Blood doping and its detection

Wolfgang Jelkmann¹ and Carsten Lundby²

¹Institute of Physiology, University of Lübeck, Lübeck, Germany; and ²Center for Integrative Human Physiology, University of Zürich, Zürich, Switzerland.

Running title: Blood doping

Manuscript type: Review

Wolfgang Jelkmann, M.D.
Professor of Physiology
Institute of Physiology
University of Luebeck
D-23562 Luebeck, Germany
e-mail: jelkmann@physio.uni-luebeck.de
Phone: xx49-451 5004150
FAX: xx49-451 5004151
Abstract

Hemoglobin mass (Hb\textsubscript{mass}) is a key factor for maximal exercise capacity. Some athletes apply prohibited techniques and substances with intent to increase Hb\textsubscript{mass} and physical performance, and this is often difficult to prove directly. Autologous red blood cell (RBC) transfusion cannot be traced, and also recombinant erythropoietic proteins are detectable only within a certain timeframe. Novel erythropoietic substances, such as mimetics of erythropoietin (Epo) and activators of the \textit{Epo} gene may soon enter the sports scene. In addition, \textit{Epo} gene transfer maneuvers are imaginable. Effective since December 2009, the World Anti-Doping Agency (WADA) has therefore implemented “Athlete Biological Passport Operating Guidelines”, which are based on the monitoring of several parameters for mature RBC and reticulocytes. Blood doping may be assumed, when these parameters change in a non-physiological way. Hematologists should be familiar with blood doping practices as they may play an important role in evaluating blood profiles of athletes with respect to manipulations, as contrasted to the established diagnosis of clinical disorders and genetic variations.
Introduction

The World Anti-Doping Agency (WADA) defines blood doping as “the misuse of certain techniques and/or substances to increase one's red blood cell mass, which allows the body to transport more O₂ to muscles and therefore increase stamina and performance”.¹ Prohibited procedures include the use of synthetic O₂ carriers, the transfusion of red blood cells (RBC), the infusion of hemoglobin (Hb), and the artificial stimulation of erythropoiesis. This review will focus on erythropoietic substances and RBC parameters that are affected by blood doping and provided the basis for WADA’s “Athlete Biological Passport Operating Guidelines”.² Synthetic O₂ carriers, such as Hb-based O₂ carriers or perfluorocarbons are not considered here. The topic is timely. Experts having knowledge in the fields of clinical hematology, laboratory medicine/hematology and physiology/hematology may become involved in the evaluation of athletes’ blood profiles. The experts must be able to analyze and certify whether a blood value abnormality is the result of doping, or due to an acute disorder respectively a genetic variation.³

Several paragraphs of the “2011 Prohibited List” of the WADA are relevant as regards blood doping.¹ First, under “Prohibited Substances” (“S2. Peptide hormones, growth factors and related substances”) several erythropoiesis stimulating agents (ESAs) are itemized: Erythropoietin (Epo), darbepoetin alfa, hypoxia-inducible factor (HIF) stabilizers, methoxy polyethylene glycol-epoetin beta (CERA), and peginesatide (Hematide™; Affymax; Palo Alto, CA). Second, under “Prohibited Methods” forbidden blood products are specified (“M1. Enhancement of oxygen transfer”). Furthermore, i.v. infusions (unless clinically legitimated) and the sequential withdrawal, manipulation and re-infusion of whole blood are prohibited (“M2. Chemical and physical manipulation”). Finally, genetic interventions with the potential to enhance sport performance are defined (“M3. Gene doping”), including “the transfer of nucleic acids or nucleic acid sequences, the use of normal or genetically modified cells, and the use of agents that directly or indirectly affect functions known to influence performance by altering gene expression”.¹

Hemoglobin mass and physical performance

In aerobic sport disciplines – such as long-distance running, cycling or cross country skiing – the main factors determining performance are a high delivery of O₂ to the exercising skeletal muscles and its utilization (Figure 1). The rate of maximal O₂ uptake (VO₂ max) is dependent
on a high cardiac output (Q) and a wide difference for arterial-venous O₂ (a-vO₂), i.e. the Fick equation: \( \dot{V}O₂_{\text{max}} = Q_{\text{max}} \times \text{a-vO₂}_{\text{max}} \). Since (i) \( Q_{\text{max}} \) is difficult (if not impossible) to manipulate to higher values during competitions, (ii) the distribution of Q during maximal exercise to the working skeletal muscles is close to 80%, and (iii) arterial O₂ extraction is already in the range of ~ 90% at maximal exercise, the only variable that remains open for manipulations in regards to increasing exercise performance is the arterial O₂ content. Accordingly, in a given individual, changes in Hb concentration ([Hb]) by either RBC transfusion or hemodilution will increase or decrease \( \dot{V}O₂_{\text{max}} \), respectively.\(^4\) On the group basis however, [Hb] is not predictive of \( \dot{V}O₂_{\text{max}} \), whereas the total mass of Hb (Hb\(_{\text{mass}}\)) correlates very well with \( \dot{V}O₂_{\text{max}} \).\(^5\) In fact, a somewhat reduced [Hb] is sometimes, but not always observed among athletes, whereas Hb\(_{\text{mass}}\) is usually increased as compared to normal healthy individuals (Figure 2).

The first experiments with blood transfusions and exercise were performed by Pace and colleagues,\(^6\) who demonstrated that the transfusion of 450 mL of whole blood on four consecutive days decreases submaximal exercise heart rate (in hypoxia) for several weeks (wks), and hence predicted that exercise performance would be increased. Accordingly, it was calculated in a recent review that a change of 1 g in Hb\(_{\text{mass}}\) will produce a change in \( \dot{V}O₂_{\text{max}} \) of 4 mL min\(^{-1}\),\(^7\) whereas the effects on submaximal exercise performance are likely variable according to competition distance. It should also be noted here that volume loading, i.e. plasma volume expansion in itself does not lead to an improved exercise performance in elite athletes,\(^8\) again highlighting the role of Hb\(_{\text{mass}}\). If, however, a plasma volume expander is administrated simultaneously with increments in Hb\(_{\text{mass}}\), then performance will be likely to increase more than when just augmenting the total red cell volume.\(^9\)

The influence of Epo on exercise performance

The performance enhancing (ergogenic) effect of recombinant human Epo (rhEpo) in aerobic sports was investigated shortly after the medicine became available.\(^10,11\) It soon became clear that subcutaneous (s.c.) administration of rhEpo at doses of 60-350 units (U) per kg\(^{-1}\) body weight (b.w.) and wk for 4-6 wks increases \( \dot{V}O₂_{\text{max}} \) and the time to exhaustion substantially.\(^10,12,13\) More recent studies in which rhEpo was applied to healthy volunteers in lower dosages demonstrated that \( \dot{V}O₂_{\text{max}} \) is increased by 6-12% when the hematocrit (Hct) is increased to approximately 0.50, but also demonstrated that time to exhaustion (in the laboratory) at a given level of \( \dot{V}O₂_{\text{max}} \) is increased by up to 50%.\(^14\) A challenge for anti-doping work is that when rhEpo administration is discontinued in healthy volunteers, \( \dot{V}O₂_{\text{max}} \)
remains elevated for at least three wks. Effects of rhEpo in normal humans have been reviewed recently. Although Epo is reported to activate several non-hematologic factors (i.e. in addition to stimulating erythropoiesis), which are usually also associated with improvements in aerobic performance, the primary mechanism by which Epo increases exercise performance in humans is through augmented erythropoiesis. ESAs are particularly effective in combination with iron supplementation. The administration of iron results in increased ferritin levels in athletes. Ferritin levels >1,000 μg L⁻¹ have been observed.

There are as yet no reports on physical performance in healthy humans with increased circulating Epo and Hbmass due to the administration of compounds stimulating the expression of the endogenous Epo gene or following Epo gene transfer.

**Direct detection of blood doping**

Blood and urine samples can be taken in-competition and out-of-competition. With respect to reservations that a venipuncture is a medical intervention and may violate the tenets of certain religious or cultural groups, the WADA has stated that there is no basis for such provisos.1

**RBC transfusion**

A test for detection of allogeneic blood transfusion doping was implemented in 2004. The test uses blood group antisera to identify mixed RBC populations in blood samples by flow cytometry. Nelson et al. applied antisera against 12 blood group antigens and demonstrated that the presence of allogeneic cells can be assessed in the blood of subjects who had previously received at least one unit of allogeneic blood. Giraud et al. carried out a single-blind and single-site study to validate the flow cytometry method as a forensic quality standard analysis and to allow objective interpretation of real cases. No false positive results were obtained in an analysis of 140 blood samples containing different percentages (0-5%) of a minor RBC population, indicating a 100% specificity of the method. Most samples containing a 1.5% minor RBC population were unambiguously detected, yielding a 78% sensitivity. The method proved to fulfill the ISO-17025 accreditation and validation requirements. Athletes making use of allogeneic blood transfusion are thus very likely to be caught if tested.

Autologous RBC manipulations can at present only be detected via indirect measures, which represents a major problem in anti-doping efforts. The CO re-breathing technique for
detecting non-physiological increases in Hbmass is still investigational, and besides practical difficulties related to this method, its potential inclusion in the blood passport may be problematic, since the margin of variation when assessing Hbmass (biological and measurement errors) would still allow athletes to manipulate with blood volumes that would increase exercise performance considerably. Finally, it should also be considered that from an athlete’s point of view it may not be desirable to breathe CO shortly before a competition as this may limit exercise performance.

Peptidic ESAs

Currently available rhEpo preparations (epoetins) are produced in Epo cDNA transfected Chinese hamster ovary (CHO) or baby hamster kidney (BHK) cell cultures. The only therapeutic rhEpo engineered in human cells (epoetin delta) is off market since the beginning of 2009 (Table 1). Since the patents of the originator epoetins have expired, biosimilar products have been approved in many parts of the world. Furthermore, various copied CHO cell-derived rhEpops are available in countries without a regulated market.

Endogenous Epo and the epoetins have an invariant sequence of 165 amino acids, but they differ in glycosylation. Compared to the epoetins, endogenous Epo isoforms are more acidic and smaller in size. Epo can be separated by isoelectric focusing (IEF) or electrophoresis of urine samples. After IEF, a double blotting procedure is performed. The mutein darbepoetin alfa migrates more in the acidic range than Epo on IEF. The WADA has established criteria to achieve harmonization in the performance of the test for epoetin and darbepoetin in urine. Actually, when urine samples from rhEpo treated subjects were submitted to two WADA-accredited laboratories the results were not fully consistent, which, as claimed by the laboratories, was apparently due to methodological differences. A recent detection problem has arisen with the addition of proteases by athletes to their urinary samples, which destroys the erythropoietic proteins. The adulteration of urine with proteases is a prohibited method, and techniques have been developed for the detection of their misuse.

Another difficulty relates to the fact that once [Hb] has been raised in athletes by the administration of recombinant ESAs, only microdoses or less frequent injections of the drugs are needed to maintain [Hb] at the high level. In this situation the window of detection of rhEpo in urine is only 12-18 h, compared to about three days on regular dosing (50 U kg⁻¹ b.w. three times a wk (TIW)). Thus, while the detection of rhEpo in urine is effective if the
injection frequency is high, this is certainly not the case when the injection rate is reduced to weekly injections. Because darbepoetin alfa has a 3- to 4-fold longer half-life (24–26 h) than the epoetins (6-8 h), the window of detection of darbepoetin alfa is prolonged to about 7 days. CERA has an even longer half-life of about 6 days. IEF of CERA yields bands in the less acidic area when compared to native Epo. IEF for investigation of doping with CERA has also been applied to blood samples. In addition, CERA can be detected by enzyme-linked immunoassay (ELISA).

Table 1 gives an overview of recent Epo-like molecules and -derivatives that have entered preclinical or clinical trials and are potential candidates for misuse in sports. Of particular interest are recombinant fusion proteins of Epo with the Fc region of human IgG, since one of these was shown to stimulate erythropoiesis, when administered as an aerosol in a Phase I trial.

Epo mimetic peptides (EMPs) are synthetic cyclic peptides of about 20 amino acids. A potent pegylated EMP dimer (INN: peginesatide; Hematide™) proved to stimulate erythropoiesis in experimental animals and in healthy male volunteers. Peginesatide is currently in Phase III trials for the treatment of patients with chronic renal failure (CKD). Peginesatide can be detected by ELISA. In a clinical trial on 14 patients with CKD, who had pure red cell aplasia due to anti-Epo antibodies and were treated with peginesatide for 28 months, neutralizing antibodies against the drug occurred in one of the patients. This should further discourage athletes to use the medicine as a doping means.

In an alternative approach, EMPs have been constructed onto human IgG1-based scaffolds by recombinant DNA technology. The seminal compound, CNTO 528 (Centocor; Radnor, PA), produced a reticulocytosis and increased [Hb] on i.v. administration in a Phase I study in healthy men. The follow-on product CNTO 530, a dimeric EMP fused to a human IgG4 Fc scaffold, has been shown to expand the pool of erythroid progenitors in vitro and in vivo.

Drugs activating the endogenous Epo gene

The Epo enhancer is under the control of hypoxia-inducible transcription factors (HIFs), heterodimetric proteins composed of the subunits α and β. HIF-2 is the main factor inducing Epo expression. The C-terminus of HIF-α comprises proline residues that are hydroxylated in the presence of O₂. Prolyl hydroxylated HIF-α binds the von Hippel-Lindau tumor suppressor protein (pVHL) in complex with an E3-ligase and undergoes immediate proteasomal degradation. The transcriptional activity of the HIFs is suppressed by O₂-
dependent hydroxylation of an asparagine residue. The HIF-α hydroxylases contain Fe\(^{2+}\) and are inactivated by Fe\(^{2+}\) removal.\(^{55}\) However, iron chelators are not suited for stimulation of erythropoiesis in the long-term, because iron is required for heme synthesis. HIF-dependent Epo expression is augmented by divalent transition metals such as cobalt or nickel. It has been known for long that cobalt increases erythropoiesis in experimental animals.\(^{56}\) Cobalt binds to HIF-α thereby preventing the docking of pVHL.\(^{57}\) Cobalt is a very potent inducer of Epo transcription. In fact, the international Epo unit (IU) was originally defined as the dose eliciting the same erythropoiesis stimulating response in rats as five micromoles of cobaltous chloride.\(^{58}\) The treatment of anemic CKD patients with cobalt (commonly administered as enteric-coated tablets, 30-150 mg daily)\(^{59,60}\) is no longer performed because of its toxicity.\(^{61}\) However, cobalt may be misused by athletes as a legitimate means to enhance Epo levels and Hb\(_{\text{mass}}\).\(^{62}\) Cobalt is very potent, inexpensive and not comprehended in the WADA’s Prohibited List. Furthermore, the HIF-α hydroxylases require α-ketoglutarate for their catalytic action.\(^{55}\) α-Ketoglutarate competitors ("HIF stabilizers") are orally active compounds that stimulate Epo production and erythropoiesis.\(^{63,64}\) A number of chemically different HIF stabilizers has been identified.\(^{65,66}\) A Phase I clinical trial investigating effects of the α-ketoglutarate competitor FG-2216 (FibroGen; San Francisco, CA) in CKD patients has been reported.\(^{67}\) However, HIF stabilizers induce the expression of >200 genes apart from Epo,\(^{65,66}\) which may result in serious unwanted effects in athletes. On the other hand, it is likely that some of the HIF-activated genes encode proteins which may increase physical performance (e.g. glycolytic enzymes, glucose transporters, angiogenic peptides).

GATA inhibitors are non-peptidic organic compounds that prevent GATA-2 from suppressing the Epo promoter.\(^{68,69}\) Initially, the GATA inhibitor K-7174, a diazepane derivative, was used. Subsequent reports have indicated that the follow-on product K-11706 exerts even stronger erythropoietic effects in vitro and in experimental animals.\(^{69,70}\) K-11706 was already shown to increase physical performance in mice.\(^{70}\)

**Epo gene transfer**

A viral gene delivery vector carrying the human Epo gene under the control of an O\(_2\) dependent hypoxia response-element (Repoxygen\(^{\text{TM}}\); Oxford BioMedica, Oxford, UK) was earlier developed that might have been misused for Epo gene doping. Reportedly, however, the technique never proceeded beyond animal experiments.\(^{71}\) In addition, in vivo Epo gene transfer could probably be detected if applied by athletes, as an IEF study revealed unusual
Epo glycosylation forms on allogeneic Epo transfer into skeletal muscle of cynomolgus macaques via adeno-associated virus (AAV).\textsuperscript{72} In the initial studies of AAV-mediated allogeneic Epo cDNA transfer to macaques severe anemia developed in many animals after a few months, which was likely due to an immune reaction.\textsuperscript{73,74} However, in using a rapamycin dimerizer-regulated gene expression system, Rivera et al.\textsuperscript{75} achieved controlled, long-term production (up to 6 years) of Epo in rhesus monkeys, with no apparent immune response. Regarding the possibility of Epo gene doping in humans, strategies are under development to specifically amplify intron-less DNA sequences and PCR protocols allowing the detection of small amounts of transgenic DNA in blood.\textsuperscript{76-78} The tests take into consideration that transgenes are usually derived from the complementary DNA (cDNA) for the gene to be transferred and cDNA does not contain introns.

An autologous ex vivo approach was chosen in the first human Epo gene therapy trial on patients with CKD.\textsuperscript{79} An individual dermal core sample was transfected with Epo cDNA inserted into a vector containing the CMV promoter and the simian virus-40 polyA site. When the dermal cores were re-implanted under the abdominal skin, serum Epo levels peaked in most cases on day 3 and then decreased reaching baseline levels, likely due to immunologic rejection of the transplants. The transient Epo increase produced a reticulocytosis but was not sufficient to raise [Hb] levels.\textsuperscript{79}

In conclusion, Epo gene transfer is possible, but medically little explored with respect to efficacy, safety and immunogenicity. It seems less likely that any of the techniques has entered the sports scene.

**Other erythropoietic hormones**

Several hormones may stimulate the renal and/or hepatic production of Epo, including prostanoids, thyroid hormone, angiotensin II, growth hormone (GH) and testosterone. The latter are of particular interest regards blood doping (Figure 3).

A study in anemic CKD patients has shown that plasma Epo levels increase 6 h after the start of GH infusion, with peak values reached after 96 h.\textsuperscript{80} The fact that the rise in plasma Epo occurred earlier than the rise in insulin-like growth factor-I (IGF-I) indicates that GH directly stimulates Epo production. IGF-I was earlier shown to promote the growth of erythrocytic progenitors.\textsuperscript{81} The concentration of circulating IGF-I correlates with Hct in CKD patients.\textsuperscript{82} Synthetic GH secretagogues (ghrelin mimetics), recombinant human GH and recombinant human IGF-I are available for therapeutic purposes.
Anabolic-androgenic steroids also increase both the production of Epo and the proliferation of erythrocytic progenitors in the bone marrow, as reviewed elsewhere.83

**WADA’s Biological Passport**

Traditional anti-doping analyses are based on the detection of a substance in biological fluids (“Adverse analytical finding”). This approach has major limitations regarding blood doping. As outlined above, autologous blood cannot be detected, there is a plethora of ESAs, the detection window is limited and there is urine manipulation. Some sports federations earlier introduced upper [Hb] and Hct limits to escape from this dilemma. Athletes tested above the limits were declared unfit for competition (“No-start rule”). However, [Hb] and Hct are influenced by external factors such as body posture, exercise, or residence at altitude. Also, “clean” athletes can have naturally high [Hb] and Hct values. A large retrospective study on male blood donors in Denmark revealed that 3.9% of non-athletes and 10.4% of elite rowers had Hct values >0.51, i.e. above the recommended limits for athletic competition.84 In addition, Cazzola21 has warned that the adoption of upper [Hb] and Hct limits may paradoxically generate more blood doping, because by ESA misuse [Hb] and Hct can be manipulated with the aim of approaching the target values without exceeding it.

Hematologic parameters depend on ethnicity, age and gender. Even [Hb] values differ.85 Hence, it has been suggested to use longitudinal blood profiles together with heterogeneous factors, such as ethnicity and age, to develop models with improved sensitivity to detect blood doping.86-88 Some blood parameters, such as the concentration of Epo and reticulocytes (Ret) increase on administration of ESAs (ON-score), while they decrease after RBC transfusion or after the cessation of ESA administration (OFF-score).86,89-94 The “Abnormal Blood Profile Score” (ABPS; not presently used for the assessment of abnormal blood profiles based on the passport data) regards additional red cell parameters, such as the mean corpuscular Hb concentration (MCHC), mean corpuscular volume (MCV), mean corpuscular Hb mass (MCH), Ret counts, serum Epo and soluble transferrin receptor (sTfR).95 Algorithms have been used that are sensitive during one of the two phases, with ON-score being sensitive during ESA treatment and OFF-score during the cessation phase. Details of the calculation of these scores are described elsewhere.96

Having become effective in December 2009, the “Athlete Biological Passport Operating Guidelines”2 equip Anti-Doping Organizations with a framework in which to pursue anti-
doping rule violations in accordance with Article 2.2. of the World Anti-Doping (WAD) Code (“Use or Attempted Use by an Athlete of a Prohibited Substance or a Prohibited Method”). The guidelines include mandatory requirements for collection, transportation, analysis of blood samples, and results management. The following markers are considered in the Athlete Biological Passport hematologic module: Hct, Hb, RBC count, Ret% (Ret percentage), Ret# (Ret number), MCV, MCH, MCHC, and OFF-hr score (Index of stimulation derived from the formula ([Hb] (g L⁻¹) - (60 x √(Ret%)); normal range: 85-95). In addition, parameters of interest can be the mean Ret cell volume (MCVr), Ret Hb concentration (MCHCr) and Ret Hb content (MCHr), as measured by flow cytometry like in clinical routine. The results reported to the WADA are processed by an “Adaptive Model” that identifies abnormal blood parameter changes related to the athlete’s individual profile. In particular, [Hb] or OFF-hr score abnormalities with a 99.9% probability or more shall be reviewed by experts.2

RBC parameters associated with autologous re-transfusion

The failure to obtain direct proof for autologous blood transfusion has prompted the search for indirect evidence. In a preliminary anti-doping context, Damsgaard et al. reported changes in hematologic parameters following blood withdrawal and re-infusion. Ten healthy men were subjected to withdrawal of 20% of their blood volume (and hence much more than common doping practice) which was replaced by 1.3 L of hydroxyl-ethyl starch. Circulating Epo increased 4-fold within a day, declining exponentially thereafter. Ret# increased 2.4-fold after 7 days, remaining elevated for another 7 days. [Hb] remained reduced on average by 15% for 2 wks. sTfR increased by 60% by day 14 and remained elevated until 3 days after re-infusion of 0.8 L of packed RBC, which was performed one month later. Thereby, [Hb] increased acutely by 8% returning to the initial baseline value after 7 days. Epo concentrations remained unchanged whereas Ret# were reduced by about 30% from day 7-21. Only one of the men in this study showed [Hb] values higher than 170 g L⁻¹, thereby exceeding the upper limit offset by some sport federations for male athletes. None of the men demonstrated positive OFF-scores according to the model of Gore et al., which renders this model less effective in detecting blood transfusion doping. The loss of Hb_mass of about 75 g (measured by CO re-breathing) after donation of 550 mL blood has been shown to be recovered after a mean of 36 days. Following the re-transfusion of one RBC unit Hb_mass acutely increased by 51 g, showing a continuous decrease from wk 2 until wk 8, albeit Hb_mass was still elevated when compared to pre-re-infusion values. Based on the results of a retrospective longitudinal blinded study, the same group of investigators has reported that the use of an adaptive model
incorporating hematologic measures ([Hb], Ret%, OFF-score) allows for detection of autologous blood transfusion.\textsuperscript{101} In a comparative study of three blood passport approaches and four blood markers Mørkeberg et al.\textsuperscript{102} re-transfused 29 subjects with either 1 or 3 units of autologous blood. Hbmr (derived from the formula \([4.51 \times \ln (\text{Hb}_{\text{mass}}) - \sqrt{\text{Ret}\%}]\); currently not part of anti-doping testing) demonstrated superior sensitivity in detecting blood transfusion.\textsuperscript{102} The same authors have reported that the determination of the ratio between the mass of Hb in the mature erythrocyte population and in the reticulocyte fraction (RBC\textsubscript{Hb}: Ret\textsubscript{Hb} ratio) is the best indicator of autologous blood doping.\textsuperscript{103}

**RBC parameters associated with ESA doping**

There are no major differences in basal [Hb], RBC count, Hct and MCHC values in elite athletes in comparison to healthy non-athletes.\textsuperscript{104} When blood samples obtained from 413 female and 739 male elite athletes from 12 countries were screened for hematologic abnormalities, 1\% of the females and 1.4\% of the males had hemoglobinopathies.\textsuperscript{105} Furthermore, 2.4\% of the females and 0.7\% of the males were iron deficient with or without anemia.\textsuperscript{105} Accelerated erythropoiesis due to the use of rhEpo may lead to the production of iron-deficient reticulocytes (reduced MCHr), even when iron stores are normal.\textsuperscript{106} An increase in hypochromic red cells has been seen on rhEpo therapy despite the use of parenteral or oral iron.\textsuperscript{107} Ret\# was not affected by i.v. iron administration in healthy humans subjected to a bolus injection of rhEpo (300 U kg\textsuperscript{-1} i.v.).\textsuperscript{19} However, MCHr and Ret [Hb] were increased in the i.v. iron/rhEpo group compared with the group receiving rhEpo alone. Thus, i.v. iron increases the hemopoietic response to rhEpo in normal subjects, and this therapy is likely practiced by cheating athletes. Note that parenteral iron alone did not produce a change in Hb\textsubscript{mass}, [Hb] or specific RBC parameters in young female athletes, despite their low baseline [Hb] (128 g L\textsuperscript{-1}) and serum ferritin (35 \(\mu\)g L\textsuperscript{-1}) levels.\textsuperscript{108}

There is fair stability of Ret\# in top-level athletes,\textsuperscript{109} although decreases were observed in some athletes during competition periods.\textsuperscript{110} High and middle fluorescence (immature) Ret with a high RNA content (IRF) are relatively frequent in athletes owing to continuous bone marrow stimulation linked to hemolysis, which is typical of sports activities.\textsuperscript{110} Bolus rhEpo injections (150 U or 300 U kg\textsuperscript{-1} b.w.) further increase the IRF.\textsuperscript{111} The increase in immature Ret starts 36 h after a single dose of rhEpo, reaching a peak after 3-4 days and normalizing within 7 days.\textsuperscript{111} A pharmacodynamic model calculation has revealed that rhEpo transiently increases the lifespan of circulating Ret from the baseline value of 1.7 days to 3.4 days.\textsuperscript{112
Thus, the treatment with rhEpo appears to increase Ret values twofold: by increased Ret release from the bone marrow and by prolonged maturation time of circulating Ret.

Audran et al.\textsuperscript{12} studied the time-course of Ret\textsuperscript{#} following repeated s.c. injections of rhEpo (50 U kg\textsuperscript{-1} b.w. every day) in athletes. Ret\textsuperscript{#} were increased from day 10 to 24 and remained elevated for 7 days after cessation of rhEpo therapy. Ret\textsuperscript{#} were significantly lower than the baseline values 14 and 25 days after the last rhEpo injection. During treatment up to 14 days after the last rhEpo injection sTfR and the sTfR/serum protein ratio were elevated above baseline.\textsuperscript{12} Russell et al.\textsuperscript{113} administered first high (50 U kg\textsuperscript{-1} b.w. TIW for 3 wks) and then low doses of rhEpo (20 U kg\textsuperscript{-1} TIW for 5 wks), with oral or parenteral iron supplementation. Ret\% approximately doubled by day 8 of the high-dose rhEpo treatment, but during the low-dose phase was not different from baseline values or from those of the placebo group, irrespective of the route of iron administration. During the washout phase Ret\% fell to about half of the baseline values in the rhEpo treated subjects. In a similar study, following frequent weekly injections for 14 days and a concomitant doubling in Ret\%, Ret\% returned to basal levels despite weekly rhEpo injections and continuously high [Hb], suggesting a decreased sensitivity to prolonged rhEpo treatment.\textsuperscript{39} In accordance, low-dose treatment with rhEpo (about 15 U kg\textsuperscript{-1} TIW) did not increase Ret\% above normal in subjects with elevated [Hb] due to previous high doses of rhEpo.\textsuperscript{40} However, there are no published data to exclude the possibility that low dosed rhEpo may stimulate erythropoiesis sufficiently to mask the decrease in Ret\% following RBC transfusion. Parisotto et al.\textsuperscript{90} subjected recreational athletes to rhEpo treatment (50 U kg\textsuperscript{-1} TIW for 4 wks), either supplemented with oral or intramuscular iron. The authors analyzed combinations of Hct, Ret-Hct, serum Epo, sTfR, and \% macrocytes by logistic regression. The ON-model identified 94-100\% of rhEpo group members during the final 2 wks of the treatment phase. One false positive was recorded from a possible 189. The OFF-model, incorporating Ret-Hct, Epo and Hct, identified 67-72 \% of recent uses with no false positive, when applied during the washout phase and the period of 12-21 days after the last rhEpo injection.\textsuperscript{90}

Following a single administration of high-dose Epo (200 U kg\textsuperscript{-1}) [Hb] and Hct did not increase in spite of an increase in Ret\#.\textsuperscript{114} The s.c. administration of rhEpo (about 200 U kg\textsuperscript{-1} wk\textsuperscript{-1}) and oral iron (270 mg day\textsuperscript{-1}) for 30 days produced an increase in Hct from 42.7 to 50.8, as well as in sTfR (from 3.1 to 6.3 mg L\textsuperscript{-1}) and the ratio between sTfR and ferritin (from 3.2 to 11.8).\textsuperscript{13} Casoni et al.\textsuperscript{115} administered rhEpo s.c. at doses of 30 U kg\textsuperscript{-1} b.w. every other day for 30 to 45 days to 20 subjects practicing sports at an amateur level. rhEpo treatment was
accompanied by twice weekly administration of parenteral iron (62 mg i.v.) and oral vitamins. The rhEpo treated subjects had higher values for RBC concentrations, [Hb], Hct, MCV, Ret%, macrocyte (volume >120 fL) and hypochromic macrocyte counts (MCH <28 pg) compared to a control population of 240 elite athletes from various sport disciplines. Breymann et al. studied the effect of rhEpo in healthy adults when given at different time intervals. 15 volunteers were randomly selected to receive twice rhEpo (300 U kg\(^{-1}\)) and parenteral iron (200 mg), either within a 24 h or 72 h interval. Controls received parenteral iron only. When second rhEpo administration was after 72 h, volunteers showed significantly higher Ret# in the high percentage of young RNA-rich Ret (HFR ratio) over several days compared to those who received rhEpo within a 24 h interval. Both rhEpo treated groups showed an increase in MCVr. MCHCr was inversely correlated with the increasing cell size with a nadir on day 8.

However, apart from blood transfusion or ESA administration, other (legal) stimuli can affect some of the parameters included in the blood passport. One such example is altitude exposure. Residence at altitude may be associated with an Epo-induced increase in [Hb], and it is important to discriminate between the effects of hypoxia and rhEpo misuse. Parisotto et al. have reported that Ret#, Ret Hb mass (Ret-Hb), and the ratio between RBC Hb mass (RBC-Hb) and Ret-Hb in non-athletic subjects treated with rhEpo (1,200 U kg\(^{-1}\) b.w. over a 9-10 day period) are more significantly increased than the ones in elite cyclists training at altitude (1,780 and 2,690 m). Ashenden et al. retrospectively evaluated hematologic data from 19 elite cyclists who lived and trained 2,690 m above sea level for about 1 month, from 6 elite canyon runners who lived 2,100 m above sea level but descended to compete at sea level competitions, and from 39 well-trained subjects who resided at sea level but slept at a simulated altitude of 2,650–3,000 m for 20-23 days of either consecutive or intermitted nightly exposure. Upon ascend to a terrestrial altitude, ON- and OFF-model scores increased immediately, mainly because of an increase in [Hb]. Scores had not returned fully to baseline 3 wks after return to sea level, because of the persistence of the raised [Hb] for the ON- and OFF-scores and the fall in Ret% for OFF-scores. Abellan et al. have reported that short-term hypoxia exposure (simulated altitude of 4,000–5,500 m in a hypobaric chamber) for 3 h day\(^{-1}\), 5 days a wk, for 5 wks does not cause an increase in Ret%, [Hb] and sTfR. Interestingly, the hypoxia exposure was associated with a shift of urinary Epo isoforms towards the basic area on IEF. However, these shifts could not be confused with the pattern on rhEpo misuse. It should be kept in mind, however, that none of the above mentioned altitude studies were able to show increases in Hb\(_{mass}\) or performance, and that they did not
comply with the minimum recommendations of at least 400 hours of altitude/hypoxia exposure needed to increase performance. Hence, if the passport approach was to be tested in combination with an altitude setting actually leading to performance gains, it seems very likely that also many of the parameters included in the blood passport will change substantially, which needs to be accounted for during the evaluation process.

Comments

The WAD Code states that a positive analytical result, i.e. proof of the presence of a prohibited substance, will always establish liability for a doping offence.\textsuperscript{119} If a medication an athlete is required to take to treat an illness or condition falls under the “Prohibited List”, a “Therapeutic Use Exemption” (TUE) may give the athlete the authorization to take the needed medicine.\textsuperscript{1}

Regards blood doping, the traditional analyses based on the detection of a substance in biological fluids have major limitations. Presently, only the misuse of allogeneic blood can be directly detected, while re-transfused autologous blood is not detectable. There is a plethora of novel ESAs that are difficult to uncover. To overcome the detection problems, the “Athletes Biological Passport” has been developed, which is based on the monitoring of selected RBC parameters. Blood doping may be suspected, when these parameters change in a non-physiological way. There are several subjects for debate concerning the passport approach, including (i) the measuring devices, (ii) the processing of the analytical data and the assessment of abnormal parameters to be due to doping, (iii) the applicability in sports practice, and (iv) the impact on research.

There are methodological problems due to the lack of clear standardization and harmonization in anti-doping testing. The longitudinal evaluation of several hematologic variables needs high comparability among various analytical technologies used by the different accredited laboratories. Although some parameters (i.e. \([Hb]\) and \(Hct\)) are quite comparable when measured on different instrumentations, others (f.e. percentage of macrocytes or Ret parameters) are peculiar.\textsuperscript{26} This bears the risk of false positive results in athletes. On the hand, when 400 blood samples obtained from 24 subjects receiving rhEpo injections were screened by means of the passport parameters, 42\% of the subjects were not identified as rhEpo doped.\textsuperscript{120}
The statistical approach for evaluating the passport data is focused on the biological variation of hematologic values. Critical experts in the analysis of laboratory data have claimed that anti-doping tests are based on fraud statistics. Sottas et al. have stated that anti-doping is a forensic science, not a medical one. In forensics the traditional assumptions of “absolute certainty” and “discernible uniqueness” are abandoned in favor of an empirical and probabilistic approach.

Current anti-doping actions in competitive sports are advocated for reasons of fair-play and concern for the athlete’s health. Most of the efforts concern elite athletes with much less impact on amateur sports and the general public. Indeed, anti-doping rules adopted pursuant to the WAD Code normally apply only to international- and national-calibre athletes. The monitoring of RBC parameters according to the biological passport is not performed in recreational-level or masters competitors who are not current or potential national-caliber competitors. Thus, the procedure is of little use in leisure sports.

Finally, a comment should be passed with respect to plans of the WADA to extend the passport by working on an endocrine module that includes androgenic steroid profiling (“Endocrine module”) as well as on other possible modules. In order to propose that an adverse analytical finding is due to doping, knowledge of the action of the suspected substance must first be gained in healthy athletes. For example, the effects of androgenic steroids and recombinant human growth hormone needed to be investigated in healthy young subjects. In the authors’ mind, this is an ethical dilemma.
Authorship

W. J. and C. L. are the authors of the manuscript. W. J. has evaluated research grant applications to the World Anti-Doping Agency and the Federal German Institute of Sports Science. C. L. has on numerous occasions received funding from the Danish Anti Doping Agency for his research.

Correspondence: Wolfgang Jelkmann, Institute of Physiology, University of Luebeck, D-23562 Luebeck, Germany; e-mail: jelkmann@physio.uni-luebeck.de.
References


4.   Calbet JA, Lundby C, Koskolou M, Boushel R. Importance of hemoglobin concentration to

5.   Martino M, Gledhill N, Jamnik V. High VO2max with no history of training is primarily due

6.   Pace N, Consolazio WV, Lozner EL. The effect of transfusions of red blood cells on the

7.   Schmidt W, Prommer N. Impact of alterations in total hemoglobin mass on VO2max. *Exerc

8.   Warburton DE, Gledhill N, Quinney HA. Blood volume, aerobic power, and endurance
      66.

9.   Sawka MN, Convertino VA, Eichner ER, Schnieder SM, Young AJ. Blood volume:
      importance and adaptations to exercise training, environmental stresses, and trauma/sickness.

10.  Ekblom B, Berglund B. Effect of erythropoietin administration on maximal aerobic power in


120. Bornø A, Aachmann-Andersen NJ, Munch-Andersen T, Hulston CJ, Lundby C. Screening for recombinant human erythropoietin using [Hb], reticulocytes, the OFF(hr score), OFF (z


<table>
<thead>
<tr>
<th>Compound/Technique</th>
<th>Manufacture</th>
<th>Development/Approval status</th>
<th>Pharmacological references</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recombinant products</strong></td>
<td></td>
<td></td>
<td>(R = review)</td>
</tr>
<tr>
<td>Originator epoetins (alpha, beta,</td>
<td>Recombinant DNA technology</td>
<td>Country- and product-specific marketing authorization in North America, Australia, Asia,</td>
<td>28(R), 29(R), 46(R), 58(R)</td>
</tr>
<tr>
<td>theta)</td>
<td></td>
<td>European Union (EU)</td>
<td></td>
</tr>
<tr>
<td>Epoetin alfa copies</td>
<td>Epo transfected CHO cells</td>
<td>Marketed in Asia, Central and South America, Africa</td>
<td>29(R), 46(R), 125(R)</td>
</tr>
<tr>
<td>Epoetin omega</td>
<td>Epo transfected BHK cells</td>
<td>Marketed in South Africa</td>
<td>46(R)</td>
</tr>
<tr>
<td>Epoetin delta</td>
<td>CMV promoter transfected HT-1080 cells</td>
<td>No longer available (marketing stopped in 2009)</td>
<td>29(R), 46(R), 125(R)</td>
</tr>
<tr>
<td>Methoxy-PEG-Epoetin beta</td>
<td>Epo transfected CHO cells, pegylated</td>
<td>Marketed in EU and Asia</td>
<td>29(R), 45(R), 46(R)</td>
</tr>
<tr>
<td>Darbepoetin alfa</td>
<td>Mutated Epo transfected CHO cells, hyperglycosylated</td>
<td>Marketed in EU, North America, Australia, Asia</td>
<td>42, 43, 29(R), 46(R)</td>
</tr>
<tr>
<td></td>
<td>Recombinant DNA technology</td>
<td>Clinical trials</td>
<td>48, 125(R)</td>
</tr>
<tr>
<td><strong>Epo fusion proteins</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------</td>
<td>--------------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>(Epo-Epo, Epo-Fc, Epo-βHCG)</td>
<td>Chemical synthesis</td>
<td>Clinical trials</td>
<td>29(R), 46(R)</td>
</tr>
<tr>
<td><strong>Peptidic Epo mimetics</strong></td>
<td>PEG coupled</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pegisenatide;</td>
<td>Fused to recombinant immunoglobulin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CNTO 528, CNTO 530</td>
<td>Chemical synthesis</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Epo gene activators</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIF stabilizers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobalt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>α-Ketoglutarate competitors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GATA inactivators</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Epo gene transfer</strong></td>
<td>In vivo gene transfer</td>
<td>Preclinical trials</td>
<td>68-70</td>
</tr>
<tr>
<td></td>
<td>In vitro gene transfer</td>
<td>Preclinical trials</td>
<td>71-75</td>
</tr>
</tbody>
</table>

Modified from Jelkmann"
Legends of the Figures

Figure 1. Parameters determining the aerobic capacity. The aerobic capacity, as measured as the maximal O2 uptake, depends primarily on the individual’s total hemoglobin mass, the maximal cardiac output and the maximal O2 extraction in the heart and the skeletal muscles. The total hemoglobin mass results from the blood hemoglobin concentration and the blood volume.

Figure 2. Hematocrit (%) and total hemoglobin mass (g.kg\(^{-1}\)) in moderately trained young males (Danish) (commuting to work/school on bicycle and engaged in easy aerobic training 1-3 times per week, in trained runners (French, all finishers of the “Ultra Trail du Mont Blanc”; 166 km of mountain trail running with 9,500 meter of altitude gain), in national level cyclists (Danish, US, Canada), and in national team cross country skiers (German, Swedish and French) including several Olympic and World Championship medalists. The figure illustrates that elite athletes may have similar hematocrit values as compared to healthy individuals, but that hemoglobin mass is increased (*P < 0.001 vs. moderately trained individuals). The data were collected by Carsten Lundby, Paul Robach and Bengt Saltin between 2005 and 2011 in a joint effort.

Figure 3. Control of erythropoiesis and starting points for blood doping. The hormone erythropoietin (Epo) which derives from kidneys and liver stimulates the survival, proliferation and differentiation of the erythrocytic progenitors in hemopoietic tissues. The enhanced release of reticulocytes leads to an increase in the blood hemoglobin concentration and, thus, the O2 capacity of the blood and the total hemoglobin mass. Epo gene expression in the kidneys and the liver is controlled at the transcriptional level. Because the Epo enhancer is activated by the hypoxia-inducible transcription factors (HIFs) chemicals stabilizing HIF such as cobalt and \(\alpha\)-ketoglutarate competitors increase Epo-expression. GATA inactivators release the Epo promoter from the inhibition by GATA-2. Androgenic steroids and growth hormone (GH), respectively insulin-like growth factor 1 (IGF-1), augment the production of Epo and the proliferation of erythrocytic progenitors.
Figure 1

Hemoglobin concentration → Hemoglobin mass
Blood volume → Max. cardiac output
Max. heart rate → Max. cardiac output
Max. stroke volume → Max. cardiac output
O₂-affinity of the blood → Max. O₂-extraction
Mitochondrial respiratory capacity → Max. O₂-extraction

Aerobic capacity (Max. O₂ uptake)
Figure 3

Epo production

- Androgens
- GH / IGF-1
- HIF stabilizers
- GATA inactivators

Erythropoiesis

- Epo
- IGF-1
- Androgens

GH
Androgens (?)
Blood doping and its detection

Wolfgang Jelkmann and Carsten Lundby