Revisiting dose–response relationships between heart rate zones, TRIMPs, and aerobic-related physiological and performance markers in elite team sports

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Internal load | Cardiovascular load | Training adaptation | HRmax | Metabolic load | VO_2max | vVO_2max | Lactate threshold | V2mmol·L^{-1} | V4mmol·L^{-1} | vOBLA | MLSS (maximal lactate steady state) | Critical speed | Respiratory compensation point | Intermittent exercise | Small-sided games | High-intensity interval training (HIIT) | Yo-Yo IR1 | 30-15 IFT | Training impulse (Banister) | Load quantification | Microcycle planning | Mesocycle monitoring | Return-to-play (RTP) | Athlete profiling | Match demands

Headline

Since the early 2000s, HR monitoring was the cornerstone of load monitoring in (team) sports (Achten 2003, Dellal 2012, Figure 1). However, as the field has shifted from the physiologically grounded approach of sport science 1.0 to the data-driven model of sport science 2.0 (Buchheit & Laursen 2024), many practitioners have turned to GPS and other wearable technologies. While GPS can provide helpful data on external load, it offers no information on metabolic load (Buchheit & Simpson 2017; Buchheit & Hader 2025). Unfortunately, many practitioners still fall short in using appropriate tools and metrics to monitor both metabolic and neuromuscular load (i.e., muscle activation levels and tendon strain, Buchheit & Laursen 2013), resulting in an incomplete understanding of training demands (Buchheit & Hader 2025). Replacing HR with GPS has not resolved the essential need for tracking internal, metabolic, and cardiovascular load. Attempts to use GPS-derived metabolic power (Osgnach 2010) as a substitute for HR have also proven inadequate, as the measure fails to accurately capture systemic metabolic load in team-sport contexts (Buchheit & Simpson 2017).

This distinction is essential, as metabolic and neuromuscular load are the two primary sources of physical load in team sports, and each requires a specific monitoring approach (Buchheit & Laursen 2013, Buchheit & Hader 2025). In practice, for metabolic and cardiovascular load, HR remains the only usable proxy for cardiopulmonary stress, despite its limitations.

This paper aims to re-establish the value of HR monitoring by acknowledging its limitations and focusing on how best to leverage the meaningful information it can provide. By focusing on the dose-response relationship using meaningful adaptation measures, such as aerobic-related physiological and performance markers (Buchheit 2025), we can identify the minimal effective dose of training needed to maintain or improve fitness and recognize the point of diminishing returns (Spiering 2021). This has direct applications both for healthy and injured athletes during their return to play journey.

Aim

This paper revisits the rationale for HR-based monitoring, outlines its limitations, and evaluates its potential for characterizing dose–response relationships in elite team sports. Specifically, it examines how time in HR zones (THRZ) and TRIMP-based (Training Impulse) metrics relate to aerobically driven physiological and performance adaptations, with the goal of defining both the minimal effective dose and the magnitude of response to training.

Today's challenges of HR monitoring

The reduced adoption of HR monitoring in applied team sport settings reflects a mix of technological, practical, and interpretative challenges. A longstanding issue is the discomfort and intrusiveness of traditional chest straps, which often limit player compliance and compromise data reliability/validity during prolonged or high-intensity sessions. Newer alternatives such as wrist-based, arm-based, or garment-integrated sensors have addressed comfort but remain hindered by poor accuracy, high costs, and limited durability, especially in contact sports and demanding training environments (Figure 2, Buchheit & Hader 2025).

Signal quality and data loss present further barriers. Movement artefacts are frequent in team and other intermittent sports, making it difficult to capture consistent HR data across an entire squad. Even when signals are captured reliably, interpretation challenges persist. HR primarily reflects cardiovascular strain, but not necessarily true metabolic load and is strongly influenced by external factors such as heat, hydration, or caffeine (see below).

Practical adoption is also hampered by integration issues. HR data often remains siloed within proprietary platforms that do not easily align with GPS systems, metabolic testing outputs, or broader performance databases. The lack of interoperability makes it difficult for practitioners to combine HR with other metrics into a comprehensive framework of internal and external load. For many high-performance staff, this fragmentation diminishes the perceived value of HR monitoring and disrupts efforts toward building holistic monitoring systems.

Fig. 1. **How everything all started. Image Source: ebay**

Metabolic Power: Why it failed to replace heart rate in team-sport internal load monitoring

Altogether, these technological, practical, and interpretative challenges have reduced the willingness of staff in elite team sports to rely on HR monitoring. As Buchheit & Laursen (2024) noted, while the technology remains relevant for capturing metabolic and cardiovascular strain, the accumulation of limitations has contributed to its decline in favor of more user-friendly but not necessarily more informative tools (e.g., GPS).

One of the most popular GPS-derived alternatives has been metabolic power, originally proposed as a hybrid variable to convert both high-speed and acceleration demands into metabolic equivalents (i.e., W/kg, Osgnach 2010). While conceptually attractive, subsequent validation studies have revealed severe limitations. Across multiple independent groups, locomotor-derived metabolic power has consistently differed from the "true" metabolic demands measured via indirect calorimetry (VO_2), being overestimated during walking (Brown 2016) but underestimated during shuttle running and sport-specific movements (Stevens 2015; Buchheit 2015; Highton 2017).

Criticisms of these findings (Osgnach 2016) pointed to methodological issues such as inclusion of resting VO_2 or underestimation of anaerobic contributions, but detailed rebuttals have shown that these factors do not account for the discrepancies (Buchheit 2015; Buchheit, 2016).

Beyond this validity issue, GPS-derived metabolic power also offers limited practical value. As a partial measure of locomotor-related metabolic cost, it does not reflect systemic metabolic stress, making it an incomplete proxy for internal load. At the same time, as a broad external-load indicator combining high-speed and acceleration demands, it fails to capture the mechanical specificity practitioners need for managing recovery, training adaptations, or injury risk. For example, injuries in team sports such as football are more strongly related to exposure to high-speed running than to accelerations, and both definitely matter more than potential spikes in global energy consumption. Similarly, GPS-derived metabolic power is dissociated from muscle activation patterns, as illustrated by large differences in the GPS-derived metabolic power /EMG ratio between accelerating and decelerating actions (Hader 2016).

Overall, our present understanding is that metabolic power is at best an incomplete reflection of both mechanical locomotor demands and metabolic cost, dissociated from muscle-specific activation patterns and systemic cardiopulmonary load (Buchheit 2015; Buchheit & Simpson, 2017, Hader 2016). For these reasons, despite its widespread adoption in practitioner reports, metabolic power cannot replace HR as a measure of internal load.

Fig. 2. Three decades on, comfort and accuracy improved—but no single device has solved team-sport constraints.

Beyond averages: zone-based HR monitoring and (i)TRIMPs

Monitoring cardiovascular load using average HR or peak values (Dellal 2012) fails to capture the intensity distribution and physiological relevance of the session. To address this, two main approaches have historically been used to quantify cardiovascular load: time spent in HR zones (Riebe 2018) and TRIMP-based models, including the original TRIMP (Banister 1991), its individualized version, iTRIMP (Manzi 2009), and both Edwards' (Edwards 1994) and Lucia's TRIMP (Lucia 2003).

Physiological rationale for time in HR zones

Training adaptations, especially central cardiovascular ones, are most influenced by time spent near or above the respiratory compensation point (RCP) or 85–90% VO_2max (Buchheit & Laursen 2013; Inglis 2024, 2025; Spiering 2021). When training load is distributed mainly at moderate intensities, even with matched volume, these adaptations are less pronounced (Helgerud 2007; Inglis 2024, 2025; Buchheit & Laursen 2013; Storoschuk 2025).

Time-in-HR-zone (THRZ) methods quantify exposure to such critical intensities, typically by calculating time above predefined HR thresholds (e.g., >85 or 90% HRmax, Figure 3). These cutoffs are often chosen to approximate markers like RCP, maximal lactate steady state, critical speed, or VO_2max (Figure 4, Buchheit & Laursen 2013; Inglis 2024, 2025; Scharhag-Rosenberger 2010). Anchoring zones to physiological markers such as lactate thresholds (e.g., >HR at 2 or 4 mmol·L^{-1}) (Castagna 2011b, 2013) or to HRmax-based ranges (85–90% for RCP, >90–95% for VO_2max) provides a closer link to metabolic disturbance and the potential for adaptation. Whether 90% HRmax truly corresponds to 90% VO_2max remains uncertain, but this issue is addressed in detail in the following sections on HRmax determination and the HR–VO_2 relationship (Castagna 2007, 2011a; Buchheit 2009; Esposito 2004). However, numerous studies (Impellizzeri 2006, 2008; Bravo 2008; Helgerud 2001, Hill-Haas 2009) have demonstrated that training at or above 90% HRmax effectively enhances aerobic fitness, supporting this intensity as a practical, evidence-based threshold for aerobic development in football.

Compared with THRZ, TRIMP methods condense the entire intensity spectrum into one score (see section below). This global approach masks the distinct role of high-intensity exposures. iTRIMP refines the model by weighting HR according to individual lactate profiles, yet it still aggregates all values into a single metric (Manzi et al., 2009, Akubat et al., 2014, Malone et al., 2020). As a result, the same TRIMP score can arise from very different distributions—for example, 90 minutes below 80% HRmax versus 45 minutes above 80%. Such aggregation likely blurs the contribution of time spent above key thresholds, making it harder to isolate the high-intensity efforts most relevant for adaptation (Buchheit & Laursen 2013; Helgerud 2007; Inglis 2024, 2025; Storoschuk 2025).

THRZ methods, however, also have limitations. Their accuracy depends on correct HRmax determination, which is often estimated rather than measured (see section on HRmax). Fixed %HRmax thresholds apply a one-size-fits-all model and do not account for individual HR–VO_2 relationships (Castagna 2011a; Buchheit 2009). They may also miss efforts that fall just below cutoffs (e.g., slightly under 85% HRmax but above RCP), which can still elicit adaptation (Inglis 2024, 2025). Finally, all efforts within a zone are treated equally: 10 minutes at 86% HRmax counts the same as 10 minutes at 93%, despite clear differences in stimulus (Scharhag-Rosenberger 2010; Denedai 2006).

Fig. 3. Heart rate trace during a football match recorded with the Firstbeat system, using a 5-zone intensity model. The black line shows relative heart rate (%HRmax), and the purple line indicates movement intensity. Time spent in each zone was: Z1 (recovery, 25:25; 17%), Z2 (aerobic 1, 19:53; 13%), Z3 (aerobic 2, 23:24; 15%), Z4 (anaerobic threshold, 38:34; 25%), and Z5 (high intensity, 19:11; 13%).

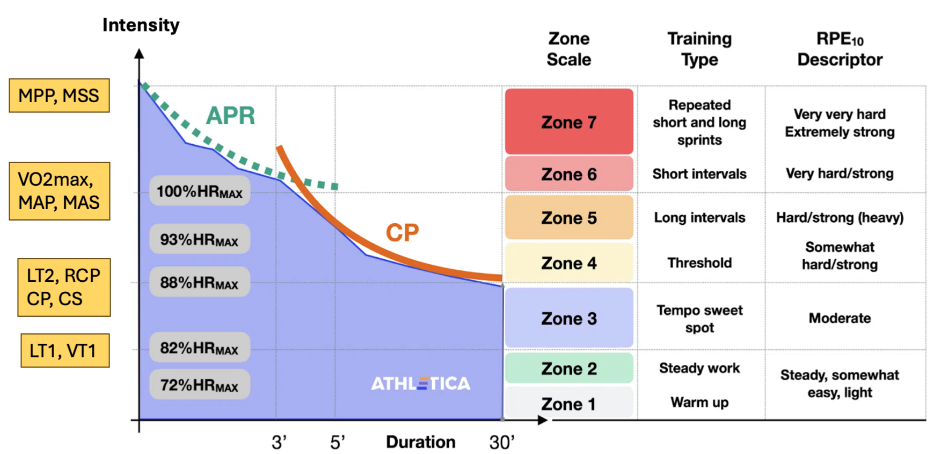

Fig. 4. Description of the different zones when it comes to assessing exercise intensity. MPP: maximal peak power, MSS: maximal sprinting speed, MAP: maximal aerobic power, MAS: maximal aerobic speed, LT1 and LT2: first and second lactate threshold, respectively, VTI and VT2: first and second ventilatory thresholds, respectively, RCP: respiratory compensation point, CP: critical power, CS: critical speed, APR: anaerobic power reserve (and ASR for Speed, not mentioned). Source: Athletica.

Getting HRmax right

Accurate measurement of HRmax is essential for valid interpretation of HR-based monitoring in elite team sports (Póvoas 2019 and 2020). Without precise HRmax, training intensity zones (Figure 5) become unreliable, compromising the assessment of cardiovascular load. Specifically, because intensity tends to drive adaptations (Buchheit & Laursen 2013, Inglis 2024, 2025, Spiering 2021, Storoschuk 2025), errors in HRmax can propagate into misclassification of 'minimal dose' exposure.

The commonly used formula HRmax=220–age, despite its popularity, lacks scientific validation and introduces large errors, on average ±10–12 beats per minute, with individual errors exceeding ±20 bpm (Robergs & Landwehr 2002). Even alternative predictive equations (e.g., Inbar et al. 1994: HRmax=205.8–0.685×age) only slightly reduce this error. There is such a large variability in HRmax for the same age range that making predictions is simply impossible (Figure 5).

Supporting this, Marx et al. (2018) found that 86% of subjects were classified into the correct training zone when using predicted HRmax. However, in 14% of cases, subjects were misclassified (though never by more than one zone), and discrepancies ranged from 1% to 4% from the intended zone. While this suggests reasonable accuracy at the group level, such approximations may be problematic in elite settings where precision matters, particularly at high intensities, where small deviations can alter the training stimulus. If we believe that adaptations are zone-dependent, especially near or above thresholds like RCP or VO_2max, relying on predicted HRmax introduces unacceptable uncertainty. In high-performance contexts, where training precision is critical, this limitation becomes a major concern.

To minimise error, HRmax should ideally be determined through a formal maximal exercise test (Póvoas 2019 and 2020). However, many clubs bypass this step and instead use the highest HR recorded during a match (often from pre-season friendly games) to estimate each player's HRmax. While this approach offers a practical workaround, it frequently underestimates true HRmax, particularly if the player has not reached full physiological effort. Until a proper maximal test is performed, there is no certainty that the estimated value reflects the player's actual maximum, which remains a key limitation of current HR monitoring practices. Despite this, many clubs favour submaximal assessments for routine monitoring and avoid maximal testing altogether (Buchheit 2025). In practice, a pragmatic solution is to consolidate all available sources (i.e., estimated HRmax, peak HR from matches, training, and lab tests, Póvoas 2019) to refine the HRmax estimate over time. Practitioners are then advised to update the player's profile every time a new, higher value is reached. In practice, even when laboratory tests are performed, match-play data often yields slightly higher values for some players. This likely reflects the challenges of eliciting a true maximum in the lab and the variation in criteria used to define maximal HR (Midgley 2007). Nonetheless, relying solely on estimated values without direct measurement risks imprecise load quantification and weakens the reliability of the entire load–response monitoring process.

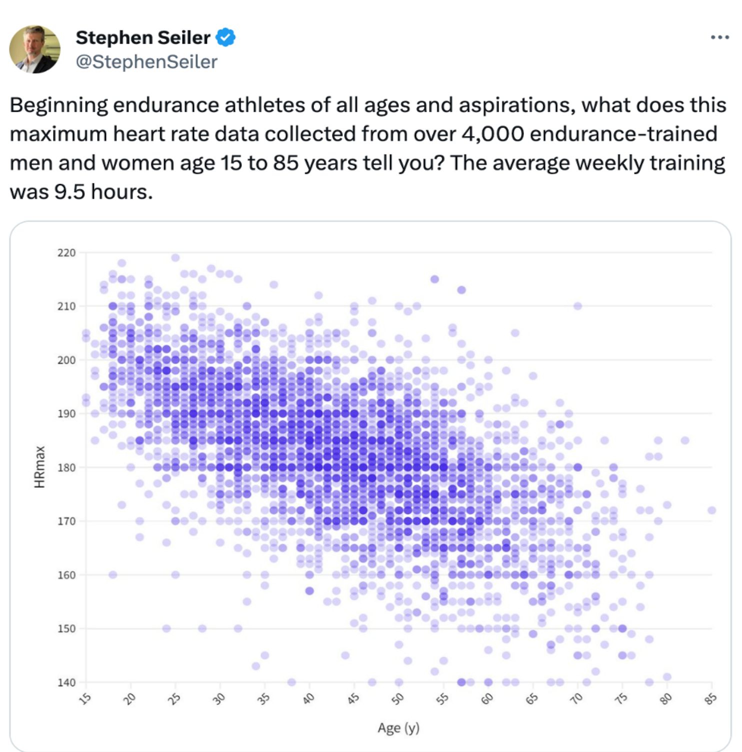

Fig. 5. Distribution of maximal HR as a function of age. Source Stephen Seiler X account.

HR and VO_2: an imperfect and context-dependent relationship

The relationship between the percentage of HRmax (%HRmax) or the percentage of HR reserve (%HRR) in predicting oxygen uptake (VO_2) is highly individualised, complex, and context-dependent (Ferri Marini 2021). While %HRR is theoretically closely aligned to $\%VO_2$ reserve ($\%VO_2R$), due to its adjustment for resting values, emerging evidence suggests that this physiological equivalence is not consistently observed across populations, testing protocols, or exercise modalities (Ferri Marini 2023). In practice, %HRR has in some cases shown a stronger correlation with $\%VO_2max$ than with $\%VO_2/HR$, undermining its theoretical superiority. The superiority of %HRR over %HRmax is reflected in its selection as the reference index in Banister's original TRIMP model (Banister 1991) and in later adaptations. Such discrepancies are likely influenced by a range of methodological and individual factors, including the choice of exercise protocol (e.g., treadmill ramp vs. Bruce protocol, Yo-YoIR, 30-15IFT, Time-Trial), variability in the measurement of resting VO_2, and between-athlete differences in autonomic and metabolic regulation (Cunha 2010; Castagna 2011a; Buchheit 2009; Ferri Marini 2023). These findings highlight the inherent difficulty in applying a universal model to describe the HR–VO_2 relationship. Despite the theoretical advantages of %HRR, its practical application is limited because it requires accurate measurements of resting HR, which is often unavailable in field settings. For this reason, practitioners typically use %HRmax as a simpler, more pragmatic option for defining HR zones (Figure 4), despite its limitations.

Complicating matters further is the variable relationship between HR and VO_2 during intermittent exercise, which is characteristic of most team sports. Under continuous, steady-state conditions, %HRmax and $\%VO_2max$ are generally linearly related (Lounana 2006). However, in intermittent or stop-start activities, this relationship can become erratic and misleading. Studies such as Castagna et al. (2007) confirm that during recreational 5-a-side indoor soccer, while HR explains a substantial portion of VO_2 variance during intermittent play ($r \approx 0.71$), individual estimation errors can be large, limiting precision at the player level. At exercise onset, HR lags behind actual VO_2 demands due to the kinetics of cardiac response, often leading to an underestimation of aerobic contribution (Billat 2001). Conversely, during recovery intervals, HR remains elevated, reflecting sympathetic nervous system activity and residual metabolic stress (blood acidosis) rather than ongoing oxygen demand; these in turn can lead to an overestimation of metabolic intensity (Billat 2001; Buchheit 2011). With repeated high-intensity efforts and the associated rise in blood acidosis, HR recovery becomes progressively slower across repeated efforts, which are commonplace within team sport training and match-play (Buchheit 2019). This, in turn, increases the likelihood of overestimating metabolic load. This is further complicated by cardiac drift (Coyle 2001), where HR rises over time without a corresponding increase in VO_2. As drift increases, the dissociation between HR and actual VO_2 demand becomes more pronounced, i.e., VO_2 may remain stable while HR continues to rise. Additionally, during isometric exercise, such as holding and bracing positions which are common within rugby union, for example, within scrum efforts or ruck positions, HR may rise independently of oxygen demand, further distorting the relationship (Castagna 2011a, Buchheit 2009). Castagna et al. (2007) noted that non-locomotor or irregular actions such as sideward running or isometric holds could disproportionately elevate HR, adding sport-specific distortion. Similarly, Esposito et al. (2014) found that HR maintained good validity as a proxy for VO_2 across soccer match-play, though accuracy varied by role and activity type. In fact, when viewed at the group level, both Castagna et al. (2007) and Esposito et al. (2014) support the validity of HR as a surrogate for VO_2 during soccer play. The degree of error, however, is context-dependent, i.e., greater in sports or situations with frequent non-locomotor or isometric actions, and lower in more locomotor-dominant phases. A nuanced interpretation is therefore needed, recognising that HR may be both valid and biased depending on the interplay between locomotor and non-locomotor demands. Overall, it is likely that %HRmax overestimates metabolic intensity, with 90% HRmax potentially reflecting only 80–85% VO_2max during team sport practice (Castagna 2007 and 2011a, Buchheit 2009, Seiler & Tonnessen 2009). Furthermore, a given %HRmax does not consistently correspond to a specific $\%VO_2$ during these types of intermittent training. Nevertheless, despite its known limitations, HR remains the most practical and widely accessible tool for assessing cardiovascular strain in the field (Buchheit & Hader, 2025). Its continued use is warranted when interpreted with a clear understanding of its constraints. Practitioners must apply HR data judiciously, recognising that context, athlete-specific characteristics, and training objectives critically shape its validity and utility. As ever in applied sport science, perfect should not be the enemy of good, with pragmatic use of imperfect tools remaining preferable to no monitoring at all.

Accepting real-world variability in HR monitoring

These confounding factors influencing HR, such as hydration status, caffeine intake, nutritional state, ambient temperature, humidity, circadian rhythm (Acheten 2003), plasma volume shifts (Buchheit 2025), and cardiac drift (Coyle 2001), are all well documented. Practitioners must however acknowledge that we cannot control them perfectly in real-world team-sport training environments. We aren't operating in a lab where everything can be standardised; players will inevitably train on hotter days, take ergogenic performance aids., drink coffee before sessions, or experience travel-related fatigue. These variations introduce unavoidable noise into HR monitoring. Plasma volume expansion, for example, can lower HR for the same metabolic demand, falsely suggesting reduced cardiopulmonary strain when it is actually a mechanical adjustment. However, it's important to recognise that the higher the training intensity, the less these factors tend to affect HR readings. Hydration and nutrition shifts, for instance, will have a smaller impact on HR during such efforts compared to lower-intensity work. Although ideal conditions might help reduce variability, practical field settings dictate that we accept and work with this noise rather than trying to eliminate it from the training process.

(i)TRIMP: advanced methods for quantifying internal training load?

TRIMP, on the other hand, is a more global internal load index that integrates session duration, HR intensity, and weighting functions that can be generic (Banister 1991, Edwards 1994) or individualized (Manzi 2009, Lucia 2003, Stagno 2007). The individualized approach highlights the relevance of intensities most likely to drive adaptations. While the original TRIMP uses population-based HR–lactate response curve coefficients and mean session HR (Banister 1991), iTRIMP refines this by applying individualized HR–blood lactate (BLa) relationships to assign personalized weightings and calculate TRIMP values for each HR reading. In contrast with time-in-zone methods, TRIMP accounts for the physiological cost (or metabolic disturbance) of exercise, rather than only time spent in predefined intensity ranges. This distinction is critical because HR alone may not always provide a reliable marker of metabolic strain. Scharhag-Rosenberger et al. (2010) showed that exercise prescribed as fixed percentages of VO_2max produced highly variable lactate responses, even among individuals with similar aerobic capacity, indicating heterogeneous metabolic stress. These findings support the reasoning that HR-based prescription must be coupled with BLa or other metabolic variables to accurately describe exercise intensity and ensure that internal load reflects true physiological disturbance.

The TRIMP models by Edwards (1994), Lucia (2003), and Stagno (2007) follow the same general principle as the latter two approaches by applying intensity-based weightings to HR zones to assess cardiovascular load. However, instead of using an exponential function linked to the entire HR–lactate curve, they assign fixed multipliers to predefined HR zones. Edwards' model uses arbitrary, linear-like intensity coefficients, while Lucia and Stagno base their zones on physiological markers such as ventilatory or lactate thresholds. For example, Stagno's weightings were based on a team weighting as described from collated blood lactate responses of the studied population. Still, even in these physiologically anchored models, the rationale behind the exact choice of coefficients (e.g., why a zone is weighted as 3 versus 4) is not clearly justified and arbitrary.

Despite some of these limitations studies have shown dose-response relationships with Stagno's TRIMP (Stagno 2007), Lucia TRIMP (Sanders 2017), Banisters TRIMP (Sanders 2017, Taylor et al 2018) and iTRIMP (Malone 2016, Akubat et al 2012, Taylor et al 2018, Sanders et al, 2017, Manzi et al, 2009 and 2013). Proponents of TRIMPs that are exponentially weighted argue that it guards against greater contribution from lower intensity exercise. The research shows that greater individualisation is required to produce meaningful dose-response relationships (Ellis 2023). The intrusive nature of testing required for this individualisation has prevented wider adoption despite the relationships with training outcomes present.

Table 1. Overview of the different training impulse (TRIMP) methods.

Method	Formula
Banister TRIMP (1991) and Manzi's (2009) iTRIMP	$= D \times (\Delta \text{ heart rate ratio}) \times e^{(b \times \Delta \text{ heart rate ratio})}$, where D is session duration, Δ heart rate ratio is (HRavg - HRrest) ÷ (HRmax - HRrest), and the weighting factor b reflects the HR-lactate response. b = 1.92 for Banister, and has an individual value for Manzi.
Edwards' TRIMP (1994)	(duration in zone 50–60% HRmax × 1) + (duration in zone 60–70% HRmax × 2) + (duration in zone 70–80% HRmax × 3) + (duration in zone 80–90% HRmax × 4) + (duration in zone 90–100% HRmax × 5).
Lucia's TRIMP (2003)	(duration <VT1 × 1) + (duration in VT1–VT2 × 2) + (duration >VT2 × 3).
Stagno's TRIMP (2007)	(duration in zone 65–71% HRmax [moderate activity] × 1.25) + (duration in zone 72–78% HRmax [lactate threshold training] × 1.71) + (duration in zone 79–85% HRmax [steady-state training] × 2.54) + (duration in zone 86–92% HRmax [OBLA training] × 3.61) + (duration in zone 93–100% HRmax [maximal training] × 5.16).

iTRIMP-based dose–response relationships across studies

The dose-response relationship between several studies which used the same training adaptation measures are presented below. In Figure 6 below studies that used iTRIMP in running, cycling, rugby and soccer and a lactate test with speed at 4m·mol^{-1} during a lactate test (S4) were amalgamated (Ellis 2023). This was done to try to better understand the relationships efficacy and applicability where small sample sizes in individual studies often leave wide variation. The results suggested that a figure between 450 and 500 iTRIMPs on a weekly basis would provide enough stimulus for maintenance of fitness for a large proportion of athletes. A r^2 value of 0.5 represents 50% of future change of fitness could be explained by variations in iTRIMP. Figure 6 illustrates that when all data is combined, iTRIMP explains 50% (95%CI= 0.38 to 0.58) of the variance with percent changes at S4. The required iTRIMP to maintain 0% at S4 was 567 AU (95%CI= 84 to 1058 AU). When only examining soccer, Figure 7 suggests that 66% (95%CI= 0.53 to 0.73) of the variance is explained between iTRIMP and percent changes at S4. The required iTRIMP to maintain 0% at S4 was 517 AU (95%CI= 153 to 893 AU).

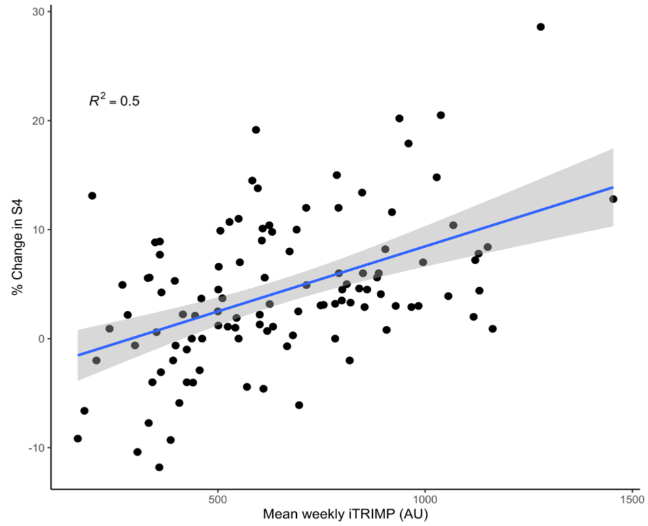

Fig. 6. Relationship between weekly iTRIMP and changes in speed at 4 mmol·L^{-1} (S4) across running, cycling, rugby, and soccer data (Ellis 2023). The regression line suggests that 450–500 weekly iTRIMP represents the minimal effective dose for cardiovascular fitness maintenance.

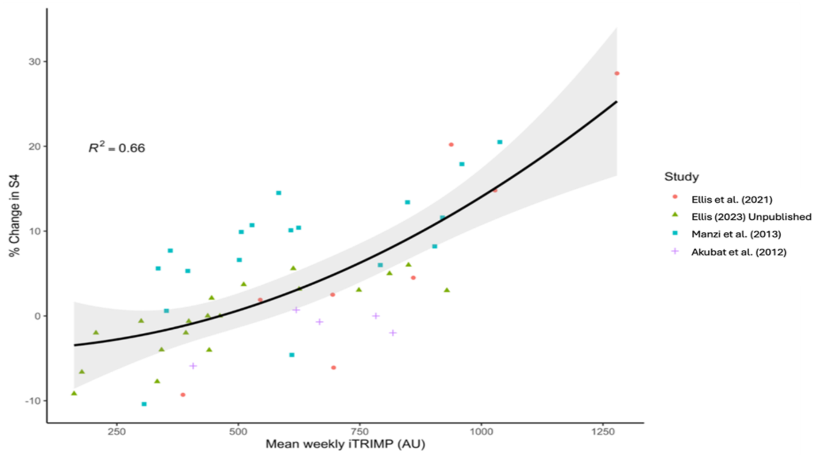

Fig. 7. Pooled analysis of four datasets in exclusively soccer players (Ellis 2023) showed that weekly iTRIMP explained 66% of the variation in fitness changes.

THRZ vs (i)TRMP: What actually works on the pitch/court?

In elite team sports environments, simplicity often dictates adoption. Despite some limitations highlighted above, THRZ monitoring is widely preferred due to its low cost, minimal setup, and ease of interpretation. Coaches only need HR data and an estimate of HRmax to implement it. This approach doesn't require lab testing, software, or specialized expertise.

iTRIMP, while physiologically the more refined approach (Ellis 2023), is rarely used outside of controlled research or elite individual sport contexts. It requires lactate testing to establish the individual HR–lactate curve, followed by software to apply individualized weighting, which makes it less practical for daily use in most team sport environments. Perhaps the biggest limitation is that iTRIMP does not lend itself to prescriptive planning—you cannot realistically program a session by prescribing "200 units of iTRIMP." This could change if software allowed live calculation during training, but for now iTRIMP is only available after sessions, which prevents real-time monitoring and direct prescription. In contrast, using THRZ offers a clear and practical approach, allowing coaches to target specific durations above thresholds like 85% or 90% HRmax with far greater applicability (Tables 4 and 5). As such, %HRmax-defined zones remain a practical and usable proxy for internal, cardiovascular load monitoring.

Revisiting the dose-response relationship: THRZ and adaptation

The current paper builds on this debate by reexamining data from published studies that reported both HR-based load and physiological and aerobically-related performance outcomes. The goal is to determine whether THRZ or (i)TRIMP-derived methods offer a clearer and more quantifiable dose-response relationship with adaptation. By focusing on elite team sport players and the left parts of the load-monitoring quadrant (internal metabolic load and associated adaptations) (Buchheit & Hader 2025), we aim to provide practitioners with clear guidelines for monitoring this specific part of players' load.

Dose-response (re)analysis

The central aim of this reanalysis is to quantify the dose–response relationship between various measures of cardiovascular load and training adaptations in team sport athletes. The analysis focuses first on time accumulated in zones defined either by percentages of maximal HR (e.g., >85–90% HRmax) or anchored to physiological markers (e.g., HR corresponding to >4 mmol·L^{-1} lactate). These relationships are then compared to those derived from aggregated internal load measures such as (i)TRIMP, which vary in their definitions and calculation methods (Table 1).

Data

The analysis draws upon previously collected datasets from elite team sports, with inclusion criteria focused on:

- Accurate and complete HR recordings during field-based training sessions and match play.
- Documented HRmax values for each athlete, obtained through maximal effort tests or verified field assessments.
- Consistent categorization of HR zones based on percentages of individual HRmax.

Analysis

The dose–response relationship was evaluated using two complementary approaches (Figure 8):

- **Minimum effective dose:** Linear and nonlinear regression models were applied to characterize the relationship between time spent in specific HR zones or TRIMP values and subsequent changes in physiological (e.g., VO_2max, lactate thresholds) and performance markers (e.g., Yo-Yo IR1, 30-15IFT). Threshold analysis was then used to identify the minimum weekly exposure required in high-intensity HR zones to prevent detraining, defined as the x-intercept of the regression line where the predicted change in fitness crosses zero. This approach is particularly relevant for return-to-play contexts.
- **Magnitude of the dose–response:** The slope of the regression line was used to quantify the expected percentage change in physiological or performance outcomes per additional 10 minutes spent in the target HR zone. This provides a practical measure of the incremental benefit of accumulating more time above the threshold.

Results

Table 2 summarizes the dose–response relationships between HR-based training load measures and variable measures of cardiometabolic fitness adaptations in elite team sport athletes, drawn from 12 studies (Stagno 2007; Castagna 2011; Akubat 2012; Castagna 2013; Manzi 2013; Malone 2016 and 2019; Campos-Vazquez 2017; Taylor et al 2017; Rabbani 2019; Ellis 2021, Malone 2025).

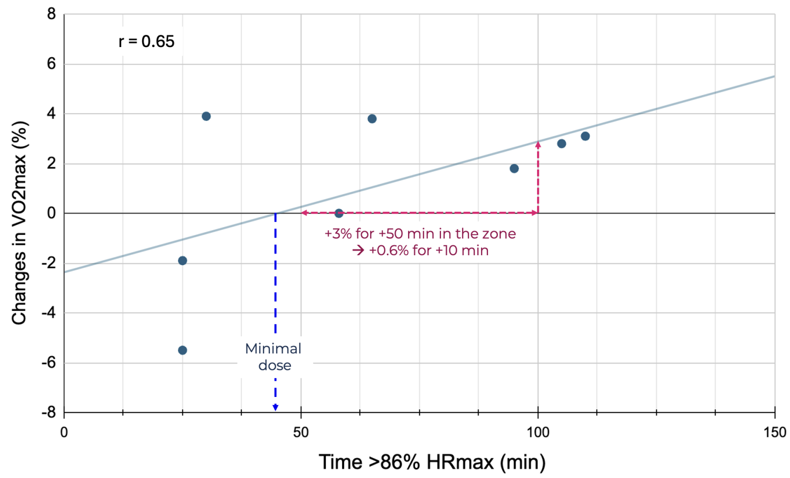

Fig. 8. **Relationship between weekly time spent above 86% HRmax and changes in VO_2max. Redrawn from Stagno et al. (2007). The regression line indicates an average minimal effective dose of ∼46 minutes per week to maintain VO_2max. Also, an additional 10 minutes per week above 86% HRmax was associated with a +0.6% improvement in VO_2max. Considerable individual responses are apparent around the regression line, showing that dose–response relationships are not uniform across players. The estimated plausible range for the minimal effective dose (∼28–64 min) was derived pragmatically from the reported sample size (n=8) and correlation strength (r=0.65), applying a ±40% margin because raw data were unavailable to compute formal confidence intervals. These ranges therefore, provide only an approximation of uncertainty and should be interpreted with caution.**

Table 2. **Summary of studies examining the dose–response relationship between HR–based training load measures and physiological or performance adaptations. Some studies reported both time in HR zones (THRZ) and various TRIMP metrics, while others included only one of the two. When possible, and where authors had access to the original data, additional load metrics were calculated and are indicated with an asterisk (*). V2mmol·L^{-1}: running velocity associated with a blood lactate of 2 mmol·L^{-1}, V4mmol·L^{-1}: running velocity associated with a blood lactate of 4 mmol·L^{-1}, RE; running economy, V_{IFT}: velocity reached at the end of the 30-15IFT.**

Author (Year)	Population & Sport	Context and Duration	Dose Definition (TRIMP and THRZ)	Response Measures	Correlation (r)	Key Findings
Stagno et al. (2007)	8 elite field hockey players	In-season, 8 weeks	Stagnos' TRIMP and weekly T>vOBLA mmol·L^{-1}, (T>86%HRmax)	VO_2max, vOBLA	TRIMP: ΔVO_2max (r=0.80; 0.35–0.95) and ΔvOBLA (r=0.71; 0.15–0.93) THRZ: ΔVO_2max (r=0.65; 0.04–0.91) and ΔvOBLA (r=0.67; 0.08–0.91)	Correlation slightly stronger with TRIMP vs Time into Zones
Castagna et al. (2011)	14 elite soccer players (Serie A)	Pre-season, 6 weeks	T>4 mmol·L^{-1} (T>90%HRmax)	V2mmol·L^{-1}, V4mmol·L^{-1}	ΔV2mmol·L^{-1} (r=0.84; 0.62–0.94), ΔV4mmol·L^{-1} (r=0.65; 0.27–0.85)	THRZ correlates with markers of metabolic fitness and performance changes, no (i)TRIMPS available

Akubat et al. (2012)	9 youth soccer players	In-season, 6 weeks	iTRIMP, Banister's TRIMP, sRPE	vLT	iTRIMP: ΔvLT (r=0.67; 0.14–0.90)	iTRIMP (ONLY) is significantly related to ΔvLT no THRZ available
Castagna et al. (2013)	18 elite soccer players (Serie A)	Pre-season,8 weeks	T>4 mmol·L^{-1} (T>90%HRmax)	VO$_2$max, Yo-Yo IR1, V2mmol·L^{-1}, V4mmol·L^{-1}	ΔV2mmol·L^{-1} (r=0.78; 0.55–0.90), ΔV4mmol·L^{-1} (r=0.60; 0.26–0.81), ΔVO$_2$max (r=0.65; 0.34–0.83), ΔYo-Yo IR1 (r=0.66; 0.35–0.84)	THRZ correlates well with markers of metabolic fitness and performance changes, no (i)TRIMPS available
Manzi et al. (2013)	18 elite soccer players (Serie A)	Pre-season, 8 weeks	iTRIMP	VO$_2$max, V4mmol·L^{-1} VT, Yo-Yo IR1	ΔVO$_2$max (r=0.77; 0.53–0.89), ΔV4mmol·L^{-1} (r=0.64; 0.32–0.83), ΔVT (r=0.78; 0.55–0.90), ΔYo-Yo IR1 (r=0.69; 0.40–0.85)	iTRIMP correlates well with fitness and performance changes, no THRZ available
Malone et al. (2016)	18 male hurling players	8 weeks	iTRIMP	VO$_2$max, RE, V2mmol·L^{-1}, V4mmol·L^{-1}, Yo-Yo IR1/2	iTRIMP vs. ΔVO$_2$max (r=0.77; 0.59–0.88), ΔRE (r=0.78; 0.61–0.88), ΔV2mmol·L^{-1}(r=0.64; 0.39–0.80), ΔV4mmol·L^{-1}(r=0.78; 0.61–0.88), ΔYo-YoIR1 (r=0.69; 0.47–0.83), and ΔYo-YoIr^2 (r=0.60; 0.34–0.78)	iTRIMP correlates well with markers of metabolic fitness and performance changes, no THRZ available
Campos-Vazquez et al. (2017)	12 professional soccer players (Spanish 2nd div.)	Pre-season, 4 weeks	Edward's TRIMP, sRPE, T>85%HRmax*, T>90%HRmax*	V$_{IFT}$	sRPE: r=0.70; 0.31–0.89); TRIMP or TZHR no correlation	Neither TRIMP nor THRZ was associated with changes in V$_{IFT}$
Taylor et al. (2017)	10 academy rugby union players	In-season, , 6 weeks	Banister's bTRIMP, Edwards' TRIMP, Lucia's TRIMP, iTRIMP	VO$_2$max,, V2mmol·L^{-1}, V4mmol·L^{-1}	bTRIMP (r=0.88; 0.64–0.96) and iTRIMP (r=0.74; 0.32–0.92) associated (quadratic function) with ΔVO$_2$max	iTRIMP correlates well with fitness and performance changes, no THRZ available
Malone et al. (2019)	30 male hurling players	Pre-championship period, 12 weeks	T≤ HR at 2 mmol·L^{-1}, T between 2–4 mmol·L^{-1}), T≥ HR at 4 mmol·L^{-1}, ∼90% HRmax)	VO$_2$max, peak treadmill velocity, V2mmol·L^{-1}, V4mmol·L^{-1}, Yo-Yo IR1/2	T≥∼90% HRmax vs. V2mmol·L^{-1} (r=0.80; 0.55–0.95), V4mmol·L^{-1} (r=0.58; 0.20–0.79), VO$_2$max (r=0.77; 0.48–0.85), Yo-Yo IR1 (r=0.65; 0.45–0.79)	Only time in high-intensity zones associated with aerobic fitness improvements. No (i)TRIMPS available
Rabbani et al. (2019)	11 professional male soccer players	In-season, 5 weeks	Banister's TRIMP, Edwards' TRIMP, T>90%HRmax	V$_{IFT}$	ΔV$_{IFT}$ vs. Banister's TRIMP (r=0.51; –0.02–0.82), Edwards' TRIMP (r=0.54; 0.02–0.83), T>90%HRmax (r=0.71; 0.30–0.90)	Correlations slightly stronger with Time into Zones vs. TRIMP

Ellis et al. (2021)	9 elite academy soccer players	Pre-season, 6 weeks	iTRIMP, multiple TRIMPs, sRPE	V2mmol·L^{-1}, V4mmol·L^{-1}, MAS	iTRIMP: ΔV2mmol·L^{-1} (r=0.93; 0.76–0.98), ΔV4mmol·L^{-1} (r=0.88; 0.61–0.97)	Individualized TRIMP best variable, no THRZ available
Malone & Buchheit 2025	26 GAA players	In-Season 11 Weeks	Edwards' TRIMP, T>90%HRmax	V_{IFT}	ΔV_{IFT} vs. Edwards' TRIMP (r=0.66; 0.42–0.81), T>80%HRmax (r=0.69; 0.47–0.83), T>90%HRmax (r=0.53; 0.24–0.73)	Similar correlations with Time into Zones vs. TRIMP

Time in zone vs. TRIMP: similar sensitivity, different usability

While the most individualized TRIMP is likely the most comprehensive, it is also the hardest to use, and since TRIMP-based metrics and THRZ show similar sensitivity, neither method shows a consistent advantage for tracking training adaptation. Across the studies reviewed (Table 2), correlation values fall within a similar range. In some cases, THRZ showed slightly stronger associations with fitness changes (Rabbani 2019), while in others, TRIMP-based approaches performed better (Stagno 2007). In the most recent work, associations were very similar (Malone & Buchheit 2025). One explanation for the absence of clear superiority of TRIMPs is that, in most direct comparisons, only generic (Stagno 2007) or Edwards-style TRIMPs (Campos-Vazquez 2017; Rabbani 2019; Malone & Buchheit 2025) were used, rather than iTRIMP. Because Edwards' TRIMP still relies on generic zone thresholds, it is inherently less precise than iTRIMP, which is weighted to individual lactate–HR profiles. Before drawing definitive conclusions about the relative value of the two methods, direct comparisons between THRZ and iTRIMP (the most physiologically robust TRIMP variant) are needed. Until then, the choice between approaches in applied settings may be better guided by practicality than by assumptions about sensitivity.

From a practical standpoint, THRZ offers clear advantages. It requires no computation, is easy to interpret, and can be used both for monitoring and for prescribing training. It is also prominently embedded in various HR and GPS monitoring software packages and on personal smart devices. In contrast, TRIMP is an aggregated value combining time spent across multiple intensity zones, using weightings that vary between models. As a result, two sessions can produce the same TRIMP score despite very different distributions of effort across zones. This makes TRIMP less useful for guiding or prescribing specific training intensities and potentially masks time spent at intensities most relevant for driving adaptation. The ecological validity of iTRIMP could be argued, because despite these limitations in team sport training and match-play, dose-response relationships are present with a targetable TRIMP value for maintenance and improvement providing macro goals. However, as previously stated microprescription (per session) is challenging using TRIMP. Considering these limitations, THRZ stands out as the more practical and actionable approach for practitioners in applied settings, especially for individual sessions.

An important limitation of the THRZ approach however is that zones must be physiologically anchored, ideally to VO_2 or lactate thresholds, and based on an accurate HRmax from an incremental test. While some data suggest that time above ∼90% HRmax may relate to adaptation, training sessions just below this cutoff would register as zero minutes and likely show no dose–response. We know that high-intensity exposure (i.e., >RCP, >critical speed or power, or >85–90% VO_2max) drives adaptation (Helgerud 2007; Inglis 2024, 2025; Buchheit & Laursen 2013; Storoschuk 2025), but does this imply that work below these thresholds has no value at all? This raises key questions about which HR zones should be used, how they should be physiologically grounded, and whether clear dose–response relationships exist across different thresholds. These issues require further investigation.

Targeting the right weekly volumes: 30 minutes (± 20) in high HR zones for meaningful adaptations?

Across studies examining the relationship between THRZ and training adaptation (Table 3), two consistent findings emerge. First, the weekly minimal effective dose required to maintain or improve cardiometabolic fitness averaged 31 minutes, with thresholds ranging from 16 minutes (Malone 2019) to 73 minutes (Stagno 2007), depending on the marker (VO_2max, lactate thresholds, or performance tests such as Yo-Yo IR1 or the 30-15IFT). Lower HR thresholds (e.g., > 80–86% HRmax) required longer exposures, while higher intensities (e.g., > 90–91% HRmax) elicited effects with shorter durations. This further reinforces the proven effectiveness of training at or above 90% HRmax. Not only as the most time-efficient way to drive aerobic and cardiovascular adaptations, but also as a strategy to maximize the return on time invested in football, effectively "hitting many birds with one stone". Second, the dose–response magnitude averaged a 1.5% improvement per additional 10 minutes spent above threshold, with slopes ranging from 0.5% (Stagno 2007, vOBLA) to 4.0% (Malone 2025, V_{IFT}).

Variation between studies can be attributed to differences in HR zone definitions, outcome markers, and contextual factors such as baseline fitness, chronic training load, and seasonal timing. For instance, Rabbani (2019) and Malone (2025) reported positive intercepts, suggesting improvements irrespective of time in zone, likely reflecting additional preseason training stimuli beyond cardiovascular load. Note that large individual differences exist around these averages, with wide confidence intervals in several studies, meaning that players can respond very differently to the same "dose" of THRZ or TRIMP.

In practical terms, accumulating approximately 30 minutes per week above 90% HRmax appears to represent a realistic minimal dose for most athletes, while every extra 10 minutes in this zone may translate into an additional ∼1–2% improvement in key fitness markers. These values should therefore be considered population-level guidelines, always applied with caution at the individual player level. A pragmatic approach would be to use the population level data as guideline and thereafter monitor training response on an individual level and iteratively adapt.

Table 3. Summary of regression-based analyses linking weekly time spent in high-intensity HR zones (>86–91% HRmax) with physiological and performance adaptations in team sport athletes. The "Minutes at zero intercept" indicates the estimated weekly duration in zone likely required to maintain or improve fitness (i.e., the point at which the regression line crosses zero). The "% change per +10 min in zone" represents the slope of the regression, showing the expected improvement for every additional 10 minutes accumulated in the target zone. Ranges represent pragmatic uncertainty bands, not formal confidence intervals, and were estimated based on reported sample sizes and correlation strength (±20% for large n and r≥0.7, ±25–30% for moderate n or r≈0.6–0.7, and ±40% for small n≤14). These approximations were used because the raw data needed to calculate formal confidence intervals for the regression intercepts were not available.

Study	Marker	HR zone (%HRmax)	Minimal dose (min/wk)	Plausible range (min/wk)	% change per +10 min in zone
Stagno 2007	VO_2max	>86%	~46	~28–64 (±40%)	~0.6
Stagno 2007	vOBLA	>86%	~73	~44–102 (±40%)	~0.5
Castagna 2011	V2 mmol	>90%	~20	~15–25 (±25%)	~1.1
Castagna 2011	V4 mmol	>90%	~17	~12–22 (±30%)	~1.3
Castagna 2013	VO_2max	>91%	~20	~14–26 (±30%)	~1.0
Castagna 2013	Yo-Yo	>91%	~40	~28–52 (±30%)	~2.5
Malone 2019	VO_2max	>91%	~30	~24–36 (±20%)	~2.0
Malone 2019	V2 mmol	>91%	~23	~18–28 (±20%)	~2.0
Malone 2019	V4 mmol	>91%	~16	~12–20 (±25%)	~1.0
Malone 2019	Yo-Yo	>91%	~25	~19–31 (±25%)	~1.0
Rabbani 2019	V_{IFT}	>90%	Y-intercept = +2.5%	N/A	~2.1
Malone 2025	V_{IFT}	>90%	Y-intercept = +3.6%	N/A	~3.5
Average / Range		>86–91%	~31 min (16–73)	±20 min relative uncertainty	~1.5 % (0.5–3.5)

Table 4. Example of how players can accumulate more than 30 minutes above 90% HRmax over the course of two typical microcycles. *Note: This is an anecdotal observation, but HR often exceeds training values during matches. External factors, such as stress and caffeine, can combine with cardiac drift late in games. As a result, players spend extended periods in high-intensity zones. This HR response is not driven solely by VO_2 demand and can overestimate actual aerobic requirements.

	Monday	Tuesday	Wed	Thurs	Friday	Saturday	Sunday	Total (min)
1 Match (playing as a substitute)	Team Training (0 min)	D-4 Team Training (8 min)	D-3 Team Training (12 min)	Team Training (0 min)	Team Training (0 min)	Match (played 30 min, 10 min in zone)	Compensation Training (15 min)	35 min (training), 10 min (matches)
1 Match (playing as a starter)	Team Training (0 min)	D-4 Team Training (8 min)	D-3 Team Training (12 min)	Team Training (0 min)	Team Training (0 min)	Match (played 90 min, 30 min in zone)	Recovery (0 min)	20 min (training), 30 min (matches)
2 Matches (playing as a starter 2x)	Team Training (0 min)	Team Training (0 min)	Match (played 90 min, 30 min in zone)	Recovery (0 min)	Team Training	Match (played 90 min, 30 min in zone)	Recovery (0 min)	0 min (training), 60 min (matches)
2 Matches (playing as a substitute and benched 2x)	Team Training (0 min)	Team Training (0 min)	Match (played 30 min, 10 min in zone)	Compensation Training (15 min)	Team Training (0 min)	Match (0 min played)	Compensation Training (15 min)	30 min (training), 10 min (matches)

What remains unclear, however, is how best to accumulate these 30 minutes: whether in one long session, a few concentrated efforts, or several shorter bouts (e.g., one of 30 min, three of 10 min, or six of 5 min). It is unlikely that most athletes can sustain 30 continuous minutes above 90% HRmax in a single bout, and in practice, this workload is typically distributed across three to four sessions per week, as illustrated in the example tables 4 and 5. How this distribution influences adaptation, however, is still unknown.

While the relationship between time spent above 90% HRmax and improvements in fitness appears broadly linear (Table 2), practitioners must weigh the cost–benefit trade-off of adding further high-intensity work. Extending exposure by 10–20 minutes per week may bring only small additional gains in VO_2max (∼1–2%), yet at the expense of greater workload, recovery demands, and potential fatigue or injury risk. For team-sport athletes, where overall performance depends on multiple interacting qualities, the practical transfer of such marginal physiological gains may be limited. Therefore, decisions to increase time in the high-intensity zone should consider both the potential physiological benefit and its impact on overall readiness, freshness, injury risk, and technical–tactical training quality (Buchheit 2025).

This 30-min (± 20 minutes) minimal dose reflects the need to reach intensities closely aligned with critical physiological thresholds (Helgerud 2007; Inglis 2024, 2025; Buchheit & Laursen 2013). Time spent above the second ventilatory threshold (RCP) or near VO_2max likely provides the metabolic disturbance required to stimulate both central and peripheral adaptations (Buchheit & Laursen 2013). While individualized prescriptions based on physiological testing are preferable (see section on the limitations of THRZ, Scharhag-Rosenberger 2010), the recommendation of accumulating 30 minutes per week above 90% HRmax offers a practical benchmark for applied settings. This is in line with findings from the 20-year review of the 30-15IFT (Figure 9, Buchheit 2021), which showed that two very short HIIT sessions per week can elicit meaningful physiological gains. Similarly, this is consistent with the typical 4 x 4 min HIIT performed >90%HRmax (Impellizzeri 2006, 2008; Bravo 2008; Helgerud 2001, Hill-Haas 2009). Such sessions typically contribute altogether around 20-25 minutes per week above 90% HRmax, with the remaining exposure achieved through team sports-specific training and match play, allowing players to consistently exceed the 30-minute threshold when all weekly stimuli are combined (Tables 3 and 4). Current results also align with the findings reported by Spiering et al. (2021), who systematically reviewed studies on the minimal training dose required to maintain endurance performance. Their analysis showed that VO_2max and endurance capacity can be maintained for several weeks with large reductions in training frequency (down to 2 sessions per week) and volume (to as little as ∼13–26 minutes per session), provided relative intensity is preserved. In contrast, reductions in intensity consistently led to declines in VO_2max.

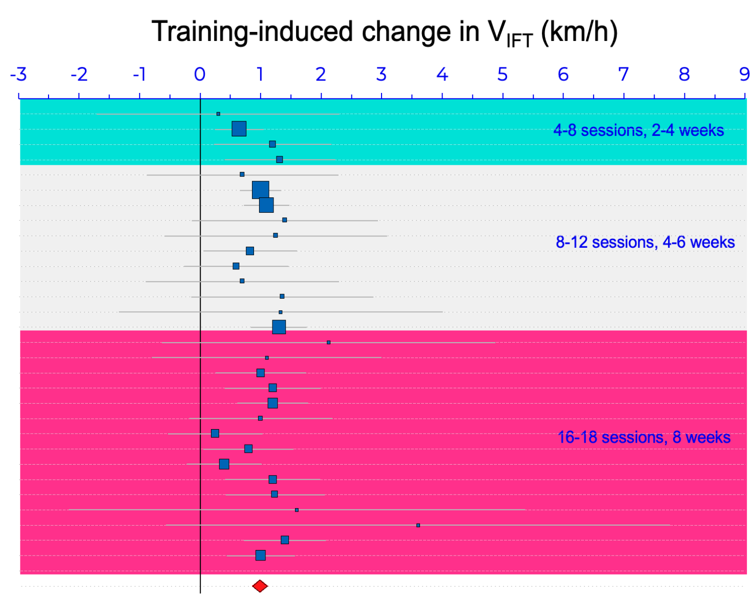

Fig. 9. Changes in VIFT following various training interventions. Taken from Buchheit 2021.

Match vs. training time in HR zone: same side of the coin?

Time spent in high HR zones can be accumulated through various training modalities, depending on player status and training context.

For healthy players, this includes matches, team-sport-specific drills that elevate HR, structured HIIT on the pitch, or complementary off-field conditioning methods such as cycling or rowing, which reduce mechanical stress while maintaining metabolic load (Table 3). Hitting the weekly high-intensity dose is straightforward in team-sport training without matches. When players also face competitive matches, an important challenge arises. Matches alone already often generate >30 min above 90% HRmax in football (Helgerud et al. 2001; Kunzmann et al. 2022), making up a large share of the weekly cardiac and metabolic load. Current practice then adds another 20–30 minutes above 90% HRmax in the microcycle—small-sided games on D-4 (5–10 minutes; Buchheit & Laursen 2013) plus extensive drills or run-based HIIT on D-3 (10–15 minutes; Buchheit 2021, 2025). In a standard 90-minute match schedule, players may accumulate (or even exceed) 60 minutes per week above 90% HRmax. However, whether HR responses during matches carry the same physiological "dose-value" as those during training remains uncertain. Match HR values are often elevated beyond training levels due to factors such as psychological stress, caffeine intake, and progressive cardiac drift late in games (Bangsbo 1994). In some cases, players may spend nearly the entire match above 90% HRmax, anecdotally reported in elite settings. This makes match-derived HR data questionable for assessing aerobic demands. Time spent in high HR zones during matches is therefore likely to overestimate actual VO_2 demands and inflate the estimated aerobic load. In practice, match and training HR data should be kept separate rather than summed (Table 3), for the reasons outlined above. While players' individual aerobic fitness likely also plays a role here, experience also shows that during periods with two matches per week, players often maintain (or even improve) their metabolic fitness, suggesting that two match loads is generally a sufficient stimulus to meet the minimal dose required. However, this does not apply to substitutes or players with limited minutes, for whom compensating through training becomes essential. In these cases, targeting the >30-min threshold above 90% HRmax through structured drills remains a practical recommendation, with adjustments based on actual match time played. There is likely a balance between match and training contributions to time in the target HR zones, but more research is needed. Most importantly, given the variability in the HR–VO_2 relationship between individuals and across match vs. training contexts, this balance should be managed on an individual basis.

Time in high HR zones during rehab: challenge or achievable target?

For injured players, time above 90% HRmax can be progressively accumulated throughout the week by combining off-field conditioning with later-stage on-field work during rehabilitation phases (Table 4). This approach supports a progressive return to performance without compromising tissue recovery or neuromuscular load management. However, in rehabilitation, it can be hard to reach high HR with upper-body exercise alone, since cardiac output depends on engaged muscle mass. As a result, expected weekly totals may be lower when cross-training replaces running.

While this lies somewhat outside the scope of the present manuscript, several strategies can be used to help players reach higher HRs during rehab. Among these, exposure to heat is a particularly valuable approach, as it raises cardiovascular strain without requiring additional mechanical work or external load (Philp 2017).

Table 5. Example of how players can accumulate more than 30 minutes above 90% HRmax over the course of a week during the rehabilitation process, across different phases involving a mix of off-field and on-field training types.

	Monday	Tuesday	Wed	Thurs	Friday	Saturday	Sunday	Total (min)
Off Field	Ski Erg / Hammer Strength (12 min)	Physio/ Gym	Rowing / Battle rope (6 min)	Physio/ Gym	Bike Heat / Ski Erg (12 min)	Recovery	Recovery	30
On & Off Field	Return to Run S1 (10 min)	Physio/ Gym	Bike Heat / Ski Erg(12 min)	Physio/ Gym	Return to Run S2 (12 min)	Recovery	Recovery	32
On field	Run-based HIIT + MDP Drills (16 min)		Top up Bike Heat / Ski Erg (10 min)		Run-based HIIT + MDP Drills (14 min)	Recovery	Recovery	40

Athlete profiles and dose–response relationships

Athlete responses to exercise are influenced by their physiological profile, which can be broadly defined by muscle fibre composition (Lievens et al., 2020) and by their anaerobic speed reserve (ASR) — the difference between maximal aerobic speed and maximal sprinting speed (Buchheit & Laursen, 2013). Recent work (Malone & Buchheit, 2025) shows that these profiles display distinct adaptive patterns to time in high-intensity HR zones. Endurance profiles demonstrate lower initial responses (y-intercepts) but steeper slopes over time, indicating stronger sensitivity to progressive exposure. Speed profiles show earlier improvements but diminishing returns with increasing exposure, while hybrids (i.e., players displaying both speed and endurance traits) display moderate responses. For every additional 10 minutes above 80% HRmax, performance improved by ∼3% on average, with endurance profiles showing the greatest sensitivity (∼3%), hybrids moderate (∼2.5%), and speed the lowest (∼2%). At >90% HRmax, the adaptation was amplified, with ∼4% average gains across groups, again with endurance athletes responding most strongly (∼4%) compared to hybrids (∼3.5%) and speed profiles (∼3%).

These findings highlight that HR-based metrics may be particularly valid for endurance athletes, as their adaptations are largely central and cardiovascular. In contrast, HR alone may underestimate total training stress in speed and hybrid profiles, given their greater reliance on peripheral metabolic and neuromuscular mechanisms. For these athletes, HR monitoring should be complemented with peripheral markers such as muscle oxygenation dynamics (SmO_2) (Buchheit & Hader, 2025) or with mechanical load indices, to allow for both central and peripheral stress to be captured.

Practically, this profile-based differentiation means that dose–response expectations and training prescriptions should be adjusted to the individual rather than assuming uniform responses. For endurance athletes, HR monitoring may remain a more valid marker of central cardiovascular load, while speed and hybrid profiles may require dual load monitoring approaches. Future studies should systematically stratify athletes by profile when assessing dose–response relationships, as pooling across groups risks masking important differences. Larger controlled trials across different team sport contexts are required to confirm the robustness of these profile-specific patterns.

Use of TRIMP and Time in Zone in Combination?

When making a decision about which HR methods to implement it is important to contextualise and conceptualise what each method offers from a training prescription, programming and monitoring perspective. TRIMPs that offer strong dose-response relationships (iTRIMP) provide the strongest measure to date to guide macro level training, recovery and performance (Figure 6 and 7). For example, if we are to assume the weekly target of ∼500 iTRIMP units are required for the maintenance of aerobic performance, we can start to examine the contributions of different activities towards that aim. For instance, examining THRZ (Figure 3) along with the iTRIMP can help target specific adaptations for each session (Tables 4 and 5) whilst also being cognisant of achieving a set weekly iTRIMP to maintain fitness.

Moreover, weekly rest/recovery schedules can also be arranged with greater assurance in these instances where the majority of the iTRIMPs is obtained in match time (with the limitations of match HR discussed), with the understanding that the required training exposure has been achieved. This is a little harder with time spent in high HR zones, as there is a lack of information about the rest of the training. As previously discussed, the nature of TRIMPs may miss important information around intensity in certain ranges, but they do amalgamate training across the intensity spectrum. Despite these limitations, a shared variance of 66% as shown above in Figure 6 is amongst the highest to be seen in any such analysis. Therefore, when examining macro trends and looking at the full spectrum of training TRIMP provides some greater inference capability. It should be noted that although various studies have shown dose–response relationships for different TRIMP models, when multiple TRIMPs are compared, not all display adequate relationships, with more generic calculations generally proving the least informative (Akubat 2012; Ellis 2021). HR in zone allows better prescription at a microlevel, giving clarity around metabolic stress and targeted training for specific adaptations (e.g. above RCP). In the future, a combination of overall TRIMPS achieved by a minimum time in a certain HR zone would provide the ultimate use of HR for both macro and micro aims informed by the evidence of dose-response presented here.

Conclusion

This paper reaffirms the relevance of HR monitoring for cardiovascular load assessment in elite team sports, particularly when properly contextualized and standardized. By revisiting dose–response relationships using both THRZ and aggregated TRIMP values, we aimed to clarify the minimal training load required to maintain or improve cardiovascular fitness and physical performance, and emphasize the importance of individual profiles and contextual factors in shaping adaptation (Malone and Buchheit 2025).

Our analysis shows no clear superiority of TRIMPs or THRZ in terms of sensitivity, as both approaches yield comparable correlations with physiological and performance outcomes (Table 2). A likely reason TRIMPs have not shown clear superiority is that most comparisons used generic (Stagno 2007) or Edwards' TRIMPs (Campos-Vazquez 2017; Rabbani 2019; Malone & Buchheit 2025), not iTRIMP (Ellis 2023). Definitive conclusions require direct comparisons between THRZ and iTRIMP.

However, practically, THRZ offers significant advantages. It is easier to compute, more intuitive to interpret, and more directly applicable for training prescription. In contrast, TRIMPs aggregate efforts across intensities, making it difficult to track or prescribe time at the most effective training loads (90 minutes below 80% HRmax can yield a similar TRIMP value to 45 minutes above 80%HRmax). In practice, THRZ is best suited for micro usage, such as setting and monitoring session- and week-level targets, while TRIMPs are better suited for macro usage, where they can capture cumulative load and dose–response patterns across mesocycles or longer training phases. Ideally, both approaches would be used together to provide complementary information (Ellis 2023). However, resource and implementation constraints often mean practitioners rely primarily on THRZ. TRIMPs remain precious at the conceptual and macro level, but their application depends on how far a team chooses to extend its monitoring system.

A limitation, however, is that THRZ methods must be physiologically anchored to VO_2 or lactate thresholds and based on accurate HRmax. Some evidence suggests time above ∼90% HRmax relates to adaptation (Helgerud 2007; Inglis 2024, 2025; Buchheit & Laursen 2013; Storoschuk 2025), yet sessions just below this cutoff would count as zero and show no dose–response. High-intensity is clearly important, but whether sub-threshold work has value remains uncertain and needs further study.

As a practical recommendation, we suggest accumulating 30 (±20) minutes per week above 90% HRmax or the HR corresponding to 4 $mmol \cdot L^{-1}$ lactate (>85-90% HRmax), to ensure sufficient metabolic and cardiovascular stimulus (Table 3). This threshold provides a usable benchmark for practitioners while allowing flexibility based on individual and contextual variation. In addition, the dose–response slopes across studies suggest that every extra 10 minutes spent in these high-intensity zones can yield an average improvement of ∼1–2% in key cardiometabolic fitness markers, which highlights the incremental value of additional time above threshold.

Considerable individual variability exists around these averages, with some players improving at lower exposures while others require higher volumes. This variability can be explained by multiple factors, including baseline fitness, chronic training load, seasonal context, and the type of marker used to assess adaptation. Athlete physiological profiles also play a major role: endurance players typically show the greatest sensitivity to high-intensity HR exposure, while speed and hybrid profiles respond less consistently, reflecting their greater reliance on peripheral and neuromuscular mechanisms (Malone and Buchheit 2025).

Taken together, these observations highlight that the 30-minute guideline should serve as an overall guide, not an individual prescription. What matters more is setting individualized weekly HR-based targets that reflect the athlete's profile and training goals. This approach brings HR monitoring back into practical use, aligning with the idea of maintaining structured control over metabolic training load within the "upper-left quadrant" framework described by Buchheit and Hader (2025).

Practical Applications

- HR captures primarily cardiovascular strain but does not fully represent aerobic metabolic contribution, especially during high-intensity intermittent efforts.
- HR shows a variable relationship with both systemic VO_2 and local muscle oxygen utilization (mVO_2) during intermittent exercise.
- Despite these limitations, HR remains the least flawed and most feasible option available for assessing metabolic load in field settings, as direct VO_2 or lactate measurements are impractical during team sports training and competition.
- Metabolic power, despite its popularity in GPS systems, cannot replace HR monitoring, as it fails to reflect true systemic metabolic demands and even its representation of partial internal load remains highly questionable.
- %HRmax should always be used for defining HR zones, as absolute HR lacks physiological meaning. Without an accurate HRmax, there is, however, no valid basis for using HR to assess metabolic demands.

- No clear difference in sensitivity between TRIMP and time in HR zones; both show similar correlations with physiological or performance outcomes (Table 2).
- TRIMPs combine efforts across intensities, limiting their usefulness for monitoring the work performed in specific training zones. The same TRIMP score can result from different training intensity profiles, reducing clarity for practical application.
- Time in HR zones (i.e., >85%, >90% HRmax) is simpler to compute and easier to interpret. It allows for direct use in training prescriptions (e.g., minutes above 90% HRmax) but may miss information at other intensities.
- However, while these generic thresholds are a practical first approach, individualizing HR zones based on individual physiological markers such as HR at the 4 mmol lactate threshold or RCP may offer greater precision. However, this requires additional testing and resources, making it a trade-off between accuracy and practicality.
- THRZ is best for micro-level monitoring (sessions and weeks), while TRIMPs are more suited for macro-level use (mesocycles and longer phases); ideally, both would be combined. However, since in team sports, consistent HR collection is difficult, TRIMPs are often impractical, though they remain a powerful tool in endurance sports.
- Current results (Table 2) highlight the importance of accumulating at 30 (± 20) minutes per week above 90% HRmax or above the HR at 4 mmol·L^{-1} to drive meaningful cardiovascular and metabolic adaptations.
- Each additional 10 minutes per week above 90% HRmax is associated with an average ∼1–2% improvement in key fitness markers.
- Individual responses vary widely however; the suggested doses should be seen as an informed starting point rather than a universal prescription.
- Time >90% HRmax can be accumulated through a mix of technical and tactical drills, structured HIIT, and off-field conditioning; this allows both healthy and injured players to reach weekly HR load targets while adjusting for mechanical load and rehab phase.
- Although time spent above 90% HRmax is linearly related to fitness gains, practitioners should balance the small additional (∼1–2%) VO_2max improvements from extra high-intensity work against the greater fatigue, recovery cost, and injury risk, especially since higher fitness does not necessarily translate into better performance in team-sport contexts.
- Athletes profiles should not be overlooked, as endurance athletes can be effectively monitored using HR as a marker of central, cardiovascular load, while speed and hybrid profiles may require complementary measures such as SmO_2 or mechanical external load indices to capture their peripheral and neuromuscular demands.

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