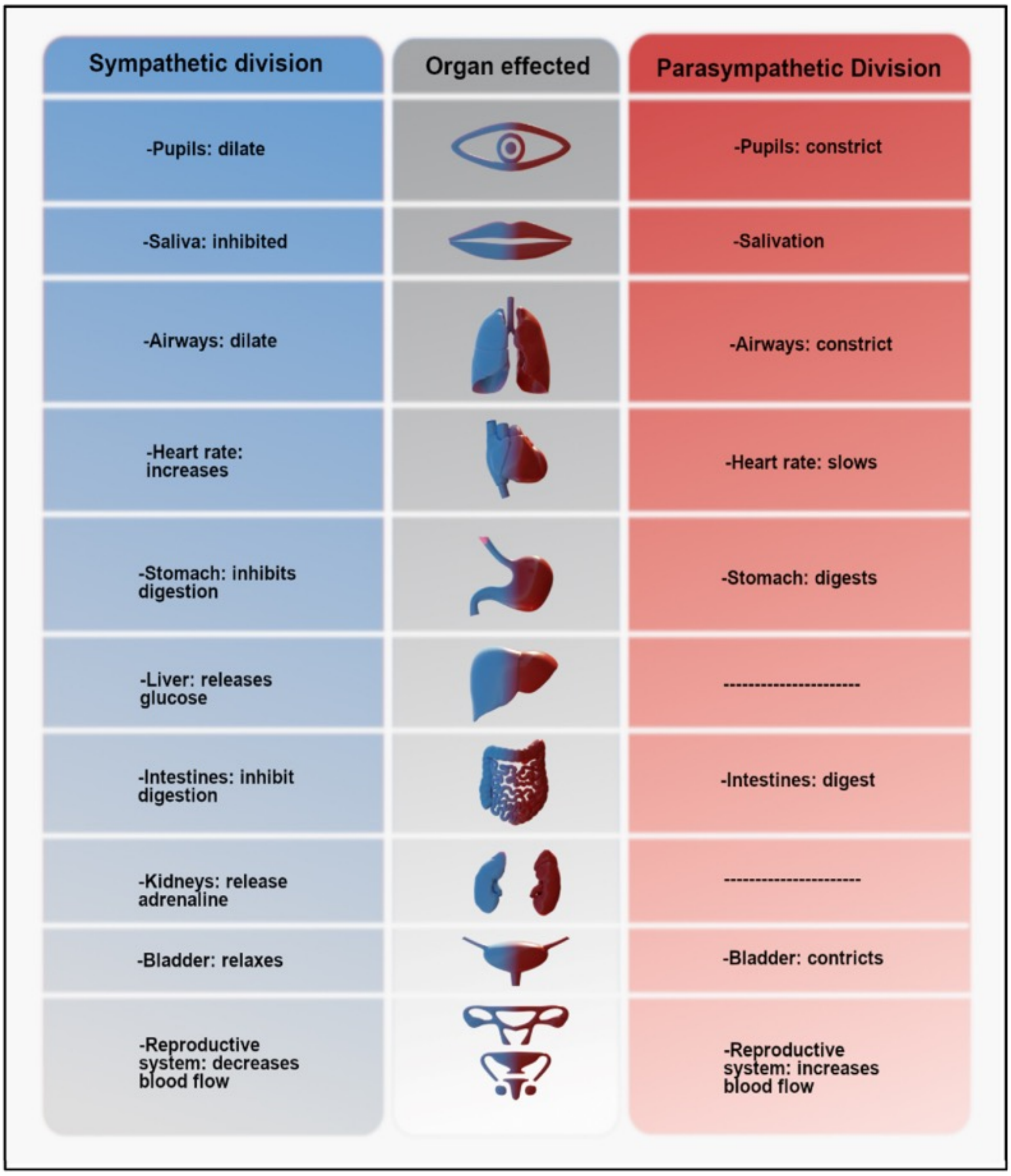


**Figure 1** shows the functions of the autonomic nervous system (5).

## WHAT INFORMATION CAN BE DISCOVERED FROM HRV DATA?

HRV data collection through technology that is affordable, non- invasive and pain free making it readily accessible as wrist watches, rings and other wearables which accurately measure HRV (9) HRV may have clinical utility, for example HRV can be used to diagnose early onset of sepsis e.g. in SARS- Covid-19 infection, as well as track patients progress and recovery (10, 11). There are four domains of analysis in HRV. Time domain, frequency domain, power domain and non-linear methods (2). Figure 2 shows the different outputs that are possible HRV analysis (8). Table 1 shows the metrics used to express HRV.

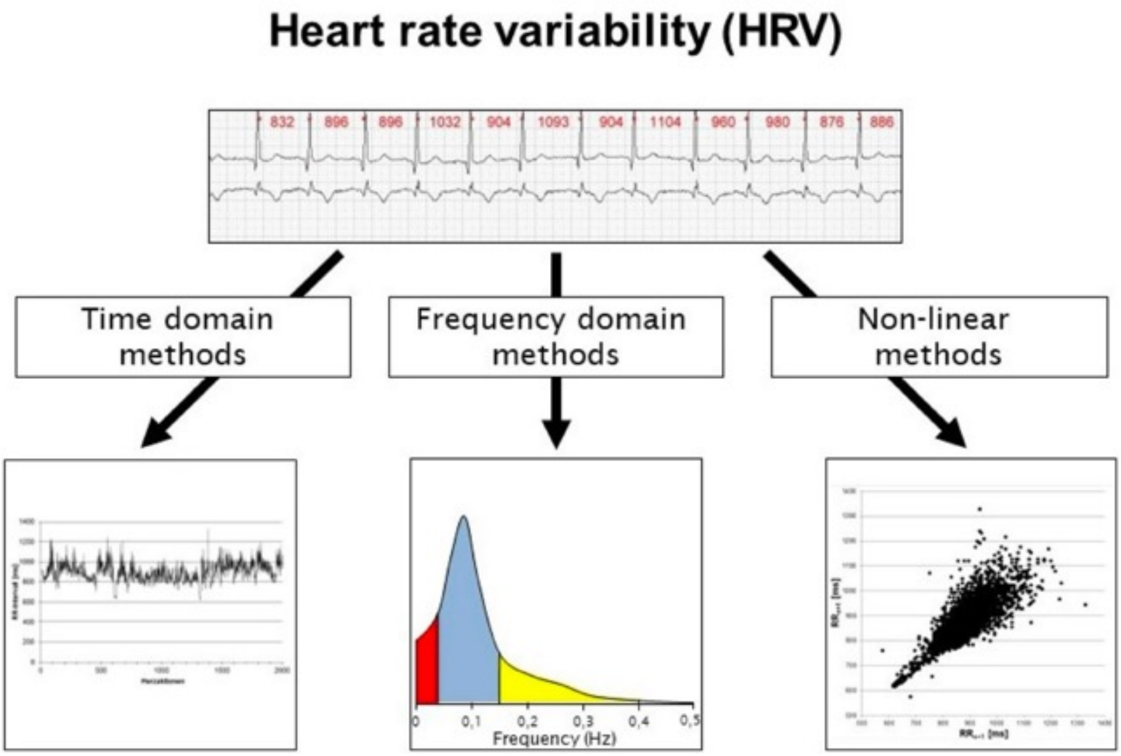


**Figure 2** shows the different outputs that are possible HRV analysis (8).

| Time Domain | | Unit | Physiological equivalent | Meaning | High level | Low level |
|---|---|---|---|---|---|---|
| | SSDN | Millisecond (ms) | Total heart rate variability correlated with ANS activities.<br>All the cyclical influences of physiological processes on the heart | Standard deviation of the normal-to-normal interval | Physiologic resilience against stress | Risk of coronary artery disease.<br>Hypertension, diabetes<br>Depression<br>Cognitive decline<br>(7) |
| | RMSSD | ms | Parasympathetic innervation of the heart<br>Free from respiratory influences | Root mean square of successive differences between normal heartbeats | Good for short term assessment of HRV in-flight | |
| | pNN50 | % | Vagal tone | Percentage of successive normal sinus RR intervals more than 50 ms | | |
| Frequency Domain | LH | (0.04 to 0.15 Hz)<br>Ms2 | PNS and SNS combined | Increased sympathetic activity during mental stress and exercise. | | |
| | HF<br>“The respiratory band” | (0.15 to 0.4 Hz)<br>Ms2 | PNS | High frequency variations in HRV | | Higher stress, panic, anxiety or worry. |
| | LF/HF ratio | | Balance between SNS and PNS activity | | SNS dominance | PNS dominance |
| | Very Low Frequency Range | 0.0033 to 0.04 Hz | Long-term regulation mechanisms, thermoregulation and hormonal mechanisms<br>Astronaut exposure to Space weather (magnetic) | | | |
| | Ultra-low Frequency<br>It can be only assessed with 24 h recording | below 0.0033 Hz.<br>Ms2 | Circadian oscillations, core body temperature. | | | |

**Table 1** Metrics used in HRV

Certain dimensions of the HRV reflect vagal nerve mediated parasympathetic tone. Short measurements over a few minutes show the respiratory cycle and baroreceptor reflexes influence on HRV, which are hence high frequency variations (HF). Low frequency variations (LF) reflect SNS and PNS combined. Non-linear analyses such as the Poincaré plot depict variations in vagal tone at baseline and under stress situations, but the most evidence is for the physiological equivalent of vagal tone (RMSSD, and HF-HRV) (12). The RMSSD is the most widely used measure of HRV and is likely to have the most practical utility in aviation, as it best reflects the domains of interest in aviation and can be accurately checked also over time through nighttime measurements using wearable devices to complement in-flight measurement of HRV (9). This monitoring may signal both to the pilots themselves and the aviation medical examiner a (chronic) undesirable change in HRV trends that may show impending reasons for incapacitation for example cardiovascular disease.

## OBSERVATIONS OF HEART RATE VARIABILITY IN CONDITIONS RELEVANT TO MEDICAL EXAMINERS.

### Cardiovascular risk

International Civil Aviation Authority regulations state prior to allowing a pilot to fly, they must have a medical certificate. Aeromedical assessment of cardiovascular and cerebrovascular risk is based on history examination and judicious requesting of specialist assessment and tests, to aid in the prediction of human factors that could cause incapacitation in flight. HRV is an established predictor of cardiovascular mortality in those with and without known coronary artery disease (13) (14) (15)). (16). HRV is also reduced with hypertension, diabetes, and ischaemic heart disease in occupational studies (8). AI supported databases use HRV to develop predictive models in cardiovascular disease (6).

## COGNITION AND AGEING

The autonomic nervous system shows age-related changes linked to lifelong patterns of behavior, and physiological responses to stressors, all being reflected in the lowering of vagal tone, the long-term consequence of stress known as ‘allostatic load’, measurable by reduced HRV (5). Autonomic dysfunction has been shown to be associated with the development of different age-related diseases, including ischemic stroke, cardiovascular disease, and inflammatory diseases which accumulate with the aging aviator, in a non-chronological manner. The vagus nerve parasympathetic nervous system, inclusive of acetylcholine receptors, downregulates inflammation the so called neuroinflammatory reflex which has been investigated using vagal nerve stimulation to treat diseases such as rheumatoid arthritis (17). In a systematic review of longitudinal studies, reduced HRV indicates poorer cognition, cerebral blood flow and working memory over time, and authors suggest HRV can be a biomarker of cognition over time. (16). HRV therefore has potential to predict inflammatory non-chronological age-related diseases in pilots relevant to the aviation medical examiner.

## MENTAL HEALTH

Pilots often withhold mental health symptoms like suicidality (18). HRV has been extensively studied in depression, posttraumatic stress disorder, stress reactivity, including its use in biofeedback for training resilience (6, 19-21). Studies have found a significant association between PTSD and reduced levels of both high-frequency HRV (HF-HRV), which is highly correlated with respiratory sinus arrhythmia (RSA), and low frequency HRV (LF-HRV) (22, 23). HRV is also a dynamic window on brain function and has been shown in studies to be reduced in threat or stress responses, associated with reduced cerebral blood flow. Higher HRV is associated with better emotional regulation (24). Dr Stephen Porges’ lifelong study of HRV led him to propose that repeated stressors can lead to down-regulation of cardiac vagal tone and chronic up-regulation of sympathetic activity (hyperarousal) at rest, thus linking anxiety and HRV and trauma, providing a valuable current model for measuring therapeutic interventions for trauma (so called Polyvagal Theory)(25).

## HRV STUDIES IN AVIATORS

Research on the complex factors affecting psychophysical state in flight may lead to measures that can reduce the contribution of human error to aviation accidents. Reduced HRV was found in those with known factors affecting HRV (high BMI, older age and increased difficulty of performance) but not CO2 levels. They observed there are complex relationships with aviators and the stress of performance, in some instance stress indicated better performance(26). In-flight HRV measurement using three 60 second periods of R-R measurements from a Faros E-motion 3 lead chest ECG, HRV showed significant quantitative differences in performance in virtual vs real flight tests, but qualitatively the changes in HRV were the same in distinct stages of a flight, e.g., take-off, downwind, landing (27).

HRV is the most studied physiological measure for stress evaluation in military reservists, guardsmen and first responders in the United States and even indicates post-traumatic growth (19) . HRV (HF-HRV) is also an objective measure of the stress response during decision making and mental workload in simulated and real flights in pilots (28) for a comprehensive narrative review. HRV can be incorporated into the cockpit environment for measurement. HRV data from pilots in flight simulations, showed subjective data such as reflective questionnaires (NASA-Task load index) alone, are limited but in flight HRV measurement was much more reliable of workload intensity and predicted the propensity to error (29). Stress lowered HRV, in helicopter pilot training when switching from analogue to digital visual presentations of the flight and navigation data (30). HRV adds value to the assessment of proficiency in aviation simulation training (31).

HRV analysis can provide inflight physiological data on the startle, surprise responses which causes mental incapacitation. Also in simulations training, providing biofeedback can aid in preparing pilots for the unexpected and better enable pilots to overcome the internal physiological responses that can create cognitive impairment, tunnelling, and lock down (32).

There may be blended states such as 'flow' states of ideal and peak performance, for example being at the peak of a U-shaped curve may be the ideal state of balance between SNS and PNS (33). Likewise HRV state may also be optimal performance and recovery from fighter pilot's stress (34).

Whilst studies have yet to link long term mental health outcome measures and baseline HRV measurement in pilots, intervention on training using HRV biofeedback to enhance resilience and wellbeing of HRV and as an outcome in pilots has shown promise (35, 36). Also HRV as biofeedback can be an adjunct to the Aviation Medical exam, as a motivational intervention as part of lifestyle precision medicine which can be tailored to a wide variety of individual medical conditions or occupational environments (37).

## HRV IN MILITARY AVIATION

In the future, individualized biofeedback in military aviation training may form part of the future evolution of human-machine cooperation and add value in the investigation of physiological episodes (PE), contributing to military aviation near-misses and accidents (38). Physiological monitoring in the military includes respiratory oxygen gas levels, functional Near infra-red Spectrophotometry (fNIRS) as a marker of cerebral blood flow (CBF), EEG and ECG, some of which are challenging to integrate into military clothing and cockpits. HRV is being used amongst several other modalities, in several countries' air forces, for fighter pilot simulator training to measure stress and cognitive load, but also the effectiveness of recovery activity (39). Vagal tone (HRV) decreases in Hyperoxia, hypercapnia, and reduces in Hypobaric and hypoxic tasks, early in gravitational loss of consciousness (G-LOC), whole body vibration, heat stress, and sleep deprivation. HRV can be increased by low frequency whole body vibration. A HRV measurement index may be able to measure the cognitive task load under simulated conditions in military training and can differentiate between successful and failed maneuvers (40). HRV is being used to quantitatively assess cognitive load during simulated flight conditions to assess and increase the safety of cadet training (41).

## OUTER SPACE AND MICROGRAVITY

HRV was the chosen outcome measure to study aging on the international space station when the surprising anti-aging effect of long-term space travel on nematodes in space was noted. HRV was associated with diurnal rhythms, and VLF-HRV the effect of geomagnetic 'space weather' in astronauts (42). HRV measurement could be used alongside artificial intelligence to enhance remote monitoring of wellbeing in space (43).

The following are drawn from guidelines regarding HRV research

1. HRV measurement is sensitive to different methodological aspects, which hinders direct comparison between studies.
2. Different outcomes require different duration of measurement e.g., SSDN needs several hours of recording for a correct analysis, very low and ultra-low frequency time outcomes may require 24 hours of measurement.
3. Any chosen outcome measure should be one with a strong physiological correlate such as RMSSD of vagal tone.
4. HRV data is rarely of value alone and must usually be supplemented by other questionnaires or physiological data when looking at the outcome being measured.
5. HRV experiments are usually underpowered to find effects sizes, so it is important to ensure researchers have powered a study correctly when planning HRV research.
6. Normal HRV values are affected by the rate of respiration which should ideally be between 9 and 24 cycles per minute and the same across subjects in particular studies. The respiratory rate should be recorded.
7. Movement artifact, whereby muscular discharges interfere with ECG measurement need to be removed prior to analysis. RR interval should ideally be measured from the observation of raw ECG data. Nocturnal measurement methods to measure resting HRV is preferred and have been validated (9).
8. The analysis of HRV data has been made very accessible through a free popular software, Kubios (44) but this can miss data, favouring raw data analysis.
9. Ideally the raw data analyst should be blinded to the intervention to prevent the introduction of bias.
10. When studying interventions on in-flight performance challenges, habituation is a recognized phenomenon, so variation in the challenge being investigated is suggested.
11. Normal measurements for Healthy adults have been published (45) but conclusions based on HRV research should ideally be from normative data in the population being studied i.e., pilots (46).
12. There are revealed large inter-personal variation for the majority of HRV measures. Making the participant their own control with at least 5 minutes resting data is suggested (3, 8).
13. As a novel environment further studies and validation of the impact of space travel on human physiology and HRV are warranted (43).

## CONCLUSION

HRV has seen increasing utility across aviation and aerospace medicine but also has potential as a marker of both mental and physical disease, non-chronological aging, stress, cognitive load, recovery and optimal performance. Data needs to be gathered on the population being studied at baseline, and under physiological stress and recovery in the long term and potentially in the occupational role. Aviation Medical examiners need to be skilled at critical analysis of HRV data in predicting incapacity particularly in the aging pilot where there may be many cofounders. HRV biofeedback may enhance aviation medical wellbeing interventions. The study of HRV and its utility as biofeedback and as a potential window on autonomic neuroplasticity is likely to enhance future developments in pilot training, mitigating the impact of occupational workload, and potentially retrospective investigation of aviation accidents.

## REFERENCES


1. Kwon O, Jeong J, Kim HB, Kwon IH, Park SY, Kim JE, et al. Electrocardiogram Sampling Frequency Range Acceptable for Heart Rate Variability Analysis. Healthc Inform Res. 2018;24(3):198-206.
2. Ernst G. Heart-Rate Variability-More than Heart Beats? Front Public Health. 2017;5:240.
3. Laborde S, Mosley E, Thayer JF. Heart rate variability and cardiac vagal tone in psychophysiological research–recommendations for experiment planning, data analysis, and data reporting. Frontiers in psychology. 2017;8:213.
4. Mather M, Thayer J. How heart rate variability affects emotion regulation brain networks. Curr Opin Behav Sci. 2018;19:98-104.
5. Alrosan AZ, Heilat GB, Alrosan K, Aleikish AA, Rabbaa AN, Shakhatreh AM, et al. Autonomic brain functioning and age-related health concerns. Current research in physiology. 2024:100123.
6. Faust O, Hong W, Loh HW, Xu S, Tan RS, Chakraborty S, et al. Heart rate variability for medical decision support systems: A review. Comput Biol Med. 2022;145:105407.
7. Togo F, Takahashi M. Heart rate variability in occupational health --a systematic review. Ind Health. 2009;47(6):589-602.
8. Sammito S, Thielmann B, Klussmann A, Deussen A, Braumann KM, Bockelmann I. Guideline for the application of heart rate and heart rate variability in occupational medicine and occupational health science. J Occup Med Toxicol. 2024;19(1):15.
9. Miller DJ, Sargent C, Roach GD. A Validation of Six Wearable Devices for Estimating Sleep, Heart Rate and Heart Rate Variability in Healthy Adults. Sensors (Basel). 2022;22(16).
10. van Wijk RJ, Quinten VM, van Rossum MC, Bouma HR, Ter Maaten JC. Predicting deterioration of patients with early sepsis at the emergency department using continuous heart rate variability analysis: a model-based approach. Scand J Trauma Resusc Emerg Med. 2023;31(1):15.
11. 
12. Colas C, Le Berre Y, Fanget M, Savall A, Killian M, Goujon I, et al. Physical Activity in Long COVID: A Comparative Study of Exercise Rehabilitation Benefits in Patients with Long COVID, Coronary Artery Disease and Fibromyalgia. Int J Environ Res Public Health. 2023;20(15).
13. Shaffer F, Ginsberg JP. An overview of heart rate variability metrics and norms. Frontiers in public health. 2017;5:258.
14. Navathe P, Drane M, Preitner C. Aeromedical decision making: from principles to practice. Aviation, Space, and Environmental Medicine. 2014;85(5):576-80.
15. Venkatesh D, Shenoy AR, Prakash V. Alteration of heart rate variability in patients with coronary artery disease. National Journal of Physiology, Pharmacy and Pharmacology. 2018;8(6):820-3.
16. Tsuji H, Venditti Jr FJ, Manders ES, Evans JC, Larson MG, Feldman CL, et al. Determinants of heart rate variability. Journal of the American College of Cardiology. 1996;28(6):1539-46.
17. Liao D, Cai J, Rosamond WD, Barnes RW, Hutchinson RG, Whitsel EA, et al. Cardiac autonomic function and incident coronary heart disease: a population-based case-cohort study: the ARIC Study. American journal of epidemiology. 1997;145(8):696-706.
18. Marsal S, Corominas H, de Agustín JJ, Pérez-García C, López-Lasanta M, Borrell H, et al. Non-invasive vagus nerve stimulation for rheumatoid arthritis: a proof-of-concept study. The Lancet Rheumatology. 2021;3(4):e262-e9.
19. Wu AC, Donnelly-McLay D, Weisskopf MG, McNeely E, Betancourt TS, Allen JG. Airplane pilot mental health and suicidal thoughts: a cross-sectional descriptive study via anonymous web-based survey. Environmental health. 2016;15:1-12.
20. Hourani LL, Davila MI, Morgan J, Meleth S, Ramirez D, Lewis G, et al. Mental health, stress, and resilience correlates of heart rate variability among military reservists, guardsmen, and first responders. Physiology & behavior. 2020;214:112734.
21. Clemente-Suárez VJ, Ruisoto-Palomera P. Effects of the psychophysiological stress response in human behavior. 2020. p. 112761.

22. Kim H-G, Cheon E-J, Bai D-S, Lee YH, Koo B-H. Stress and heart rate variability: a meta-analysis and review of the literature. Psychiatry investigation. 2018;15(3):235.

23. Schneider M, Schwerdtfeger A. Autonomic dysfunction in posttraumatic stress disorder indexed by heart rate variability: a meta-analysis. Psychological medicine. 2020;50(12):1937-48.

24. Hauschildt M, Peters MJ, Moritz S, Jelinek L. Heart rate variability in response to affective scenes in posttraumatic stress disorder. Biological psychology. 2011;88(2-3):215-22.

25. Thayer JF, Åhs F, Fredrikson M, Sollers III JJ, Wager TD. A meta-analysis of heart rate variability and neuroimaging studies: implications for heart rate variability as a marker of stress and health. Neuroscience & Biobehavioral Reviews. 2012;36(2):747-56.

26. Porges SW. Heart rate variability: A personal journey. Applied Psychophysiology and Biofeedback. 2022;47(4):259-71.

27. Cao X, MacNaughton P, Cadet LR, Cedeno-Laurent JG, Flanigan S, Vallarino J, et al. Heart rate variability and performance of commercial airline pilots during flight simulations. International journal of environmental research and public health. 2019;16(2):237.

28. Labedan P, Darodes-de-Tailly N, Dehais F, Peysakhovich V, editors. Virtual Reality for Pilot Training: Study of Cardiac Activity. VISIGRAPP (2: HUCAPP); 2021.

29. Masi G, Amprimo G, Ferraris C, Priano L. Stress and workload assessment in aviation—a narrative review. Sensors. 2023;23(7):3556.

30. Alaimo A, Esposito A, Orlando C, Simoncini A. Aircraft pilots workload analysis: heart rate variability objective measures and NASA-task load index subjective evaluation. Aerospace. 2020;7(9):137.

31. Hajra SG, Xi P, Law A, editors. A comparison of ECG and EEG metrics for in-flight monitoring of helicopter pilot workload. 2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC); 2020: IEEE.

32. Mansikka H, Virtanen K, Harris D, Simola P. Fighter pilots' heart rate, heart rate variation and performance during an instrument flight rules proficiency test. Applied ergonomics. 2016;56:213-9.

33. Landman A, Groen EL, Van Paassen M, Bronkhorst AW, Mulder M. Dealing with unexpected events on the flight deck: A conceptual model of startle and surprise. Human factors. 2017;59(8):1161-72.

34. Chin MS, Kales SN. Is there an optimal autonomic state for enhanced flow and executive task performance? Frontiers in Psychology. 2019;10:1716.

35. Hormeño-Holgado AJ, Clemente-Suárez VJ. Effect of different combat jet manoeuvres in the psychophysiological response of professional pilots. Physiology & Behavior. 2019;208:112559.

36. Zhang J, Li W-C, Andrews G. Applying psychophysiological coherence training based on HRV-biofeedback to enhance pilots' resilience and wellbeing. Transportation research procedia. 2022;66:49-56.

37. Zhang J, Li W-C, Braithwaite G, Blundell J. Practice effects of a breathing technique on pilots' cognitive and stress associated heart rate variability during flight operations. Stress. 2024;27(1):2361253.

38. van den Top E. Design and evaluation of an online healthy lifestyle programme: ResearchSpace@ Auckland; 2022.

39. Shaw DM, Harrell JW. Integrating physiological monitoring systems in military aviation: a brief narrative review of its importance, opportunities, and risks. Ergonomics. 2023;66(12):2242-54.

40. Mansikka H, Simola P, Virtanen K, Harris D, Oksama L. Fighter pilots' heart rate, heart rate variation and performance during instrument approaches. Ergonomics. 2016;59(10):1344-52.

41. Soares ABF, Almeida MFd, Franchini E, Ferreira FG, Campos FAD. Heart Rate Variability in Military Pilots During Flight: A Scoping Review. Military Medicine. 2024:usae390.

42. Yang J, Tang M, Cong L, Sun J, Guo D, Zhang T, et al. Development and validation of an assessment index for quantifying cognitive task load in pilots under simulated flight conditions using heart rate variability and principal component analysis. Ergonomics. 2024;67(4):515-25.

43. Otsuka K, Cornelissen G, Kubo Y, Shibata K, Mizuno K, Ohshima H, et al. Anti-aging effects of long-term space missions, estimated by heart rate variability. Scientific reports. 2019;9(1):8995.

44. Greatbatch C. The Role of Artificial Intelligence in Space Medicine. Journal of the Australasian Society of Aerospace Medicine. 2024;13(1):1-5.

45. Tarvainen MP, Niskanen J-P, Lipponen JA, Ranta-Aho PO, Karjalainen PA. Kubios HRV–heart rate variability analysis software. Computer methods and programs in biomedicine. 2014;113(1):210-20.

46. Nunan D, Sandercock GR, Brodie DA. A quantitative systematic review of normal values for short-term heart rate variability in healthy adults. Pacing and clinical electrophysiology. 2010;33(11):1407-17.

47. Ernst G. Hidden signals—the history and methods of heart rate variability. Frontiers in public health. 2017;5:265.