Detection of Tachyarrhythmias in a Large Cohort of Infants Using Direct-to-Consumer Heart Rate Monitoring

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Objective Current estimates of the incidence of tachyarrhythmias in infants rely on clinical documentation and may not reflect the true rate in the general population. Our aim was to describe the epidemiology of tachyarrhythmia detected in a large cohort of infants using direct-to-consumer heart rate (HR) monitoring.

Study design Data were collected from Owlet Smart Sock devices used in infants in the US with birthdates between February 2017 and February 2019. We queried the HR data for episodes of tachyarrhythmia (HR of ≥240 bpm for >60 seconds).

Results The study included 100 949 infants (50.8% male) monitored for more than 200 million total hours. We identified 5070 episodes of tachyarrhythmia in 2508 infants. The cumulative incidence of tachyarrhythmia in our cohort was 2.5% over the first year of life. The median age at the time of the first episode of tachyarrhythmia was 36 days (range, 1-358 days). Tachyarrhythmia was more common in infants with congenital heart disease (4.0% vs 2.4%; $P = .015$) and in females (2.7% vs 2.0%; $P < .001$). The median length of an episode was 7.3 minutes (range, 60 seconds to 5.4 hours) and the probability of an episode lasting longer than 45 minutes was 16.8% (95% CI, 15.4%-18.3%).

Conclusions We found the cumulative incidence of tachyarrhythmia among infants using direct-to-consumer HR monitors to be higher than previously reported in studies relying on clinical diagnosis. This finding may represent previously undetected subclinical disease in young infants, the significance of which remains uncertain. Clinicians should be prepared to discuss these events with parents. *(J Pediatr 2021;232:147-53)*.

Tachyarrhythmias encompass a number of conditions resulting in a supraphysiologic elevation of the heart rate (HR), which can range from relatively benign to life-threatening. Supraventricular tachycardia (SVT) is by far the most common arrhythmia found in children, accounting for roughly 97% of all tachyarrhythmias in this age group.[1,2] The distribution of SVT in children is bimodal with peaks in infancy and early adolescence.[3,4] Tachyarrhythmias in infants can be difficult to identify clinically because many patients remain asymptomatic, despite persistent arrhythmia. Undiagnosed and untreated tachyarrhythmias, if persistent for hours, can lead to symptoms of heart failure such as poor feeding, failure to thrive, and fussiness.[5] The insidious nature of tachyarrhythmias in infants makes it all the more important for clinicians to understand the natural history in this population and support earlier diagnosis and management.

Historical estimates of the prevalence of tachyarrhythmia are primarily driven by SVT. In the general pediatric population these estimates have ranged widely from 1 in 25 000 to 1 in 250, with up to 1 in 4 cases presenting in infancy.[6-9] Two large, population-based studies out of northern England and Taiwan in the modern era estimate the prevalence of SVT in infancy between 0.10% to 0.25%.[1,2] These studies provide valuable insight into the epidemiology of clinically identifiable SVT. However, their reliance on diagnosis codes from administrative databases creates the possibility of missing subclinical or undetected episodes of SVT. Recently, several new technologies have led to an increase in the use of direct-to-consumer HR and oxygen saturation (SpO_2) monitoring.[10] One consequence of increased monitoring is the detection of otherwise asymptomatic episodes of tachyarrhythmia.[11] The objective of our study was to use direct-to-consumer HR monitoring data to investigate the epidemiology of tachyarrhythmias in infants.

Methods

This study was reviewed and approved by the Institutional Review Board at the Cleveland Clinic. All study participants agreed to the use of their data for research

bpm	beats per minute
HR	heart rate
OSS	Owlet Smart Sock
SpO_2	oxygen saturation
SVT	supraventricular tachycardia

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J.H. is a former employee of Owlet Baby Care and is currently a consultant for the company. The other authors declare no conflicts of interest.

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purposes upon registration of their device. A de-identified dataset was provided by Owlet (Owlet Baby Care Inc) to the study investigators, including demographic information and monitoring data from sessions with a suspected episode of tachyarrhythmia. Data transferred to the Cleveland Clinic servers were provided in raw form, and all processing and statistical analyses were planned and performed independently by the study investigators. This study is reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology reporting guideline.[12]

Study data were prospectively collected on a large cohort of infants who used the Owlet Smart Sock (OSS) for HR and SpO_2 monitoring. Infants eligible for inclusion (1) were within the US, (2) had a reported birthdate between February 1, 2017, and February 1, 2019, and (3) had a minimum of 24 cumulative hours of monitoring data.

Parent-reported demographic data were collected from individual profiles generated by OSS users when they created a profile during device registration (**Appendix**; available at www.jpeds.com). We also collected HR, SpO_2, and temperature values at 2-second resolution while infants were wearing the device. Data were collected in unique monitoring sessions, which were defined as the time that the sock was used between charging or disconnecting (charging or disconnection must last >1 hour). We excluded any data where skin temperature was less than 78°F because these readings may be inaccurate owing to incorrect placement or removal of the sock.

The OSS is a wireless pulse oximeter that is intended for healthy infants between 6 and 25 pounds to wear while sleeping. The device is embedded in a sock that is worn on an infant's foot and connects to a base station via a Bluetooth connection (**Figure 1**; available at www.jpeds.com). The base station gathers data from the OSS at a 2-second resolution and pushes the data to the cloud via Wi-Fi, where it is subsequently ingested, stored, aggregated, and served to the parent's mobile device through a mobile app.

Pulse oximeters, including the OSS, determine the HR and SpO_2 by measuring the absorption of red and infrared light in the blood via photoplethysmography.[13] More light is absorbed during systole than at diastole, resulting in a waveform with each cardiac cycle. The calculated frequency of these variations represents the peripheral pulse and is the source of the HR recorded by the device. The OSS uses a 20-second moving average for HR and SpO_2 calculations to decrease potential false alarms, compared with the 2- to 8-second moving averages standard in hospital pulse oximeters.[14] In the event that the vitals are too high (HR >220 beats per minute [bpm]) or too low (HR <60 bpm or SpO_2<80%), both the base station and the app will both sound a notification. Near real-time vitals are visible on the app along with past history.

Consistent with industry practice, the HR accuracy of the OSS was tested with a commercial pulse oximeter analyzer (Fluke ProSim SPOT SpO_2 Test Module). Across the range of 30 to 300 bpm the mean error was −0.310 bpm and the SD was 0.4708 bpm. Additionally, a recent clinical study demonstrated good accuracy of the OSS, with a 100% specificity for detecting bradycardia.[15] The OSS is currently intended for healthy babies, and is not marketed as a prescription medical device. Instead, the OSS is marketed as a consumer wellness device under the US Food and Drug Administration's General Wellness guidance.[16] This designation is common for fitness trackers and other wearables, which does not require the same strict US Food and Drug Administration regulatory review necessary for medical devices.

Direct-to-consumer HR monitoring was used to detect suspected episodes of tachyarrhythmia. We characterized episodes of tachycardia from pulse oximetry as tachyarrhythmia with a high degree of confidence based on the characteristics that separate pathologic tachyarrhythmias from sinus tachycardia (1) nonphysiologic HR, (2) significant change from baseline HR to tachycardia, and (3) limited variation in the HR during tachycardia.

First, to identify nonphysiologic HR a suspected episode of tachyarrhythmia was defined as a HR of ≥240 bpm for ≥60 seconds. We also required a minimum of 30 consecutive or nonconsecutive valid HR data points for identification of an episode of suspected tachyarrhythmia regardless of the duration of the episode.

Second, we evaluated for significant changes in the HR from baseline to tachycardia. The baseline HR was defined as the average HR from the 30 valid HR data points immediately preceding the episode. This finding was compared with the average HR across the entire episode of tachycardia. To be included in the study, we required a change of >60 bpm from baseline to tachycardia, a cutoff based on clinical judgement. We also recorded the time over which the HR changed to identify 2 different types of episode, the first being rapid onset tachycardia likely related to a re-entrant mechanism and the second being more gradual onset tachycardia from mechanisms related to automaticity. **Figure 2** shows a sample tracing from a suspected episode of tachyarrhythmia.

Finally, we compared the variation in the HR before an episode with the variation during a suspected episode of tachyarrhythmia to evaluate the possibility of motion artifact causing erroneous doubling of the HR.[17,18] The SD of the HR was calculated for the minute before the episode as well as the for the duration of the episode. If doubling occurred, we would expect the SD of the HR during tachycardia to be twice that of the SD before the episode.[19] We removed any episode where the SD during tachycardia was doubled.

Descriptive statistics were calculated for the overall cohort, including the cumulative incidence, counts, and proportions. The incidence per month was calculated using the number of incident cases of tachyarrhythmia for that month divided by the number of infants with any monitoring data during that month after subtracting the number of infants previously diagnosed with tachyarrhythmia. Comparisons between infants with and without tachyarrhythmias were made using χ^2 or t tests for proportional or continuous variables

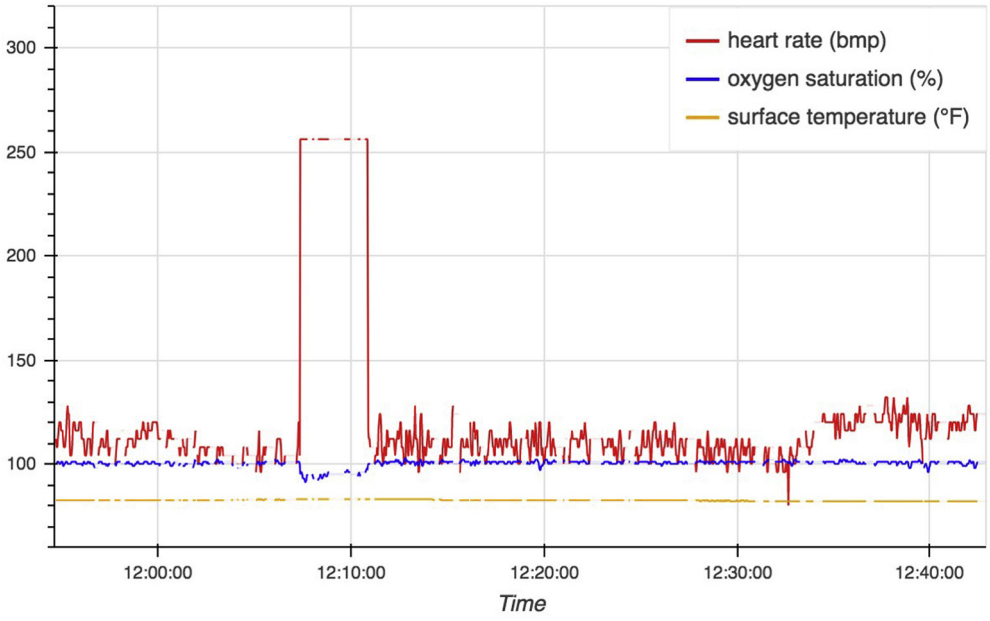

Figure 2. Sample HR, SpO_2, and temperature tracings demonstrating a 4-minute episode of tachyarrhythmia in a 6-month-old infant. This episode demonstrates characteristics consistent with SVT, including (1) supraphysiologic HR, (2) an abrupt change in HR, and a (3) decrease in the variability of the HR during tachycardia.

respectively, and the Fisher exact test was used for comparison of categorical variables with ≥20% of expected cell counts of <5. The probability of an episode of tachyarrhythmia lasting longer than a predetermined cutoff for clinical significance (45 minutes) was calculated using a Kaplan-Meier survival curve to account for right censoring of an episode if recording was interrupted before termination of the episode. Analyses were performed using Python software, version 3.7 (Python Software Foundation) and Matlab, version R2019a (MathWorks).

Results

We identified 100 949 infants born between February 2017 and February 2019 who met inclusion criteria. In total, 202 232 404 hours of monitoring were recorded for the entire cohort, which is an average of 2003 hours per infant. The average duration of use for the OSS was 6 months (approximately 4300 hours) and 174 unique monitoring sessions. Demographic information is presented in **Table I**.

In total, there were 5070 suspected episodes of tachyarrhythmia observed in 2508 infants. The cumulative incidence of tachyarrhythmia in our cohort was 2.5%, or approximately 1 in 40 infants, over the course of the first year of life. The incidence of tachyarrhythmia by month was 1.58%, 0.78%, 0.28%, 0.10%, and 0.12% for ages 1, 2, 3, 6, and 12 months respectively (**Figure 3**). The median number of episodes per infant was 1, with 644 (26%) infants having >1 episode, and 122 (5%) having >5 recorded episodes (**Table II**; available at www.jpeds.com).

Before implementing our strict definition of tachycardia there were 14 083 alarms triggered for a HR of >240 bpm lasting >10 seconds. The application of our criteria decreased the number of suspected episodes of tachycardia by 74% to the 5070 episodes noted elsewhere in this article. This dramatic

Table I. Cohort characteristics

		All infants (n = 100 957)		
Characteristics	Overall	Tachyarrhythmia	No tachyarrhythmia	*P* value
Number	100 957	2508	98 449	
Male	46 234 (50.8)	932 (43.2)	45 302 (51)	<.001
Race				
Caucasian	38 614 (87.6)	875 (83.3)	37 739 (87.7)	<.001
Hispanic	4794 (10.9)	136 (13.0)	4658 (10.8)	.029
Asian	1580 (3.6)	49 (4.7)	1531 (3.6)	.056
African American	1405 (3.2)	43 (4.1)	1362 (3.2)	.090
American Indian	589 (1.3)	15 (1.4)	574 (1.3)	.792
Pacific Islander	378 (0.9)	9 (0.9)	369 (0.9)	.999
Other	1806 (4.1)	56 (5.3)	1750 (4.1)	.041
Gestational age				.584
Full-term	38 628 (82.5)	929 (83.1)	37 699 (82.5)	
Preterm	8205 (17.5)	189 (16.9)	8016 (17.5)	
Comorbidities				
CHD	522 (1.4)	21 (2.3)	501 (1.4)	.021
CLD	459 (1.2)	11 (1.2)	448 (1.2)	.993
Down syndrome	102 (0.3)	1 (0.1)	101 (0.3)	.524*
Other	2476 (6.5)	69 (7.5)	2407 (6.5)	.197

CHD, congenital heart disease; *CLD*, chronic lung disease.
Values are number (%).
*Fisher exact test.

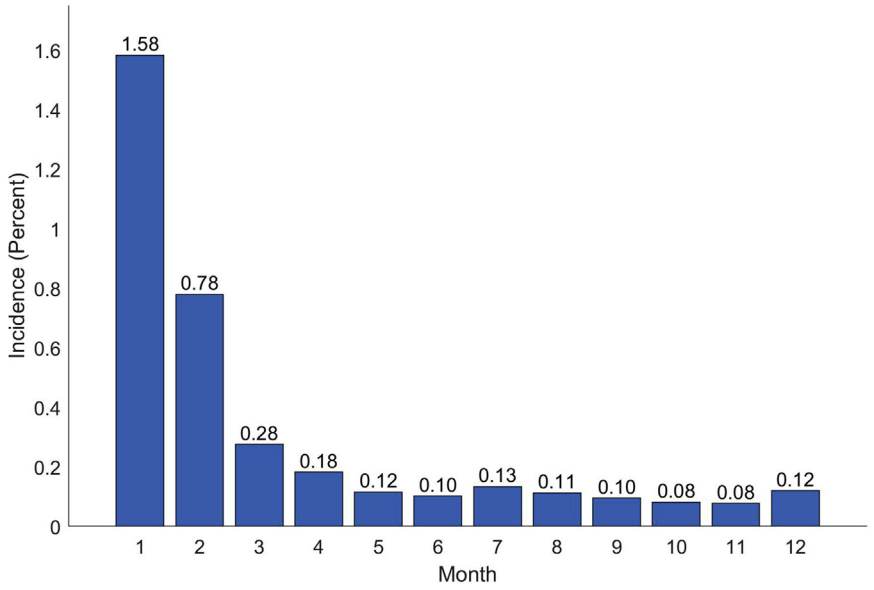

Figure 3. Incidence of tachyarrhythmia in infants by month of age.

decrease indicates a high number of false alarms that are less likely to indicate true arrhythmia.

The median age at the first episode was 36 days (range, 1-358 days). There was a small but statistically significant difference between the age at first episode for preterm infants compared with full-term infants (58 days vs 33 days; $P < .001$). However, there was no statistically significant difference between the percentage of preterm infants with tachyarrhythmia episodes compared with full-term infants (2.3% vs 2.4%; $P = .584$). There was a significant difference between the proportion of tachyarrhythmia in infants with congenital heart disease compared with those without congenital heart disease (4.0% vs 2.6%; $P = .021$). However, there was no statistically significant difference between prevalence of tachyarrhythmia in infants with chronic lung disease, Down syndrome, or other medical conditions compared with infants without these comorbidities. Males had a slightly lower incidence of tachyarrhythmia than females (2.0% vs 2.7%; $P < .001$).

The average HR immediately preceding an episode of tachyarrhythmia (the baseline) was 126 bpm, and the average HR during the episode of tachyarrhythmia was 267 bpm. The resulting average increase in HR from baseline to tachycardia was 141 bpm, with 99% of episodes having an increase of >95 bpm. With respect to the rate at which the HR changed from baseline to tachycardia, 94.1% of episodes began with a rapid increase in HR (≤2 seconds), suggesting that typical SVT, compared with 3.2% of cases with a less rapid onset (>5 seconds), suggesting atrial ectopic tachycardia. In >99% of episodes, the variance of the HR during tachycardia was decreased compared with the recordings immediately preceding the events, which is highly suggestive of true tachyarrhythmia rather than false alarms.

The median length of an episode of tachyarrhythmia was 7.3 minutes (range, 60 seconds to 5.4 hours). In total 1817 (36%) of the 5070 recorded episodes lasted <5 minutes and 304 episodes (6.0%) lasted >45 minutes. It is important to note that, during 64% of all recorded episodes, data transmission was interrupted before termination of the episode (presumably owing to removal of the OSS) resulting in the duration of the episode being cut short or "right censored." To account for censoring, we used a Kaplan-Meier survival curve to examine the probability of episodes lasting various lengths of time. A cutoff of 45 minutes was prespecified to identify the percentage of episodes that would be of potential clinical interest. The probability of an episode of tachyarrhythmia lasting longer than 45 minutes in our cohort was 16.8% (95% CI, 15.4%-18.3%), as shown in **Figure 4**.

Discussion

The discrepancy between the historical estimates of the prevalence of tachyarrhythmias and the prevalence in our study (2.5%) provides valuable clinical context to the detection of tachyarrhythmia using home monitoring. It is important for clinicians to understand how commonly episodes of supraphysiologic tachycardia are detected with home-based monitoring. At the same time, increased detection of these events does not necessarily suggest there is clinical action to be taken. Clinicians should use clinical judgment when evaluating patients with a possible episode of tachyarrhythmia. Signs and symptoms to watch for include fussiness, lethargy, pallor, vomiting, poor feeding, or failure to thrive. For short asymptomatic episodes, it is reasonable to obtain an electrocardiogram to rule out the possibility of Wolff-Parkinson-White syndrome. For illustrative purposes, several instances

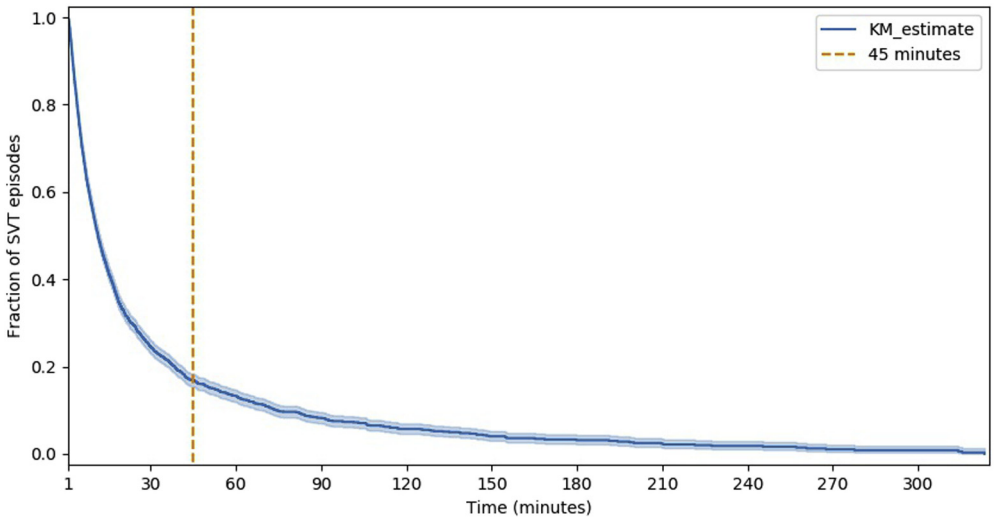

Figure 4. Kaplan-Meier estimates for the length of episodes of tachyarrhythmia in infants. A predetermined cutoff of 45 minutes was selected to identify prolonged episodes. There was an approximately 16.8% probability that an episode of tachyarrhythmia will last more than 45 minutes.

of SVT detection by an OSS with subsequent clinical follow-up and diagnosis are included in the **Appendix**.

These results must be interpreted with caution, owing to our inability to verify the diagnosis in these infants by electrocardiogram or clinical history. Our methodology focused on excluding sinus tachycardia and double counting as confounders. By removing all episodes with tachycardia of <60 seconds, with gradual increases in HR, and with significant increases in HR variation, the vast majority of false-positive alarms are filtered out. With these criteria, only 26% of all tachycardia alarms were included as suspected episodes of tachyarrhythmia. However, without electrocardiogram confirmation, the possibility remains that some of these episodes do not represent tachyarrhythmias. Additionally, in rare instances the HR during tachyarrhythmia may exceed 300 bpm, the upper limit of reliability testing in the OSS. Our inability to capture extremely high HRs could lead to an underestimation of the incidence of tachyarrhythmia in our population. Finally, by placing the lower threshold for tachyarrhythmia classification at 240 bpm, tachyarrhythmias at rates of <240 bpm would not be identified in our study.

We have used the broad terminology of tachyarrhythmia in our study. Based on previous research, it is likely that the preponderance of cases we identified represent SVT.[2] Thus, the estimate provided by our study may serve as reasonable estimate for the incidence per month of age of SVT. We found the majority of episodes associated with a rapid onset/offset of tachycardia, which would be consistent with a re-entrant mechanism.[20] The minority of episodes with a relatively slower onset are more likely to be the result of automaticity mechanisms, such as ectopic atrial tachycardia.[21] Additionally, a small number of the episodes we identified may represent ventricular arrhythmias, such as ventricular tachycardia. However, in previous epidemiologic studies ventricular tachycardia occurred in as few as 3% of cases.[2]

It is important to recognize that the American Academy of Pediatrics discourages the use of routine home cardiorespiratory monitoring in infants for the detection and prevention of sudden infant death syndrome based on evidence from several clinical trials.[22-24] Although these studies found no benefit from monitoring to detect apnea, bradycardia, or hypoxemia in association with sudden infant death syndrome, there have been no studies conducted to date that have specifically focused on home monitoring for tachyarrhythmias. With recent increases in the affordability, availability, and popularity of direct-to-consumer monitoring devices, many parents continue to use this technology independent of medical society guidelines. At the time of this writing roughly 170 000 infants use an OSS each night, which will likely continue to result in increased detection of tachyarrhythmias in infants given the findings in our study.

Our study also confirms previous findings that tachyarrhythmias occur with the highest frequency in young infants and the incidence decrease around 3-4 months of age.[5,25] This pattern may indicate a period of cardiac development that carries an increased risk of tachyarrhythmia, particularly SVT. Incomplete development of the annulus fibrosus, the fibrous barrier between atrial and ventricular electrical conduction, at birth may predispose these young infants to transient development of accessory pathways.[26,27] These accessory pathways decrease in size and number as cardiac development continues after birth. The self-limiting nature of these connections is the leading explanation for the early distribution of SVT among infants and children.[1,28]

There were a number of associations detected in our study between demographic data and tachyarrhythmia. We found an increased prevalence of tachyarrhythmia in infants with reported congenital heart disease compared with infants

with presumed structurally normal hearts, consistent with previously published results.[1,29] Infants with chronic lung disease did not have an increased prevalence of tachyarrhythmias. However, this condition is thought to have an association with chaotic atrial tachycardia, which has a lower ventricular response rate and may explain why no association was seen in our study. The ethnic distribution of infants with tachyarrhythmia had a slightly higher proportion of Hispanic infants and a lower proportion of Caucasian infants compared with those without tachyarrhythmia. This finding is most likely reflective of the imbalanced ethnic makeup of the cohort rather than a true difference. It is interesting to note that we did not identify any difference in the prevalence of tachyarrhythmia between preterm and full-term infants. However, it should be recognized that the OSS is intended for use by healthy infants between 6 and 25 pounds. As such, there is likely a large population of preterm infants not included in our cohort that may influence the incidence of tachyarrhythmia.

There are several limitations to our study. We made several assumptions by using direct-to-consumer HR monitoring to identify tachyarrhythmia. Additionally, there is a significant amount of demographic information missing from our dataset, and all demographic data are parent reported, which opens our study to potential bias. For our analyses, we chose to exclude missing data for any comparisons we made. We felt the large sample size of our cohort allowed for the exclusion of significant amounts of data while still permitting meaningful analysis. Our sample size should also decrease some of the noise created by parent reporting of demographics. Additionally, the data for this study come from individuals who had the financial means to purchase commercial home pulse oximeters for their infants. Our study population likely represents infants in families of higher socioeconomic status. Our monitored cohort is not reflective of the ethnic makeup of the US population as a whole.[30] Medical comorbidities may also drive parents to use home monitors, which may inflate the prevalence of various conditions within our population. We also have no data on patients with an established diagnosis of arrhythmia or medication management, nor data on clinical follow-up after the episode(s) of tachyarrhythmia detected by the OSS.

The increased detection of tachyarrhythmia in our study likely represents subclinical disease. With the growing popularity of direct-to-consumer HR monitors, clinicians should be prepared to provide reassurance and counsel patients with incidentally discovered tachyarrhythmias. ■

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Data Statement

Data sharing statement available at www.jpeds.com.

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50 Years Ago in *The Journal of Pediatrics*

Evolution of Imaging for Diagnosis of Abnormal Migration of the Thyroid Gland

Ashkar F, et al. A new rapid technique for the localization of abnormalities in migration of the thyroid gland. J Pediatr 1971:870-3.

In May 1971, Ashkar et al introduced a novel technique of dynamic imaging to identify malformed or ectopic thyroid tissue. They emphasized the benefits of technetium-99m (Tc-99m) over the conventional I-131 for this diagnostic purpose. Tc-99 m has low-energy gamma emissions with almost no beta emissions, a shorter half-life that allows for a faster study, and less production cost than conventional I-131.

Since the publication of this article, I-123 has been isolated and has replaced I-131 and Tc-99m as the optimal agent to use for thyroid scanning. Similar to Tc-99m, I-123 emits gamma emissions and no beta emissions, so the radiation exposure to the thyroid and surrounding tissues is minimal.[1] Unlike Tc-99m, I-123 is organified and trapped in thyroid follicles, and its uptake can be used as a direct measure of thyroid function. I-123 uptake is also specific to thyroid tissue, whereas Tc-99m may be taken up by other bodily organs such as the salivary glands. Therefore, I-123 is the ideal isotope for scintigraphy. However, owing to high costs, limited availability, and the longer half-life of I-123, Tc-99m is still used for diagnostic thyroid imaging in some institutions. Additionally, I-123 may not reliably demonstrate tissue with low iodine avidity.

Advances in other imaging modalities over the last 50 years have offered alternatives to dynamic thyroid imaging for detection of irregular thyroid descent. Computed tomography scans and magnetic resonance imaging can provide anatomic information not only of the ectopic thyroid tissue, but also on its relationship to the surrounding tissue. The advent of ultrasound examination with Doppler has made scintigraphy unnecessary in most circumstances, because it can take advantage of vascular information to sufficiently identify ectopic tissue, particularly thyroglossal duct cysts.[2] Nevertheless, scintigraphy remains an important modality to use when functional information is needed or when a normal thyroid gland is not visualized in its usual anatomic location on ultrasound examination.

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References

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Figure 1. The OSS collects HR, SpO_2, and surface temperature data from sleeping infants.

Table II. Epidemiologic profile of tachyarrhythmia in infants

Characteristics	No. (%)
Infants with tachyarrhythmia	2508 (2.5)
Episodes detected	5070
Median age at first episode (days)*	36 (1-358)
Median number of episodes	1
>1	644 (26)
>5	122 (5)
Median episode length (minutes)*	7.3 (1-324)
<5	1817 (36)
>45	304 (6)

*Median (range).