RESEARCH PAPER

EFFECTIVENESS OF THE ATHLETE BIOLOGICAL PASSPORT IN DETECTING BLOOD DOPING: A SYSTEMATIC REVIEW ACROSS SPORTS DISCIPLINES

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ABSTRACT

The Athlete Biological Passport (ABP) haematological module has become a cornerstone of indirect blood-doping detection in elite sport, yet existing evidence on its effectiveness across disciplines remains fragmented. This systematic review integrates findings from 150 primary studies, books, and technical reports to evaluate the sensitivity, specificity, and sport-specific detection patterns of the ABP haematological module. Across included cohorts in endurance-dominated sports such as cycling, athletics, and cross-country skiing, the ABP flags abnormal haematological profiles in 10–18% of monitored athletes over multi-year periods, with approximately 30–40% of flagged profiles leading to sustained Anti-Doping Rule Violations. Blood doping-related ADRV detection sensitivities are estimated to range from moderate to strong, whereas specificities remain very high, constantly demonstrating the strength of the module even in the presence of confounding factors, e.g., altitude training, illness, and training load, when these factors are explicitly addressed. Sport-wise breakdowns show significantly greater detection and ADRV conversion rates in endurance sports, for which not only performance depends on oxygen-carrying capacity but also the frequency of testing is highest; on the other hand, non-endurance and team sports show comparatively lower ABP-based "yields." The review mentions the ABP's role as a detection and deterrent tool, points out the need for contextual data and expert panel review, and sets forth the main areas for methodological improvements, e.g., the incorporation of more advanced longitudinal models and additional biomarkers into the ABP-based surveillance framework.

Keywords: Athlete Biological Passport, doping, anti-doping, Haematological module, Sensitivity and specificity, Sport-specific effectiveness

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INTRODUCTION

The Athlete Biological Passport (ABP) is a real game changer in today's anti-doping science. Instead of simply detecting banned substances in a single sample, ABP aims at a more complex and long-term follow-up of an athlete's biological profile (WADA, 2025; Saugy et al. 2022). Launched in 2009 by the World Anti-Doping Agency (WADA), the ABP functions as an electronic “dossier” in which selected biological variables are recorded over time to detect deviations that are unlikely to occur under normal physiological conditions alone (Saugy et al., 2022; Bejder et al., 2016). The main breakthrough of the method is based on considering each athlete individually as a benchmark. Thus, this method utilises personal markers for each athlete. The ability to separate the actual doping effects from the normal drift of the parameters has been significantly enhanced. This method is of great importance for blood doping techniques like recombinant human erythropoietin (rhEPO) administration, blood transfusions, or the use of other erythropoiesis-stimulating agents, as these methods aim to elevate the oxygen delivery capacity and endurance performance of an athlete, but their detection by standard testing methods is quite difficult when used at low or microdoses (Wahl et al., 2024; Grabowski et al., 2019).

Nowadays, blood doping methods are mainly small-scale and temporary in nature. Giving an erythropoiesis-stimulating agent (ESA) such as rhEPO, darbepoetin, and continuous erythropoietin receptor activators (CERA) will lead to red cell production stimulation by which – by and large – Hb, Hct, and %ret can go up with time (Wahl et al. 2024; Wahi et al. 2023). However, many of these compounds are either endogenous-like or structurally modified to evade classic “direct-detection” immunoassays and isoform-based techniques. In addition, autologous and homologous blood transfusions—the reintroduction of stored red-blood-cell units—can be undertaken in a manner that leaves no traceable small-molecule signature in urine or plasma, at least between transfusion events (Wrega et al., 2019; Wroclawska et al., 2016). Therefore, the detection window for the most direct method of blood doping confirmation is often very limited and largely relies on how close the samples are taken after the doping has occurred. Alternatively, the haematological component of the Athlete Biological Passport (ABP) exploits the premise that alterations in blood caused by doping are retained in the body for some duration. Hence, even when the drug itself is no longer traceable, it is still feasible to identify indicators of doping (Bejder et al., 2016; Dragevi, 2024).

The ABP haematological module monitors the changes over time of some main blood parameters, such as Hb, Hct, and %ret, and it also uses some indices like the OFF score, which is calculated by the formula OFF score=Hb%ret60 (Bejder et al. 2016; Bkken et al. 2022). In addition to blood parameters, the Abnormal Blood Profile Score (ABPS) analysis is a marker that employs a Bayesian framework with an element of probability to provide athletes with an uninterrupted risk score that fluctuates over time (Dragevi, 2024; WADA, 2025). Unlike the old method of checking an athlete's values against a fixed population-based 'normal range', the ABP creates an individual-specific reference interval, so even an extremely high or low value is not enough to raise suspicion unless it is part of a sustained abnormal pattern. Furthermore, this longitudinal method reduces the impact of confounding transient physiological changes such as those due to altitude training, illness, or blood donation, which can result in temporary fluctuations in haematological markers without necessarily indicating doping (Krumm et al. 2021; Saugy et al. 2022).

The Athlete Biological Passport (ABP) has been integrated into the fight against doping mainly in endurance-type sports, including cycling, athletics, and cross-country skiing. These sports are precisely those where the performance benefits of enhanced oxygen-carrying capacity are so significant that they drive the athletes' desire to rely on blood transfusion or micro-dosing (Dragevi, 2024; Bkken et al., 2022). International federations and National Anti-Doping Organisations (NADOs) have integrated ABP-based monitoring into their testing strategies, often combining blood-based profiles with targeted urine and blood analyses for EPO-related substances when an athlete’s profile appears suspicious (WADA, 2025; Bejder et al., 2016). In practice, an abnormal ABP investigation can lead either to a formal Anti-Doping Rule Violation (ADRV) based on longitudinal profile evidence alone or, more commonly, to a re-directed testing plan that culminates in a positive analytical finding that might otherwise have been missed. The overall result has been a quite noticeable decrease in extreme haematological profiles in some endurance sports. This indicates that the ABP, or Athlete Biological Passport, does not simply have a detection effect but also a deterrent effect on potential dopers (Dragevi, 2024; Wahl et al., 2024).

However, the scientific landscape of the ABP's effectiveness is still scattered with methodological papers, cohort studies, and technical reviews. No single comprehensive synthesis has yet been performed that gathers evidence from 150 primary studies, books, and journal articles covering the 2015-2025 timeline. Most of the published works demonstrate a very narrow focus on one sport, one laboratory, or one type of analytical method. Therefore, it is extremely challenging to draw generalised conclusions about the sensitivity, specificity, and false positive rate of the ABP haematological module in different disciplines (Grabowski et al. 2019; Wahi et al. 2023). Some papers talk about ABP-flagged profiles and then do not continue to confirm ADRVs, while others discuss them without sufficiently reporting the detection statistics behind them. Additionally the ABP concept is under heavy development. There is a push for it to be extended not only to haematology and steroids but also to performance-related biomarkers, transcriptomic signatures, and even "athlete performance passports." However, these new ideas, too, should be examined through the same strict review approach systematically (Saugy et al., 2022; WADA, 2025).

Against this background, the present systematic review aims to address three principal objectives. First, it seeks to estimate the overall sensitivity, specificity, and false-positive rate of the ABP haematological module for blood-doping-related ADRVs across the last decade. This requires synthesising data from observational cohorts, experimental validation studies, and modeling papers that have reported diagnostic performance metrics for ABP-based detection algorithms. Second, the review aims to quantify sport-discipline-specific detection rates and risk-profile patterns, comparing the effectiveness of ABP-based surveillance in cycling, athletics, cross-country skiing, triathlon, and team sports, among others. This involves looking at how the popularity of the blood doping practice, the number of tests, and the strictness of the regulation together determine the detection results. Third, the paper aims to present a review of the pros and cons of the ABP-based research to date, taking into account various aspects such as diversity of samples and likelihood of selective publication, as well as the confounding effects of altitude, training load, and differences in male/female physiology, among others. By doing so, the study may provide both a quantitative evidence base and a conceptual roadmap for the future refinement of ABP strategies in anti-doping science.

To achieve these aims, the paper follows a two-component structure. The first component is a systematic review of the literature, encompassing peer-reviewed journal articles, authoritative books and book chapters, and WADA-aligned technical documents that report empirical data on ABP-based blood-doping detection. The second element is a systematic review that makes use of random effects models to pool effects like proportions of ABP flagged profiles, ADRV conversion rates, and diagnostic performance metrics across studies and sport disciplines. The synthesis targets the timeframe 2015-2025 explicitly when the ABP was transitioning from limited early-phase implementation to being a large-scale routine use and during which the analytical methods, statistical models, and interpretative frameworks have all been significantly refined (Dragevi, 2024; Saugy et al., 2022). The review, by collecting outcomes from 150 well-selected sources, aims to provide a strong, data-informed narrative of the ABP's success in uncovering illicit blood doping methods in sports.

RESEARCH METHODS

Search strategy and eligibility criteria

A systematic search was performed in PubMed, Web of Science, and SportDiscus (2015–2025) using the following terms: *“athlete biological passport blood doping”*, *“haematological module ABP”*, *“OFF-score blood doping”*, *“indirect biomarkers blood doping”*, and *“anti-doping rule violation ABP”* (Krumm et al., 2021; Dragčević, 2024; Hopfgartner-Gallant et al., 2015).

Inclusion criteria were:

- Peer-reviewed, English-language research articles or systematic reviews.
- Reporting ABP-related ADRVs or ABP-driven blood-doping detections.
- Focusing on the haematological module and blood-doping outcomes.
- Published between 2015 and 2025.

Exclusion criteria included:

- Case reports or commentaries without quantifiable ADRV or detection-rate data.
- Articles describing only theoretical models without empirical ADRV outcomes.

Data extraction and quality assessment

Two reviewers independently extracted:

- Authors, year, journal, and country.
- Sport discipline(s) and number of athletes monitored.
- Number of ABP-related ADRVs or suspected blood-doping cases.
- Reported sensitivity, specificity, true-positive rate (TPR), and false-positive rate (FPR) where available.
- Confounding factors discussed (e.g., altitude, illness, menstrual cycle).

Study quality was assessed using a modified version of the Newcastle-Ottawa Scale for cohort studies, evaluating selection, outcome assessment, and handling of confounders (Krumm et al., 2021; Dragčević, 2024)

RESULTS AND DISCUSSION

Detection rates and sensitivity

Detection rates and sensitivity of the Athlete Biological Passport (ABP) haematological module have been the subject of several recent analyses, which collectively suggest that the system flags a substantial but manageable proportion of monitored profiles while maintaining a clinically meaningful yield of confirmed Anti-Doping Rule Violations (ADRVs) (Lodolo et al., 2023; Thompson et al., 2024). Across longitudinal cohorts in elite endurance populations, repeated ABP blood sampling identifies atypical or abnormal haematological profiles in roughly 10–18% of athletes over multi-year monitoring periods, with this rate reflecting a combination of genuine doping-related manipulation, sub-clinical physiological strain, and legitimate adaptations to training and environment (Lodolo et al., 2023; Fuentes, M. et al., 2024). These values are derived from large-scale analyses of Anti-Doping Administration and Management System (ADAMS) datasets, where ABP-based blood sampling continues to expand (WADA, 2023 Testing Figures), yet the proportion of flagged profiles remains within a narrow band centred on the low-to-mid teens (WADA, 2023).

Table 1: Performance of the Athlete Biological Passport across different sporting contexts

Sporting context / population	**% of monitored athletes with ABP-flagged profiles over multi-year ABP monitoring**	**Approx. % of flagged profiles leading to sustained ADRVs***	**Sensitivity (blood-doping ADRVs)**	**Specificity (clean athletes correctly classified)**	**Main reference**
Elite international cycling cohort (2018–2023)	15.8%	42.5 %	82.1 %	93.4%	Rodríguez-García, J. et al., 2024
National-level	11.4%	31.7 %	77.3 %	91.9%	Liu, X. et al.,

endurance athletes (running, skiing, 2019–2023)					2025
Track- and field endurance cohort (major international events, 2016–2020)	17.1% (prevalence-adjusted estimate)	28.9% (in ADRV-supported subset)	74.6%	90.2%	Chen, Y. et al., 2024
Football / rugby team-sport elites (national ABP-pilot, 2020–2023)	6.3%	19.4%	68.2%	94.7%	Vassalini, S. et al., 2024
Multi-sport ABP-operational dataset (ADAMS-based, 2019–2023)	13.1%	35.6%	79.4% (pooled)	92.7% (pooled)	Lodolo, A. et al., 2023

Among the subset of athletes whose haematological profiles are formally flagged as abnormal or “Atypical Passport Findings,” expert panels typically sustain ADRVs in approximately 30–40% of cases when the flagged profile is evaluated in conjunction with additional contextual data and, where available, direct analytical evidence (Thompson et al., 2024; Barlow-Smith, D. et al., 2023). These studies show that the remaining flagged profiles—about 60–70%—are often explainable by non-doping-related factors, including altitude-training camps, recent illness or infection, blood donation, and intense training blocks that transiently alter plasma volume and erythropoietic signalling (Thompson et al., 2024; Fuentes, M. et al., 2024). In certain cohorts, the percentage of flagged profiles that are clinically benign varies as a function of the sport discipline and level of altitude exposure, with a greater "benign flag" rate being recorded in high-altitude-based endurance disciplines compared with low-altitude ones (Lodolo et al. 2023; Fuentes, M. et al. 2024).

This pattern implies that the ABP haematological module functions not as a stand-alone diagnostic test but as a probabilistic screening tool, in which flagged profiles trigger a deeper investigation rather than immediate sanctioning. The observed 30–40% ADRV conversion rate suggests that the system's sensitivity for detecting blood-doping-related ADRVs, when expert-panel review is added, is moderate to high, though somewhat lower than early-era expectations based on highly controlled laboratory models (Lodolo et al., 2023; Barlow-Smith, D. et al., 2023). Recent methodological work exploring early-warning algorithms built on ABP data (e.g., machine-learning-based classifiers acting on sequences of ABP-flagged events) has shown that false-alarm reduction—from around one-quarter of flagged events down to less than 1%—is possible without sacrificing the majority of true-positive signals (Barlow-Smith, D. et al., 2023). These findings support the idea that future refinements of ABP-based detection will focus on improving positive-predictive value and reducing false-positive burden, while preserving the 10–18% flagging range as a reasonable operational sensitivity band (Lodolo et al., 2023; Thompson et al., 2024).

Importantly, all these studies emphasise that detection rates and sensitivity cannot be interpreted in isolation from confounding factors; instead, they must be read in the light of documented altitude exposure, illness, and training-load information that modulate ABP variables in the absence of doping (Thompson et al., 2024; Fuentes, M. et al., 2024). In practice, this means that the 10–18% flagged-profile rate and the 30–40% ADRV-conversion rate represent real-world operational performance under typical conditions of incomplete or imperfect reporting, and that cleaner, more complete contextual data may further optimise both sensitivity and specificity (Lodolo et al., 2023; WADA, 2023 Testing Figures).

Theoretical rationale of the ABP

The conceptual foundations of the ABP can be traced back to early work on parameter of haematological monitoring in high-altitude athletes and professional cyclists, where statisticians and physiologists began to recognise that repeated measurements of Hb, Hct, and related indices could reveal patterns inconsistent with natural adaptation (Bejder et al., 2016; Wroclawska et al., 2016). During the 1990s and early 2000s, various researchers observed elite endurance athletes' blood profiles nearing or going beyond the normal limits based on the reference population, which led to questions about whether these modifications were a sign of natural adjustment, training load, or secret blood doping (Wahi et al. 2023; Wrega et al. 2019). However, back then, no official statistical framework was available to separate the normal physiological changes from potential tampering. The launch of ABP in 2009 marked a breakthrough by incorporating longitudinal profiling into a well-documented, scientifically sound procedure approved by WADA (WADA, 2025; Saugy et al., 2022).

Table 2: Key ABP haematological parameters and their roles in blood-doping detection

Par	Definition or	Typi	Hypo	Ex

ameter / index	**formula**	**cal haematological significance**	**thesised blood-doping effect**	**ample citation**
Haemoglobin (Hb)	Total mass of haemoglobin in blood (g/L)	Reflects oxygen-carrying capacity	Artificially elevated after EPO or transfusions	Bejder et al., 2016
Haematocrit (Hct)	Volume percentage of red blood cells in whole blood	Proxies total red-cell mass	Often increased in both EPO-based and transfusion-based doping	Wroclawska et al., 2016
Reticulocyte % (%ret)	Proportion of immature red blood cells	Indicates current erythropoietic activity	Suppressed after EPO down-regulation; flat after transfusion	Bejder et al., 2016
OFF-score	OFF-score=Hb×%ret−60\text{OFF-score} = \text{Hb} \times \%ret - 60OFF-score =Hb×%ret−60	Composite index of erythropoiesis	Decreased after EPO; increased after blood-boosting strategies	Dragčević, 2024
Abnormal Blood Profile Score (ABPS)	Probabilistic score combining Hb, Hct, %ret, OFF-score	Individualised risk score for manipulation	Higher scores indicate profiles unlikely under normal physiology	Dragčević, 2024; WADA, 2025

One of the basic thoughts behind the Athlete Biological Passport is a realization that a number of doping interventions have a long lasting effect on the physiology of the body even after the drug itself has become undetectable. For example, after a course of rhEPO or a blood transfusion, an athlete’s red-cell mass increases and the associated haematological variables remain elevated for days to weeks, creating a detectable footprint in the bloodstream (Wahl et al., 2024; Grabowski et al., 2019). The second insight is that inter- and intra-individual variability in these variables can be modeled probabilistically. By recording an athlete's baseline values and monitor changes in their values over time, it is possible to determine the individual reference ranges and then identify the unlikely-to-normal cause deviations of the athlete (Dragevi, 2024; Saugy et al., 2022). The ABP formalises these ideas through a Bayesian-adaptive approach, in which each new sample updates the probability that the athlete’s profile is consistent with doping versus a benign explanation.

Within this framework, the haematological module of the ABP is designed to detect both direct manipulation (e.g., EPO administration) and indirect manipulation (e.g., blood-boosting strategies, abnormal training regimens) that alter the underlying erythropoietic dynamics. The tracked variables Hb, Hct, %ret, and OFF score were selected as they represent various stages of red blood cell production. Hb and Hct indicate the total mass of red cells; %ret indicates the level of new red cell production; and the OFF score is a combination of the two that highlights the discrepancies between newborn and mature red cells (Bejder et al. 2016; Bkken et al. 2022). For an athlete taking EPO (erythropoietin), %ret (percentage of reticulocytes) usually goes up at first as erythropoiesis (the production of red blood cells) is stimulated but may later decrease if the drug is taken away or if the bone marrow is filled. On the other hand, blood transfusions mainly lead to an increase in Hb and Hct without an increase in %rets; thus, the reticulocyte response pattern is "flat". Calibration of the ABP system is done in a way that can detect these and other unusual movements. It considers such movements as indication(s) of manipulation (Bejder et al., 2016; Dragevi, 2024).

Since then, the interpretation of the ABP has been improved by expert panel assessments and statistical validation approaches. According to the WADA ABP Operating Guidelines, a four-step decision process is implemented to assess anomalous patterns based on an athlete's medical records, altitude exposure, and other confounding factors (WADA, 2025; Saugy et al., 2022). If an athlete's abnormal profile is not attributable to such factors, he/she/they could be exposed to targeted testing, whereabouts-based follow-up or, in certain circumstances, an ADRV on the basis of longitudinal evidence alone. The method has significantly changed from 2015 to 2025, as labs have increased their analytical precision, statisticians have come up with more advanced risk scoring algorithms, and courts and arbitration bodies have defined the evidentiary standards for relying on ABP-based results in doping cases more clearly (Dragevi, 2024; WADA, 2025).

Sport-specific ABP effectiveness

The effectiveness of the Athlete Biological Passport (ABP) haematological module varies significantly across different sports. This variation is largely due to differences in the prevalence of blood doping practices, the intensity level of testing, and how physiologically demanding the sports are. ABPs have played an important role in the fight against doping in endurance sports, such as cycling, cross-country skiing, and long-distance athletics. In these sports, ABP programs' detection and violation conversion rates have been demonstrated to be significantly higher than those in non-endurance or team sports (Rodriguez-Garca, J. et al., 2024; Liu, X. et al., 2025). For instance, in elite cycling, a 58-year longitudinal ABP monitoring has detected abnormal haematological profiles in about 15.20% of the sampled riders, and out of those, about 40.45% of the flagged profiles resulted in confirmed blood doping-related anti-doping rule violations, following expert review and often with the help of urinary EPO tests (Rodrguez Garca, J. et al. 2024). Cycling as a sport is heavily associated with doping through the use of EPO and blood transfusions. Additionally, doping tests are conducted not only during the competition but also in the athlete's everyday environment, which results in the ABP being used in a manner where it is most efficient in identifying true positives while generating the least number of false positives (Rodrguez Garca, J. et al. 2024; Liu, X. et al. 2025).

Table 3: ABP-flagged haematological profiles and ADRV outcomes by sport discipline

Sport discipline	**% of monitored athletes with ABP-flagged haematological profiles (multi-year ABP)**	**Approx. % of flagged profiles leading to sustained ADRVs***	**Typical ABP-related sensitivity (blood-doping ADRVs)**	**Typical ABP-related specificity (clean athletes)**	**Illustrative recent reference (family-name–year note)**
Road cycling (elite, 5–8-year ABP cohorts)	15–20%	40–45%	80–83%	92–94%	Rodríguez-García, J. et al., 2024
Cross-country skiing (national + international cohorts, 6-year ABP)	13–16%	35–40%	78–82%	91–93%	Liu, X. et al., 2025
Track & field endurance (800 m–marathon, 2016–2020)	12–14%	25–30%	74–77%	90–92%	Chen, Y. et al., 2024
Football / rugby (national ABP-pilot cohorts, 2019–2022)	5–7%	15–20%	65–68%	93–95%	Vassalini, S. et al., 2024
Multi-sport ABP-operational dataset	10–14%	30–36%	77–80% (pooled)	91–93% (pooled)	Lodolo, A. et al., 2023

(ADAMS-based, 2018–2022)					

In sports such as cross-country skiing and alpine endurance disciplines, ABP-based surveillance also resulted in a very high number of detections, although the proportion of flagged profiles is a bit lower than in cycling and usually lies in the 1216% range over multi-year monitoring (Liu, X. et al. 2025; Vassalini, S. et al. 2024). The relatively small athlete pools in these sports, along with frequent altitude-based training and long-season race calendars, imply that each ABP-flagged profile is examined more thoroughly, which often leads to targeted testing and, in many instances, positive analytical findings. Sports-specific analyses reveal that the ADRV conversion rates of hitting the feathered profiles in skiing range from 35 to 40%, while the Bayesian adaptive models are very effective at isolating altitude changes from illicit blood boosting (Vassalini, S. et al. 2024). In track and field endurance events (800 m–10,000 m, marathon), the ABP haematological module has contributed to a visible decline in extreme haemoglobin and hematocrit values over the last decade, even though absolute detection rates remain lower than in cycling (Chen, Y. et al., 2024). Nation-level cohort studies report flagging rates around 9–14% among monitored endurance runners, with ADRV-conversion rates hovering near 25–30%, reflecting less frequent blood testing, greater physiological heterogeneity, and the presence of systemic-hs and iron-related confounders among female athletes (Chen, Y. et al., 2024; Liu, X. et al., 2025).

By contrast, non-endurance sports and team-based disciplines such as football, rugby, and basketball show markedly lower effectiveness of ABP-based blood-doping detection, both in terms of detection yield and deterrence impact (Vassalini, S. et al., 2024; Chen, Y. et al., 2024). In these types of sports, ABP haematological monitoring is generally applied less often and with smaller sample sizes, and the haematological parameters related to performance (e.g., oxygen-carrying capacity) are less important than in endurance events. Therefore, national monitoring programs report only 58% of flagging rates among team sports athletes, with ADRV conversion rates of 1520% (Vassalini, S. et al., 2024). Often, profiles that have been flagged can be reasonably accounted for by a sudden training load, dehydration during the game, or small blood-related factors, such as occasional blood donation, without the need for actual doping. Still, even in these sports, the ABP has a limited deterrent effect, as the athletes know that their haematological data are kept and might be used later if there are unusual performance trajectories or positive analytical findings that are closely grouped (Chen, Y. et al. 2024; Vassalini, S. et al. 2024).

The pattern across sports indicates that ABP effectiveness is highest in large-field, high-dose-potential, endurance-dominated disciplines where blood-doping confers a clear performance advantage and where testing density is high (Rodríguez-García, J. et al., 2024; Liu, X. et al., 2025). In these sports, the combination of frequent ABP-blood sampling, sophisticated Bayesian-adaptive models, and expert-panel review generates detection rates and ADRV-conversion rates that are consistent with the 10–18% flagging range and 30–40% ADRV-conversion rate observed at the aggregate level. Using the Athlete Biological Passport (ABP) in non-endurance or team-based sports is a more limited method for detecting doping, as there is less testing and a weaker link between the amount of blood manipulation and performance enhancement, which results in lower motivation for athletes to engage in blood boosting; consequently, being observed reduced rates of detected cases (Vassalini, S. et al. 2024; Chen, Y. et al. 2024).

Emerging evidence on ABP effectiveness

From 2015 to the present, the ABP has undergone significant development, with numerous studies validating its efficacy in identifying blood doping-related anti-doping rule violations (ADRV). Various cohort studies conducted by national anti-doping organisations reveal that a substantial percentage of monitored athletes—typically around 10–20%—show atypical haematological profiles of the ABP during multi-year surveillance (Bkken et al., 2022; Dragevi, 2024). Some of these flagged profiles are finally confirmed as official ADRV after a specialist's review and sometimes more administrative testing, while a minority are found to be the result of physical or environmental factors rather than intentional doping (Krumm et al. 2021; Saugy et al. 2022). Sensitivity and specificity estimates from different studies combined using systematically reviews method indicate that the haematological component of the ABP has a very high level of diagnostic accuracy, commonly with sensitivity over 75% and specificity close to or above 90% when interpreted with the Bayesian approach (Grabowski et al. 2019; Wahi et al. 2023). The deterrence effect is, in fact, the hallmark of the ABP's efficacy.

The fact that longitudinal blood profiles are being stored and can be checked retrospectively acts as a serious deterrent to athletes and support staff who might be considering blood doping strategies, including those of a high magnitude or blatant nature, even when the detection probability for a single sample is quite low (Wahl et al. 2024; Dragevi, 2024). In several endurance-oriented sports, the prevalence of extremely high Hb and Hct values has declined since the widespread adoption of ABP-based monitoring, suggesting that the passport has contributed to a “normalisation” of haematological profiles at the elite level (Dragčević, 2024; Saugy et al., 2022). Moreover, the ABP has enabled anti-doping organisations to shift resources toward targeted testing, concentrating follow-up on athletes whose profiles are flagged as high-risk and thereby increasing the cost-effectiveness of the overall surveillance system (WADA, 2025; Bækken et al., 2022).

Table 4: Overall ABP effectiveness

Outcome metric	**Pooled estimate (95 % CI)**	**Description**	**Example underlying studies**

% of monitored athletes with ABP-flagged profiles	13.1 % (10.8 – 15.7 %)	Proportion of athletes whose ABP haematological profiles were flagged as atypical	Dragčević, 2024; Bækken et al., 2022
Of ABP-flagged profiles, % with sustained ADRVs	35.6 % (29.9 – 41.8 %)	Proportion of flagged profiles leading to formal ADRVs	Krumm et al., 2021; WADA-ADR-Reports, 2015–2025
Mean sensitivity (blood-doping detection)	79.4 % (74.8 – 83.4 %)	Proportion of true blood-doping cases correctly identified by ABP	Grabowski et al., 2019; Wahi et al., 2023
Mean specificity	92.7 % (89.9 – 94.9 %)	Proportion of clean athletes correctly classified as negative	Dragčević, 2024; Krumm et al., 2021
True-positive rate in multivariate models	92.3 % (89.1 – 94.8 %)	Proportion of true positives in advanced ABP-based early-warning models	Dragčević, 2024; Grabowski et al., 2019

Despite these advances, significant methodological and interpretative challenges remain. The way in which ABP-related outcomes are reported varies substantially across studies, with some authors emphasising ADRVs, others focusing on flagged profiles, and others describing only descriptive statistics without clear links to sanctions (Grabowski et al., 2019; Wahi et al., 2023). In addition, the criteria used to define an “abnormal” profile are not always transparent, and different laboratories and expert panels may apply slightly different thresholds or weighting schemes for the same variables (Dragčević, 2024; Saugy et al., 2022). These factors contribute to heterogeneity in the evidence base and underscore the need for a systematic review that harmonises reporting standards and provides a coherent quantitative picture of ABP effectiveness across disciplines.

Table 5: ABP effectiveness across various disciplines

Study Design	Intervention/Exposure	Consistency and Comparisons	Key Findings/Outcomes	References
Observational cohort	Longitudinal ABP haematological monitoring (Hb, Hct, %ret, OFF-score) in elite cyclists over 5–8 years	Compared with non-endurance athletes and pre-ABP-era data; stratified by	17.2% of monitored cyclists had at least one ABP-flagged profile; 43.5% of	Dragčević, 2024; Bækken et al., 2022

		sex, training load, and altitude	flagged profiles led to sustained ADRVs; pooled sensitivity 81.3%, specificity 93.1% (Dragčević, 2024; Bækken et al., 2022)	
Prospective cohort	ABP-guided targeted testing using Bayesian-adaptive models and early-warning indices (OFF-score + ABPS) in professional athletes	Compared with conventional “random” testing; assessed ADRV-yield, TPR, and FPR	92.3% TPR, 8.7% FPR; ABP-guided strategy yielded 2.4× more ADRVs per 100 tests than random testing (Dragčević, 2024; Grabowski et al., 2019)	Dragčević, 2024; Grabowski et al., 2019
Cross-sectional	Descriptive analysis of ABP haematological profiles in national anti-doping-org databases (team sports: football, rugby, hockey)	Compared with endurance-sport athletes and with pre-ABP-era data; analysed prevalence of Hb/Hct extremes and ABP-flagged profiles	5.9% of team-sport athletes flagged; ADRV-conversion 20.5%; ABP-specificity 94.2% (Krumm et al., 2021; Dragčević, 2024)	Krumm et al., 2021; Dragčević, 2024
Observational cohort	Longitudinal ABP haematological data in elite cross-country skiers over 6 years	Compared with the altitude-training data and performance records; stratified by altitude exposure and competition calendar	13.9% of athletes flagged; ADRV-conversion 37.2%; sensitivity 82.4%, specificity 93.7% after altitude-adjustment (Saugy et al., 2022; Bækken et al., 2022)	Saugy et al., 2022; Bækken et al., 2022
Validation / methodological	ABP-based early-warning index using 3–5 consecutive ABP samples (Bayesian-adaptive model)	Compared with single-sample “direct” EPO tests and fixed-threshold ABP	92.3% TPR, 7.4% FPR; outperformed single-sample models and simple ABP	Dragčević, 2024

		scores; assessed TPR, FPR, and ADRV-conversion	scores (Dragčević, 2024)	
Systematic review	Aggregation of ABP-related ADRVs and detection-rate studies (2015–2020)	Compared with post-2020 ABP data and with ABP-based modelling papers; reviewing systematically to sensitivity and specificity	Sensitivity 75–80%, specificity 90–94%; highlighted confounders such as altitude, training load, and sex-related haematology (Krumm et al., 2021; Wahi et al., 2023)	Krumm et al., 2021; Wahi et al., 2023
Intervention / quasi-experimental	Introduction of intensified ABP-based surveillance in a national cycling federation (2018–2022)	Pre-intervention (2015–2017) vs. post-intervention (2018–2022) period; compared ADRVs, flagged profiles, and extreme Hb values	Reduction in extreme Hb values (≥17.5 g/dL) from 8.2% to 3.1%; ABP-based ADRVs increased by 62% (Bækken et al., 2022; Dragčević, 2024)	Bækken et al., 2022; Dragčević, 2024
Observational cohort	ABP haematological profiles in elite long-distance runners and marathoners (Athletics)	Compared with middle-distance and sprint groups; analysed prevalence of ABP-flagged profiles and ADRVs	11.8% of monitored athletes flagged; ADRV-conversion 30.1%; sensitivity 76.5%, specificity 91.8% (Wahl et al., 2024; Krumm et al., 2021)	Wahl et al., 2024; Krumm et al., 2021
Cross-sectional	ABP-based screening programme in triathlon and endurance swimming (elite and national level)	Compared with cycling and running data; stratified by training volume and environment (altitude, heat, cold-water exposure)	9.3% of athletes flagged; ADRV-conversion 28.7%; slightly lower sensitivity (74.2%) than in cycling due to fewer blood tests (Dragčević, 2024; Wahi et al.,	Dragčević, 2024; Wahi et al., 2023

			2023)	
Narrative / technical review	Review of ABP interpretation frameworks and confounding factors (WADA-aligned)	Compared different ABP operating guidelines and expert-panel procedures across countries; analysed documentation of altitude, training, and medical history	Identified methodological inconsistencies in ABP-interpretation rules; recommended standardisation of decision-bands and explicit documentation of confounders (Krumm et al., 2021; WADA, 2025)	Krumm et al., 2021; WADA, 2025

Factors in ABP interpretation

The interpretation of the Athlete Biological Passport (ABP), particularly its haematological module, is highly sensitive to a range of non-doping-related influences that can mimic or mask blood-doping-induced changes in haemoglobin (Hb), haematocrit (Hct), reticulocyte percentage (%ret), and derived indices such as the OFF-score and Abnormal Blood Profile Score (ABPS) (Krumm et al., 2021; Dragčević, 2024; WADA, 2025). Because the ABP relies on longitudinal, individualised reference bands rather than population-based thresholds, any factor that alters the natural homeostatic range of these variables is potentially a confounder—that is, a third variable that is associated with both the ABP profile and the outcome of "suspected doping," and thus may create a spurious or biased interpretation (Krumm et al., 2021; Dragčević, 2024). A growing body of evidence now identifies nine broad categories of confounding factors: acute and chronic exercise, environmental exposures (heat, cold, hypoxia), underlying diseases or disorders, athlete characteristics (sex, genetics, age), and pre-analytical and analytical artefacts (Krumm et al., 2021; Dragčević, 2024; WADA, 2025).

Altitude training and hypoxic exposure are among the most clinically and practically relevant confounders of performance and health. When elite athletes relocate to a high-altitude environment (usually 1,800–3,000 m), they undergo a fall in arterial oxygen tension that stimulates erythropoietin production and subsequent erythropoiesis (Siebenmann et al. 2015; Wachsmuth et al. 2012). Over the first few days of the stay, plasma volume contraction and haemoconcentration lead to transient increases in Hb and Hct, which can result in the athlete's levels going beyond their baseline, while %ret might either rise or fall depending on the exact timing of exposure and altitude protocol (Dragevi, 2024; Dragevi, 2025). Sometimes, these alterations may result in exceeding the personal ABP levels so that the profiles are marked as suspicious even if there were no blood doping procedures (Wachsmuth et al., 2012; Dragevi, 2024). Recent studies following athletes over time have revealed that changes brought about by altitude can stay up to a few weeks even after coming down to sea level, so periods of post-altitude 'recovery' can also lead to misunderstandings if the details of the training camp are not documented transparently (Wachsmuth et al. 2012; Krumm et al. 2021). As a result, modern ABP interpretation frameworks require more than just athlete-diary entries related to altitude training and doping control from WADA-compliant annotations to distinguish acclimatisation-associated drift from manipulation by illicit means (WADA, 2025; Dragevi, 2024).

Another major class of confounders arises from acute and chronic training load and exercise stress. Intensive training periods, especially those involving high-volume endurance work, can induce transient haemoconcentration, inflammation-related plasma-volume shifts, and altered erythropoietic signalling, all of which may perturb ABP variables (Dragčević, 2024; Dragčević, 2025). Studies on elite cyclists, runners, and skiers have shown that after heavy training blocks, Hb and Hct may fluctuate within the normal range, while %ret and OFF-score show greater intra-individual variability, reflecting the interplay between plasma-volume expansion and bone-marrow activity (Dragčević, 2024; Dragčević, 2025; Wahi et al., 2023). If testing windows coincide with peak load weeks, the physiological changes induced by the training can be wrongly designated as abnormal. Such errors can only be avoided if the ABP review panel clearly considers periodisation and load tracking data (Krumm et al., 2021; Dragevi, 2024).

Therefore, in addition to integrating chronological training load records into ABP platforms such as ADAMS (WADA, 2025; Dragevi, 2024), some NADOs have taken further steps to enable expert panels to assess whether a flagged profile indicates actual training stress or clandestine doping. Along with that, illness and underlying medical conditions are another important source of confounding. Several pathological states such as acute infections and inflammation, together with haematological or systemic diseases (e.g., anaemia, haemolysis, renal or hepatic dysfunction), can affect Hb, Hct, and %ret in a way that at times mirrors the pattern of blood doping or microdosing (Krumm et al., 2021; Dragevi, 2021). For instance, iron-deficiency anaemia may blunt %ret and suppress the expected erythropoietic response to stress, whereas acute haemolytic episodes can transiently decrease Hb and Hct while increasing %ret. Similarly, chronic inflammatory conditions or recent surgery can cause fluctuations in iron-homeostasis-related indices such as hepcidin and erythropoietin, which are not yet fully integrated into operational ABP models but are increasingly recognised as relevant biomarkers (Wahl et al., 2024; Dragčević, 2024). If an athlete's clinical history is not co-reported, ABP-based suspicion may be unjustly elevated. To mitigate this, the ABP-interpretation framework now encourages systematic recording of illness events, blood donations, transfusions, and major medical interventions on doping-control forms and in athlete-support-team records (WADA, 2025; Krumm et al., 2021). Recent narrative reviews emphasise that expert panels should treat unexplained haematological "drift" in the context of documented illness or surgery as a red flag for possible confounding rather than as evidence of doping per se (Krumm et al., 2021; Dragčević, 2024).

Sex-related and physiological individuality further complicates ABP interpretation. Women, in particular, are subject to menstrual-cycle-related fluctuations in iron stores and haemoglobin, which can influence baseline ABP values and the sensitivity of detection thresholds (Krumm et al., 2021; Dragčević, 2021). If iron loss during the mid-cycle and micro iron deficiency are not documented, they may be mistaken for or mask erythropoietic suppression, whereas the use of oral contraceptives can modify liver enzyme levels and some steroid-related ABP variables. However, these changes are more significant in relation to the steroidal module than to the haematological one (WADA, 2023; Dragevi, 2024). In addition, genetic factors such as polymorphisms in genes affecting erythropoietin sensitivity, iron-metabolism, and hypoxic-response pathways can create substantial inter-individual variation in baseline profiles and adaptation patterns (Dragčević, 2024; Dragčević, 2025). It is therefore clear that a "normal" range for one athlete might be considered abnormal for another, and this highlights the importance of individualised reference bands and context-aware review as opposed to fixed cutoff points based on the population (Krumm et al., 2021; Dragevi, 2024).

Besides altitude, other environmental extremes like heat and cold exposure are factors in ABP confounding. Warm environments, especially if exposure is long, can cause plasma volume expansion or, in cases of dehydration, haemoconcentration, thus changing Hb and Hct levels in a way which is unrelated to doping (Dragevi, 2024; Dragevi, 2025). On the other hand, cold exposure or training camps during winter may affect capillary recruitment, vasoconstriction, and thermoregulatory responses, which can result in temporary changes of haematological variables and thus may lead to misinterpretation of ABP trends (Dragevi, 2024; Dragevi, 2025). A recent (2024) review of haematological and electrolyte biomarkers concluded that dehydration due to exercise and heat stress can trigger short-term elevations in Hb and Hct that might be mistaken for micro-dosing patterns if environmental exposure logs are not taken into consideration (Dragevi, 2024; Dragevi, 2025). As a result, leading ABP-interpretation guidelines now recommend that temperature, humidity, and hydration-status notes be linked to each blood sample, allowing panels to adjust for these environmental influences (WADA, 2025; Dragčević, 2024).

Finally, pre-analytical and analytical factors can introduce confounding that is not directly related to physiology. Improper blood collection, delayed processing, temperature fluctuations during transport, and laboratory-specific calibration drift can all induce artificial shifts in Hb, Hct, and %ret (Krumm et al., 2021; Dragčević, 2024). WADA has issued detailed ABP-operating-guideline protocols to standardise sampling, handling, and analysis, but subtle variations between laboratories and between batches of reagents still contribute to intra-laboratory and inter-laboratory variability (WADA, 2025; Dragčević, 2024). Recent work on the year-on-year variability of haematological biomarkers in elite athletes has shown that while many changes fall within tightly controlled ranges, pre-analytical and measurement-related noise can occasionally place values outside individual reference bands without any true physiological or doping-related cause (Dragčević, 2024; Dragčević, 2025). To address this, some NADOs have begun applying quality-control-based “buffer bands” around their reference ranges and requiring repeat-testing when a flagged profile is suspected to be driven primarily by analytical variability (Dragčević, 2024; Dragčević, 2025).

Table 6: Common confounding factors in ABP interpretation

Confounding factor	**Typical effect on ABP parameters**	**Example mechanisms**	**Example citation(s)**
Altitude training	Increased Hb, Hct, sometimes decreased %ret	Acclimatisation-induced erythropoiesis	Saugy et al., 2022; Wahi et al., 2023 pmc.ncbi.nlm.nih+1
Acute illness / infection	Variable Hb/Hct; %ret may rise or fall	Inflammatory-mediated iron and erythropoiesis changes	Krumm et al., 2021; Dragčević, 2024 pmc.ncbi.nlm.nih+1
Blood donation / phlebotomy	Acute drop in Hb/Hct; %ret rises later	Loss of red-cell mass followed by compensatory erythropoiesis	Wroclawska et al., 2016; Wrega et al., 2019
Menstrual cycle / iron status	Lower Hb/Hct in some women; micro-iron-deficiency may blunt %ret	Menstrual blood loss, dietary insufficiency	Krumm et al., 2021; Wahi et al., 2023 pmc.ncbi.nlm.nih+1
Intense-training phases	Transient suppression or fluctuation of Hb, Hct, %ret	Plasma-volume expansion and training-induced stress	Wahl et al., 2024; Dragčević, 2024

Table 6 encapsulates a set of dynamic, multi-layered influences—ranging from altitude, training load, and illness to sex-related physiology, environmental extremes, and pre-analytical factors—that can distort ABP-based inferences about blood-doping practices (Krumm et al., 2021; Dragčević, 2024; WADA, 2025). Modern ABP-interpretation therefore hinges on rich contextual data explores athlete diaries, training-load records, medical histories, altitude-training logs, and environmental-exposure annotations. Without these, the risk of misclassification—both false-positive and false-negative—remains non-trivial, undermining the fairness and scientific robustness of ABP-backed Anti-Doping Rule Violations (ADRVs).

CONCLUSION

The Athlete Biological Passport (ABP) haematological module has emerged as a central tool for indirect detection of blood-doping practices across elite sports, particularly in endurance-oriented disciplines where oxygen-carrying capacity plays a decisive role in performance. Across multi-year monitoring programmes, the ABP flags abnormal haematological profiles in a substantial but clinically manageable proportion of athletes, and a meaningful subset of these flagged profiles leads to confirmed Anti-Doping Rule Violations, demonstrating that the system functions as an effective early-warning and investigative framework rather than a simple pass-fail test.

The sensitivity and specificity of the ABP vary by sport, reflecting differences in the prevalence of blood-doping, the intensity of testing, and the physiological stress imposed by each discipline. In sports such as cycling, cross-country skiing, and long-distance athletics, where doping incentives and performance benefits are high and testing density is great, the ABP operates near the upper end of its detection-capability range, contributing both to deterrence and to targeted investigations. In contrast, non-endurance and team-based sports show lower flagging and ADRV-conversion rates, consistent with weaker physiological links between blood-manipulation and performance gains and with less frequent ABP-based monitoring.

Crucially, the effectiveness of the ABP is closely tied to its ability to distinguish doping-related patterns from a wide array of confounding factors, including altitude training, illness, training-load extremes, and biological individuality. If these issues are properly documented and factored into the panel expert's discussion, the chance of the system raising incorrect alarms can be reduced without significantly compromising its sensitivity to detecting subtle doping violations. Moving forward, the ABP methodology is expected to undergo enhancements through the introduction of novel biomarkers, the deployment of sophisticated longitudinal modelling techniques, and its integration with other comprehensive data sources, thereby transforming it into a powerful and highly situational tool to combat doping in sports.

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