Austin Journal of Cardiovascular Disease & Atherosclerosis

Open Access

Austin Publishing Group

Research Article

Automating Event Holter Monitoring: Balancing IoT and Medical Telemetry in Paediatric Care

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Received: March 01, 2024

Accepted: April 05, 2024

Published: April 12, 2024

Abstract

This study, conducted from September 2020 to March 2023, evaluates the efficacy of advanced cardiac telemetry with a focus on the EHO-MINI Event Holter in paediatric cardiology. Through an analysis of 12 201 paediatric cases, the research identifies an increase in the application of remote cardiac monitoring post-COVID-19, both in clinical settings and educational environments. The integration of smart wearables and specialised devices such as the Event Holter ECG has been found to improve the detection and management of arrhythmias in children, enhancing diagnostic precision and treatment outcomes. Results have shown a significant year-on-year increase in 'significant' test results, demonstrating the sensitivity of these tools in clinical interventions, including the performance of 33 ablations. Ethical considerations concerning the use of automated telemetry and the security of patient data are discussed, highlighting the imperative of maintaining human oversight. The study also presents statistical evidence indicating marked differences in cardiac health across diverse patient demographics. It concludes that while technological advancements in telemetry offer substantial benefits in paediatric healthcare, they must be utilized judiciously, ensuring that the enhancement of patient outcomes is balanced with the ethical imperatives of healthcare.

Introduction

With the advent of technology, the healthcare sector is witnessing significant strides in automating cardiac telemetry, particularly in paediatric groups. This transformation is characterized by the growing use of event Holter monitors, portable devices adept at continuously recording cardiac rhythms [1]. Their automated features enhance the detection of arrhythmias and enable seamless data transmission to centralized systems using the Internet of Things (IoT) and medical telemetry [2,3].

The paediatric demographic is particularly vulnerable to rhythm abnormalities, with incidence rates for certain anomalies ranging between 2 to 8 per 100,000 among school-aged children [4]. While many of these irregularities might appear benign [5], they mask underlying threats. A US-based study highlighted the gravity of the situation, attributing 55 cases per 100,000 paediatric emergency department visits to irregular heart rhythms [6]. This diagnostic challenge is further compounded when we consider that sudden cardiac deaths account for 5% of paediatric fatalities [7].

Prompt diagnosis becomes crucial given the potential repercussions these irregularities can have, including life-threatening arrhythmias and conditions like cardiomyopathy [8]. Holter ECG monitoring stands out as an essential tool, excelling in capturing transient arrhythmias. Its automation capabilities allow for correlations between ECG rhythms and concurrent symptoms, providing accurate diagnoses and shedding light on the severity of the arrhythmias [9]. Such insights guide treatment strategies and also gauge the child's overall well-being, crucial as many children limit physical activities pending treatments.

Although primary symptoms like palpitations, fatigue, and syncopal episodes might seem innocuous, they often allude to underlying cardiac concerns. Paediatricians, with their clinical expertise, play a pivotal role in early detections and referrals, ensuring timely interventions [10].

Arrhythmias in children often stem from developmental conditions, structural anomalies, or conduction irregularities, devi-

Citation: Bossowski F, Skorupska M, Ostrowska S, Kościuszko Z, Kożuchowska A, et al. Automating Event Holter Monitoring: Balancing IoT and Medical Telemetry in Paediatric Care. Austin J Cardiovasc Dis Atherosclerosis. 2024; 11(1): 1063.

ating from adult patterns where ischemic myocardial damage dominates [11]. An array of non-cardiac factors further complicates the paediatric arrhythmogenic landscape [12].

The integration of telemetry into healthcare represents a groundbreaking advancement, particularly evident in adult care settings [13]. However, its adoption in paediatric care, especially in regions like Bialystok, Poland, is still in its nascent stages. This research seeks to bridge the literature gap on telemetry's role in Polish paediatric cohorts. The primary aim is to evaluate the interplay between automated Holter monitoring, IoT, and medical telemetry, focusing on their utility and efficacy in paediatric and adolescent populations.

Delving deeper, the study will investigate prevalent cardiac and non-cardiac conditions associated with arrhythmias, and the principal causes of syncope, palpitations, and chest pain in the young demographic. Central to our exploration is the determination of the advantages and drawbacks of such tools. We will critically assess the balance, debating the merits and challenges of introducing full or partial automation in telemetry applications for paediatric care.

Methods

Holter monitoring, traditionally used for tracking cardiac activities over extended periods, provides continuous ECG data. While classic Holter devices necessitated manual operations, recent advancements have ushered in automated versions that harness the power of the Internet of Things (IoT) and medical telemetry, enhancing data accuracy and accessibility [14]. These cutting-edge tools, capable of initiating both manual and automatic ECG recordings based on patient activity and detected arrhythmias, form the core of our research. The main aim of this study, particularly emphasises modern approaches to Holter monitoring, including telemetry, automatic diagnosis, emergency signaling, and the seamless integration of these devices within the IoT ecosystem.

For the purpose of our research, we focused on analyzing data previously collected using the EHO-Mini device from the company Pro-PLUS. This device, optimized for cardiac rehabilitation, wirelessly captures and transmits 2 or 3-channel ECG recordings, making it suitable for both outpatient and at-home settings. The EHO-Mini integrates dual alert systems, with colored indicators and auditory signals, to indicate operational statuses. It facilitates both manual and automatic ECG recording triggers. Depending on its variant, the device can either utilize two interchangeable precordial leads (for the 2-channel version) or a combination of limb and precordial leads (for the 3-channel version). Importantly, clinicians have the capability to remotely adjust these lead configurations, tailoring the diagnostic process to individual patient assessments.

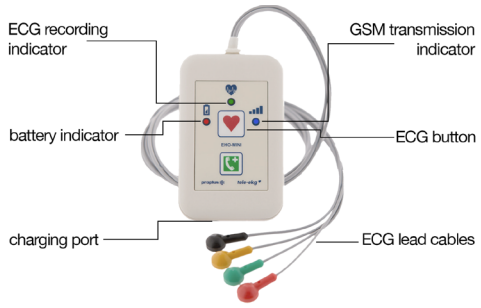

Figure 1: A schematic overview of the EHO Mini Device, with labels indicating the most crucial parts.

Figure 2: A visual snapshot of the online telemetry platform's graphical user interface.

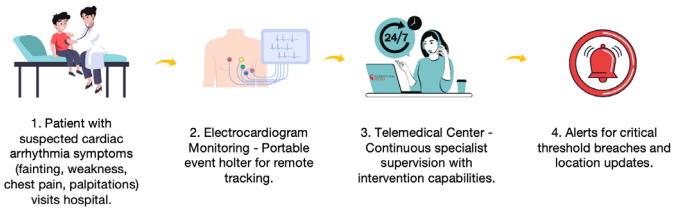

Figure 3: A schematic overview of the communication pipeline. The monitored data are sent to the physician team responsible for supervising the patient and notifying the cardiologist about any abnormal reading. The patient is then supplied with necessary medical aid, and kept under further observation. Graphics: [16].

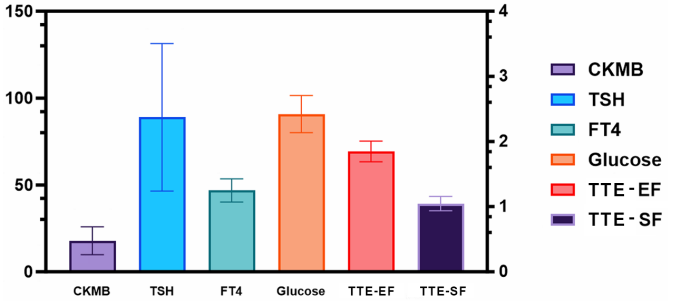

Figure 4: The bar graph of biomarker and echocardiographic measurements for the patient group.

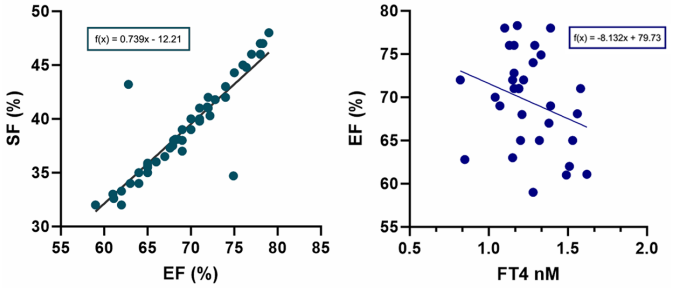

Figure 5: Comparative Scatter Plots: Correlations between EF-SF (Left) and EF-FT4 (Right).

Telemetry Device Overview

The EHO-MINI Event Holter device has been engineered to facilitate the acquisition of cardiac electrical activity, offering the capability to switch between two precordial or six limb leads in its 2-channel iteration, and an expanded array of three precordial alongside six limb leads with an additional precordial lead for 3-channel models. Lead selection is remotely configured by medical practitioners, enabling a tailored approach to each patient's condition. The apparatus captures ECG tracings and transmits them digitally via an inbuilt GSM network interface. This functionality permits both patient-initiated and automatic recording to document symptomatic and asymptomatic cardiac events.

Incorporated within the device is a GSM/GPRS module that enables the instantaneous transfer of ECG data to a designated telemedicine service, facilitating prompt analysis. Following

successful data transmission, the device automatically clears its storage, a feature complemented by an internal memory buffer to safeguard against data loss during transient medical episodes, such as syncope. The device is equipped with visual and auditory cues that signal its operational status, including battery levels, connectivity, and recording commencement.

During use, the EHO-MINI maintains a continuous recording loop. It empowers patients to actuate a recording when experiencing cardiac symptoms, such as palpitations or angina, ensuring the event is documented for subsequent medical review. The device's operational longevity post-charge exceeds 24 hours, although this may fluctuate based on variables like signal reception. In scenarios where network transmission is compromised, the device can locally store approximately 25 minutes of ECG data, which will be transmitted once connection stability is re-established.

Furthermore, the EHO-MINI is designed to work in conjunction with auxiliary medical apparatuses such as arm blood pressure monitors, weighing scales, and oxygen saturation probes, offering an integrative approach to patient health monitoring. The transmission efficiency of the GSM/GPRS feature is contingent on signal strength, which can be problematic in remote or poorly served network locales. Of note, the device is contraindicated for patients with cardiac pacemaker-defibrillators, due to its lack of shielding against defibrillation shocks, and it is not impervious to water.

For enhanced patient safety, especially during physical activities, the EHO-Mini can be optionally fitted with a GPS module. Another standout feature is the device's capability for direct voice communication. Thanks to an in-built hands-free kit and GSM modem, patients can make telephone calls directly to their doctor or monitoring unit. Furthermore, in emergencies, the recorded ECG is promptly reviewed by a team, which then communicates findings to the relevant doctors. Integration with the CardioSCP software and its corresponding web platform optimises the process of data collection and analysis. Another advantage is the device's cost-efficiency, boasting the most competitive price on the market. Additionally, there's no need to purchase replaceable batteries; the EHO-Mini features an in-built rechargeable battery, conveniently charged with the supplied charger [15].

Patient Safety

Cardiac telemetry outpatient monitoring, whilst non-invasive, can occasionally lead to skin irritations or allergic reactions from the adhesives in ECG patches. In isolated cases, infections might develop, necessitating antibiotic intervention. Event Holter ECG, akin to other ECG devices, can sometimes provide imprecise heart activity data due to issues like incorrect electrode positioning or equipment faults. However, it is pertinent to highlight that for each patient who received this telemetric Holter, precautions were taken prior to its use, and we recorded no problematic instances.

Research Group

For the methodology of our study, we analyzed all the patients from the Department of Paediatrics, Endocrinology, Diabetology with Cardiology Divisions at the Medical University of Bialystok who had undergone telemetric cardiological ECG monitoring via a Holter device. The primary objective of this research was to create a generalised patient profile based on telemetry solutions, ascertain the effectiveness and utility of this approach, and broaden our understanding of telemetric Holter applications as a smart IoT device [17].

Results

In this study, we tracked paediatric telemetry use from September 2020 to March 2023, involving a total of 186 patients aged between 3 to 18 years. The volume of examinations increased significantly year by year. In the initial trimester from September to December 2020, we conducted 386 telemetry studies, with 45 marked as significant and 6 described in detail. The following year, 2021, saw a substantial increase with 4243 studies performed, 241 of which were highlighted as crucial, and 60 thoroughly detailed. In 2022, the volume peaked at 6307 studies, with 441 marked as significant, and 126 detailed. In the initial two months of 2023, we carried out 1265 studies, 64 of them deemed important, with 45 described comprehensively, resulting in an impressive cumulative of 12,201 studies. This data signifies an amplified reliance on telemetry as a diagnostic instrument in paediatric care.

Notably, the number of patients with 'important' tests have risen from 12 in the last quarter of 2020, to 52 in 2021, decreased slightly to 35 in 2022, and were 5 in the first two months of 2023. Furthermore, as a direct consequence of these telemetry studies, 33 patients underwent ablation, highlighting the invaluable role of telemetry in the diagnosis and management of paediatric cardiac conditions.

The ECG recordings were transmitted in real-time to a 24-hour Telemedicine Center (Telemedycyna Polska S.A.), where they were evaluated by medical personnel (paramedics trained in ECG interpretation, with the possibility to consult the tracing with the cardiologist). In the event of significant rhythm or conduction disturbances, the Telemedicine Center personnel contacted the patient or his/her parents and informed physicians from the Department of Paediatrics, Endocrinology, Diabetology with Cardiology Division. In the rare cases of life-threatening arrhythmias, the medical emergency team was called.

Patient Profile

The patient group had an average age of 13.4 years (±3.796) and a median weight of 56 kg (range: 10-92 kg). They averaged a height of 159.5 cm and a BMI of 20.93 (range: 11.7-34.11), demonstrating diverse body compositions. Key biomarkers, including CKMB (mean: 17.91; range: 9.000-49.00), TSH (mean: 2.373; range: 0.9700-6.180), FT4 (mean: 1.249; range: 0.8200-1.620), and glucose levels (mean: 90.81; range: 72.00-119.0), varied across the cohort. The following data can be found in the table below.

Clinical Overview

Nearly half of our patient cohort (48%) exhibited symptoms of heart palpitations, arrhythmias, or tachycardia. Another 33% reported episodes of fainting, loss of consciousness, or dizziness. Chest discomfort was mentioned by 18% of patients. Routine cardiological evaluations or subsequent visits constituted 14% of the cases, while 4% presented with respiratory complaints. Of particular note, we identified several distinct cases in our study: 2 patients displayed COVID-related complications, 1 exhibited diabetes-related concerns, 2 had signs of hypertension or raised blood pressure, 3 reported photophobia or visual disturbances, 2 demonstrated emotional distress, and 1 was diagnosed with cardiomyopathy. These cases highlight the breadth of health issues seen in paediatric telemetry.

Table 1: Summary Statistics of Age, Weight, Height, and BMI for the Patient Group.

	Age	Weight	Height	BMI
Minimum	3	10	86	11.70
Maximum	19	92	187.5	34.11
Median	14	56	165	20.12
Mean	13.4	53.39	159.5	20.93
Std. Deviation	3.796	19.71	20.41	4.308

Table 2: Biomarker and Echocardiographic Measurements of the Patient Group.

	CKMB	TSH	FT4	Glucose	TTE (EF)	TTE (SF)
Minimum	9.000	0.9700	0.8200	72.00	45.00	32.00
Maximum	49.00	6.180	1.620	119.0	79.00	48.00
Median	16.00	2.070	1.210	89.50	70.00	39.00
Mean	17.91	2.373	1.249	90.81	69.30	39.31
Std. Deviation	8.006	1.133	0.1787	10.67	5.971	4.122

Cardiac and Biochemical Profile

In our paediatric patient study, we evaluated crucial TTE (transthoracic echocardiogram) parameters - Ejection Fraction (EF) and Shortening Fraction (SF) — to assess cardiac systolic function. The EF, reflecting left ventricular function, averaged 69.30% (range: 45.00% - 79.00%), suggesting satisfactory function in most but compromised systolic function in some. The SF, measuring myocardial fiber shortening during contraction, averaged at 39.31% (range: 32.00% - 48.00%), aligning with paediatric norms but also indicating diverse heart function within our cohort.

This variability in cardiac function, underscored by standard deviations of 5.971 for EF and 4.122 for SF, complements findings from other key biomarkers like CKMB, TSH, FT4, and glucose. The diverse cardiac conditions, etiologies, and severities we observed are further detailed in the table below, which presents our biochemical findings.

Statistical Analysis

In the comprehensive statistical analysis of medical telemetry data, an ANOVA test yielded an F-value of 1914, signalling notable differences among the evaluated groups or columns, further cemented by a remarkably low P-value below 0.0001. Supplemental assessments, including the Brown-Forsythe test, indicated an F-value of 24.55 with degrees of freedom as (5, 290), while Bartlett's test presented a corrected statistic of 452.2. Both of these tests also reported P-values of <0.0001, emphasising the robustness of the results across all columns.

Delving into specific biomarker relationships, the connection between FT4 and EF demonstrated a correlation coefficient of 0.04, coupled with another unidentified correlation at -0.359. The associated linear regression for FT4 and EF was Y = −8.132x + 79.73. Conversely, the EF-SF relationship exhibited a coefficient of 0.457, accompanied by an R2 value of 0.001, which suggests a discernible but not overwhelmingly potent association. Its regression equation was y = 0.7391x − 12.21. These observations provide invaluable insights into the intricate dynamics of cardiac metrics and their interrelationships.

Discussion

In the aftermath of the COVID era, there has been a marked shift towards remote medical solutions. This transition, initially propelled by "imposed" measures, has fortuitously found its place as a mainstay in modern healthcare practices. Our paper ventures beyond the mere exposition of applied solutions and their target patient demographics. Instead, it delves into the broader spectrum of technology and its diverse applications.

Evaluating the wider scope of medical readiness within educational institutions, it is perturbing to note that while many schools boast a resident nurse, they often lack in pivotal areas. A prime illustration is the conspicuous absence of essential tools like ECG equipment, and more critically, the expertise for its proficient use. Especially in realms such as paediatric telemetry, these provisions extend beyond mere convenience, potentially proving lifesaving. This investigation underscores the emergent transformation in medical technologies, emphasizing the rise of artificial intelligence in specialties like radiology. As the paper's authors, we spotlight the immense promise held by innovations like IoT and automation, while concurrently acknowledging their constraints when applied in real-world scenarios.

Utility of IoT in Healthcare

Driven by rapid development of IoT technologies, the recent surge in Smart Wearables, encompassing devices such as smartwatches, fitness bands, and bespoke sensors, has marked a paradigm shift in self-monitored cardiac health. While these tools are primarily regarded as lifestyle accessories, their potential in routine medical assessments is increasingly apparent. Although these devices largely employ single-lead ECGs or PPG, their versatility allows for derivation of multiple leads by repositioning the device. The accuracy range of these consumer-oriented devices is varied, yet many adhere to the stringent standards delineated by authoritative entities, such as the European Society of Cardiology and the Food and Drug Administration, for diagnosing specific arrhythmias.

Despite the growing popularity of such solutions in consumer technology, similar ideas are still in need in professional medical equipment. The recent advancements in this area is exemplified in strictly medical applications by the integration of the Event Holter ECG into paediatric healthcare. As a result, professional health monitoring may be fitted seamlessly into the daily routines of younger patients. Its discreet design ensures that children and adolescents can maintain their usual activities without obstacles during cardiac diagnostic phases. This real-time monitoring offers an unparalleled perspective into potential heart rate anomalies that might manifest during specific activities or physical exertions, thus providing a genuine representation of a child's cardiac health. Significantly, its widespread adoption among paediatric patients underscores its potential for consistent and reliable data acquisition.

Adopting a patient-centric approach, the Event Holter ECG affords patients and caregivers the capacity to annotate symptomatic events, such as palpitations or bouts of dizziness. These time-specific indicators are instrumental, aiding clinicians in correlating symptoms with ECG anomalies, and subsequently pinpointing specific arrhythmias or their underlying causes.

With this depth of data, medical professionals can adopt a comprehensive evaluation, tailoring interventions ranging from pharmacotherapies to procedural treatments. These interventions aim to secure heart rhythm stability and prevent grave complications. However, it remains imperative to recognise that while cardiac telemetry tools, such as the Event Holter ECG, offer profound diagnostic insights, they should augment, not supplant, the standard of physical examinations and thorough assessments by clinicians. Present research endeavours are di-

rected towards discerning the patient demographic poised to gain the most from these innovative diagnostic tools.

Automated Telemetry: Ethical and Practical Dynamics

The incorporation of sophisticated automated systems within the realm of paediatric electrocardiography heralds a transformative leap in cardiac telemetry. These state-of-the-art mechanisms promise rapid and precise detection of cardiac anomalies, proffering significant benefits to patient care. Yet, it is crucial to acknowledge the intrinsic constraints of such systems. Variations in cardiac anatomy and function across the paediatric cohort, coupled with the potential for signal disruptions, necessitate the continued involvement of clinical acumen alongside these technologies. The interpretation of ECG data remains a complex craft, enriched by the discerning eye of a seasoned clinician, thus ensuring that automated tools complement, rather than supplant, the indispensable expertise of healthcare professionals.

Furthermore, the advent of Artificial Intelligence (AI) in analyzing ECGs transcends traditional manual methodologies, unveiling nuanced indicators of cardiac health that may bypass conventional detection. AI's ability to identify incipient cardiac conditions and capture systemic physiological nuances augurs well for its integration into everyday clinical practice. Such integration is poised to refine patient management strategies substantially, potentially diminishing the necessity for hospital admissions and frequent consultations. However, the homogenization of AI applications across diverse patient groups remains an area ripe for thorough investigation, with the variability of model performance across different populations highlighting the need for comprehensive validation.

Advancements in telemetry have ushered in an unprecedented era of healthcare delivery, where continuous, automated cardiac monitoring is radically altering the landscape of patient management. Devices exemplifying the pinnacle of this technological evolution, such as the EHO-MINI, delineate the immense possibilities inherent in remote diagnostic procedures and instantaneous patient management. This progressive shift towards an automated telemetry infrastructure mirrors the sector's dedication to refining precision medicine via cutting-edge innovations. Automated telemetry not only enhances the capability to detect and address cardiac incidents expeditiously but also embodies a forward-thinking approach to paediatric healthcare, prioritizing rapid interventions for a particularly susceptible demographic.

Nevertheless, the march towards automation in telemetry invites a host of ethical dilemmas. The increasing dependence on such systems intensifies the imperative for a stringent ethical framework to address pressing issues of data confidentiality, cybersecurity, and equitable access to medical technology.

As telemetry apparatuses become ever more entrenched in regular care regimes, the imperative to safeguard patient data grows ever more pronounced. Moreover, while the promise of reduced systemic burden and enhanced patient outcomes is tantalising, it is imperative to maintain rigorous oversight to mitigate the risks of an over-reliance on technology and preserve the sanctity of medical judgement. Therefore, discourse on automated telemetry systems must delicately balance the fervour for innovation with an unwavering commitment to uphold the quintessence of patient care and welfare.

Redundancy

While cardiac telemetry outpatient monitoring can provide crucial information needed to diagnose a patient, in some cases it can be considered redundant, depending on the specific clinical context as it may fail to give any significant additional information compared to other monitoring methods or intermittent assessments. Continuous cardiac telemetry might be deemed excessive in situations such as:

1. **Stable Cardiac Profiles:** For patients displaying stable cardiac conditions without a pronounced threat of abrupt heart activity shifts, continuous monitoring might be unnecessary. Occasional heart rhythm checks could be sufficient for overseeing their status.

2. **Low-Risk Categories:** Patients who either have a diminished risk of cardiac incidents or have recuperated from an acute cardiac event might not necessitate ongoing telemetry oversight. Standard monitoring approaches, like manual vital readings or periodic electrocardiograms (ECGs), could adequately track their heart's functionality.

3. **Brief Monitoring Durations:** Patients needing only transient heart function observation might find continuous telemetry excessive once the initial high-risk period subsides.

4. **Ambulant Patients:** There are instances where ambulant patients - those capable of walking and self-movement - may not need ceaseless telemetry, especially if they are in a stable condition and other monitoring techniques prove effective.

5. **Resource Considerations:** The process of continuous telemetry oversight demands specialised equipment and dedicated staff. In scenarios where resources are con- strained or better deployed elsewhere, sporadic monitoring could be more suitable.

Conclusions

Over the course of our study from September 2020 to March 2023, cardiac telemetry has proven to be an increasingly relied-upon diagnostic tool in paediatric care, with a total of 12 201 studies conducted across a diverse patient profile. The marked rise in 'significant' test results year over year underscores the sensitivity of the EHO-MINI Event Holter and similar devices in detecting arrhythmias crucial for timely interventions, such as the 33 ablations performed as direct outcomes of these findings.

Our patient cohort, with an average age of 13.4 years and diverse body compositions, presented a range of symptoms, from palpitations and arrhythmias to fainting and chest discomfort. Notably, conditions such as COVID-19 complications, diabetes, and hypertension also featured in our study, illustrating the broad application of telemetry in paediatric care.

The obtained results proved to be statistically significant, with an ANOVA test yielding an F-value of 1914 and a P-value <0.0001, indicating notable differences across evaluated groups. The relationships between key biomarkers like FT4 and cardiac function metrics like EF and SF reveal the nuanced interplay within cardiac health, informing the multifaceted approach required in paediatric cardiology.

Overall, the statistical evidence from our study presents a compelling case for the integration of telemetry in paediatric cardiac diagnostics and management. With an average ejection

fraction of 69.30% and an array of symptoms addressed, telemetry stands as a cornerstone in contemporary paediatric care, balancing the art of medicine with the precision of technology.

As the technology advances, it is imperative to ensure that the enhancements in telemetry do not only lead to improved patient outcomes. The protection of patient data transmitted for telemetry analysis is just as critical, necessitating robust security measures to prevent breaches. The judicious application of telemetry is essential - continuous monitoring must be assessed against the backdrop of individual clinical needs, ensuring an optimal balance between comprehensive monitoring and prudent resource use. After all, any clinically-oriented solution must align with the ethical imperatives of healthcare, where the patient's well-being remains the ultimate priority.

In sum, the integration of advanced telemetry devices like the EHO-MINI Event Holter into paediatric cardiac care represents a significant advancement. These tools offer essential real-time insights into arrhythmias that could otherwise go undetected. However, reliance on technology must be tempered with professional oversight; symptoms must be evaluated in context, not just against telemetry readouts, particularly when considering the potential for electronic interference.

As we look ahead, advancements in telemetry promise even greater diagnostic precision and potential for autonomous emergency notification. Yet, with each technological stride, we must consider the ethical implications and strive to preserve the crucial role of human judgement in healthcare.

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