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REVIEW | *Recovery from Exercise*

Recovery of the immune system after exercise

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Peake JM, Neubauer O, Walsh NP, Simpson RJ. Recovery of the immune system after exercise. *J Appl Physiol* 122: 1077–1087, 2017. First published December 1, 2016; doi:10.1152/japplphysiol.00622.2016.—The notion that prolonged, intense exercise causes an "open window" of immunodepression during recovery after exercise is well accepted. Repeated exercise bouts or intensified training without sufficient recovery may increase the risk of illness. However, except for salivary IgA, clear and consistent markers of this immunodepression remain elusive. Exercise increases circulating neutrophil and monocyte counts and reduces circulating lymphocyte count during recovery. This lymphopenia results from preferential egress of lymphocyte subtypes with potent effector functions [e.g., natural killer (NK) cells, γδ T cells, and $CD8^+$ T cells]. These lymphocytes most likely translocate to peripheral sites of potential antigen encounter (e.g., lungs and gut). This redeployment of effector lymphocytes is an integral part of the physiological stress response to exercise. Current knowledge about changes in immune function during recovery from exercise is derived from assessment at the cell population level of isolated cells ex vivo or in blood. This assessment can be biased by large changes in the distribution of immune cells between blood and peripheral tissues during and after exercise. Some evidence suggests that reduced immune cell function in vitro may coincide with changes in vivo and rates of illness after exercise, but more work is required to substantiate this notion. Among the various nutritional strategies and physical therapies that athletes use to recover from exercise, carbohydrate supplementation is the most effective for minimizing immune disturbances during exercise recovery. Sleep is an important aspect of recovery, but more research is needed to determine how sleep disruption influences the immune system of athletes.

open window; repeated exercise bouts; immunodepression; overreaching; sleep

THE IMMUNE SYSTEM IS INTEGRAL to the body's defense against infection. It also influences other physiological systems and processes, including tissue repair, metabolism, thermoregulation, sleep/fatigue, and mental health. Over the past 40 years, exercise immunology has developed into its own discipline based on the recognition that the immune system mediates many exercise effects and that stress responses mediated through the nervous and endocrine systems play a key role in determining exercise-induced immune changes (84). A classic paradigm in exercise immunology is that an "open window" of immunodepression can occur during recovery from intense exercise. In particular, this paradigm proposes that after intense exercise, some immune variables (e.g., lymphocyte and natural killer cell numbers and antibody production) transiently decrease below preexercise levels. As a result of this immunodepression, microbial agents, especially viruses, may invade the host or reactivate from a latent state, leading to infection and illness (87). If exercise is repeated again while the immune system is still depressed, this could lead to a greater degree of immunodepression and potentially a longer window of opportunity for infection (87).

Exercise-induced fatigue exists on a continuum. Repeated bouts of intense exercise on the same day or over several days may cause acute fatigue, as indicated by an inability to maintain exercise workloads (64). An athlete who trains intensely for 1−2 wk may experience a state of "functional overreaching," which is associated with a temporary performance decrement, followed by improved performance. Intense training over an extended period without sufficient balance between training and recovery may lead to "nonfunctional overreaching" (NFOR; 64). This condition is typically characterized by persistent fatigue, performance decrement, muscle soreness,

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and psychological and hormonal disturbances that can last for weeks or months. Depending on the time needed to recover from NFOR, an athlete may be diagnosed (retrospectively) as experiencing "overtraining syndrome" (64).

Recognition of the link between excessive training and risk of illness has stimulated interest in nutritional supplements and physical therapies to counteract immunodepression and to restore immune function after exercise training. In this minireview, we update the current state of knowledge about the temporal changes in the immune system following exercise; how repeated bouts of exercise on the same day, extended periods of intense training, and sleep disruption influence the immune system; and the efficacy of various strategies for restoring immune function after exercise.

Leukocyte Redeployment During Exercise and Recovery

A single exercise bout causes profound changes in the number and composition of blood leukocytes that may persist long into exercise recovery. All major leukocyte subpopulations tend to increase in number during exercise as a result of hemodynamic shear stress and/or catecholamines acting on leukocyte β_2-adrenergic receptors (126). The postexercise recovery period is marked by opposite effects on blood neutrophil and lymphocyte numbers. Neutrophil number (and, consequently, the total leukocyte count) often continues to increase long into the recovery period (up to 6 h after exercise cessation), particularly if the exercise bout is prolonged (>2 h; 86). This sustained "neutrophilia" is characterized by an increased presence of immature, less differentiated, precursor neutrophils in the blood (117), most likely in response to the increased plasma levels of soluble agents including glucocorticoids, growth hormone, and cytokines such as IL-6 and granulocyte colony-stimulating factor, which mobilize myeloid cells from the bone marrow (117). Although this neutrophilia following prolonged exercise is akin to that observed during bacterial infection ($>7.0 \times 10^6$/ml), 24 h of recovery are usually sufficient for neutrophil number to return to normal (126). A delayed monocytosis is sometimes observed within 1−2 h after very prolonged exercise, but monocyte number typically returns to the resting level within 6 h after exercise cessation (126).

By contrast, lymphocyte number decreases rapidly after exercise. Following prolonged and/or high-intensity exercise in particular, lymphocyte number commonly decreases to below the preexercise value within as little as 30 min (126). This "lymphopenia" can often reach levels typical of clinical lymphopenia ($<1.0 \times 10^6$/ml), but the lymphocyte count is usually restored to both the resting and clinically normal level within 4−6 h of recovery (126). After prolonged bouts of exercise (e.g., 2-h cycling), natural killer (NK) cells (which account for most of the exercise-induced lymphocytosis) may be ~40% lower than the baseline value for up to 7 days after exercise (104). Exercise-induced lymphopenia reflects the preferential movement of lymphocyte subtypes with potent effector functions (e.g., NK cells, γδ T cells, and $CD8^+$ T cells) out of the blood. Even within these subsets, there is a preferential egress of discrete subtypes of highly differentiated NK cells, γδ T cells, and $CD8^+$ T cells with phenotypes associated with tissue-migrating potential and effector capabilities (107).

The rapid lymphopenia observed during the early stage of exercise recovery was initially of concern, particularly because early studies reported large rates of lymphocyte apoptosis (programmed cell death) after exhaustive exercise (62). However, these findings have not been substantiated. Subsequent studies have reported lymphocyte apoptosis of the order of 0−2% after exercise, even though the blood lymphocyte count was up to 30−40% lower than at rest (66, 105). Lymphocytes and monocytes leave the blood in large numbers during exercise recovery under the influence of glucocorticoids. Lymphocyte subtypes that preferentially egress the peripheral blood during exercise recovery also have phenotypes consistent with tissue migration (e.g., expression of surface adhesion molecules and chemokine receptors; 108). These lymphocytes most likely translocate to peripheral sites of potential antigen encounter, such as the lungs or the gut (48).

The skin has long been considered a likely destination for effector lymphocytes in response to exercise and stress in general (24). However, recent evidence indicates that $CD8^+$ T cells and NK cells mobilized by exercise do not express cutaneous homing receptors on their surface (121). Exercise appears to "prime" effector T cells, thereby allowing them to transmigrate to the peripheral tissues that require enhanced immune surveillance following physical stress (54). Compared with the resting condition, the percentage of circulating lymphocytes expressing effector cytokines is lower following prolonged exercise (115), but it is unknown whether this decline reflects impairment at the individual cell level or preferential movement of effector T cells into peripheral tissues (e.g., lungs and gut). Recent evidence showing that exercise redeploys T cells that are specific to latent herpesviruses such as cytomegalovirus (CMV) and Epstein-Barr virus (EBV; 111, 112) suggests that this response may be a countermeasure against stress-induced viral reactivation (107). Exercise may also mobilize "older" functionally exhausted/senescent lymphocytes to undergo apoptosis in the tissues and allow new "recruits" to take their place (106, 107).

Monocytes mobilized by exercise are likely to infiltrate skeletal muscle and differentiate into tissue-resident macrophages that facilitate repair and regeneration, particularly following arduous bouts of exercise that cause significant skeletal muscle damage (85). Monocytes with effector phenotypes are also preferentially redeployed after exercise. The $CD14^+$/$CD16^+$ "proinflammatory" monocytes are preferentially mobilized over their $CD14^+$/$CD16^-$ counterparts (109). Monocyte expression of pathogen recognition receptors [e.g., toll-like receptors (TLRs)] tends to decrease in response to moderate-intensity exercise (109). Conversely, prolonged, intense exercise (60-km cycling time trial) increases TLR2 and TLR4 expression on monocytes, which may indicate a heightened proinflammatory state (11). A recent study showed that acute exercise mobilizes angiogenic T cells, which may facilitate vascular remodeling during exercise recovery (53). Exercise is also known to mobilize hematopoietic stem cells, which may participate in skeletal muscle repair and regeneration after exercise (25, 49). It has been suggested that exercise may have a role as an adjuvant to mobilize stem cells in donors for hematopoietic stem cell transplantation (25).

In addition to cellular redeployment, the recovery phase of exercise, especially following very prolonged bouts of endurance-based exercise, is marked by striking alterations in the

functional capacity of several blood leukocyte populations. Neutrophil bactericidal activity is greatly influenced by the intensity and duration of exercise. For example, 1 h of cycling at 50 vs. 80% of $\dot{V}O_{2max}$ increases and reduces neutrophil oxidative burst activity, respectively (94). During the early stages of recovery after exercise, neutrophil bactericidal activity continues to increase after 40 min to 1 h of moderate-intensity exercise, whereas it remains impaired after exhaustive or prolonged exercise (86). NK cell cytotoxicity after exercise bouts of relatively short duration tends to remain unchanged on a per cell basis during recovery (81) but may decline after very prolonged bouts (33). T cell proliferation in response to mitogen stimulation typically decreases both during and after exercise, regardless of exercise modality, intensity, or duration (126). Prolonged exercise may also reduce T cell homing and migration (8), lipopolysaccharide-induced cytokine secretion by monocytes (113), and the percentage of T cells producing effector cytokines in response to mitogen stimulation (115). Thus the general trend during exercise recovery is that short bouts of moderate-intensity exercise have little effect on (or might even enhance) cellular immune function, whereas prolonged bouts (>1.5 h) of heavy exertion appear to reduce the normal functioning of all major immune cell subtypes. These effects may leave athletes susceptible to illness during recovery from competition or heavy training (87).

Repeated Exercise Bouts and Extended Periods of Intense Training

The repeated-bout paradigm (87) proposes that compared with a single bout of exercise, repeated exercise bouts on the same day (27, 73, 96, 102) or over several days (43) cause different changes in circulating cell counts, lymphocyte proliferation, and NK cytotoxicity. Subsequent research has investigated changes in other immune responses to repeated exercise bouts on the same day with short vs. long recovery and intensified training over weeks or months. Figure 1 summarizes the evidence for changes in the immune system after repeated exercise bouts and days to months of intense training.

One vs. two bouts of exercise per day. Studies on the effects of one vs. two bouts of exercise on a single day have included physically active (56–58, 63, 96, 102), highly trained (23, 88), or elite (12, 73, 98, 99) participants. The exercises involved cycling (12, 27, 56–58, 63, 96, 98, 99, 102), running (23, 88), or rowing (73). The duration and intensity ranged from <15 min at maximal intensity (27, 73) up to 2 h at medium-high intensity (i.e., 60−75% $\dot{V}O_{2max}$; 56, 96). The recovery period between exercise bouts was most commonly 3−4 h but ranged from 45 min (102) to 12 h (88). Compared with the initial bout of exercise, the following immune variables typically show either a greater relative change or a higher absolute value after a second bout of exercise: total leukocyte count (57, 63, 99, 102), neutrophil count (23, 73, 96, 99, 102), oxidative burst (per neutrophil; 12), elastase release (per neutrophil; 57), $CD4^+$ T cell count (73, 99, 102), whole blood IL-8 production (23), and NK cell activation (represented by CD69 expression; 99). Conversely, lymphocyte proliferation (96, 102) and whole blood IL-6 production (23) are typically lower following a second bout compared with the first bout of exercise.

Short vs. long recovery. Three studies on the effects of recovery duration between two bouts of exercise included highly trained or elite athletes who cycled for 65 min at 75% $\dot{V}O_{2max}$, twice each day, with either 3 or 6 h between the exercise bouts (12, 97, 98). A short recovery period (i.e., 3 h) induces either a greater relative increase or higher absolute values for neutrophil count (12, 97), oxidative burst activity per neutrophil (12), and $CD8^+$ T cell and NK cell counts (97) after the second bout of exercise. Exercise-induced changes in lymphocyte (97), monocyte, and eosinophil (12) counts; absolute oxidative burst activity (12); NK cytotoxicity (97); and plasma concentrations of IL-6 and IL-1ra (98) do not differ after a short vs. long recovery period.

Consecutive or multiple days of exercise. Studies detailing how the immune system responds to exercise repeated on consecutive days or every second day have included untrained or physically active participants (43, 116, 118) or well-trained or elite athletes (60, 73, 77, 79). Exercise included 3 × 6-min maximal rowing, repeated twice over 2 days (73), and 1−3-h cycling (77, 79, 118) or running (60) at 50−70% $\dot{V}O_{2max}$ repeated over 3 days, every second day for 3 days (43), or daily for 7 days (116). Exercise-induced changes in plasma cytokine and elastase concentrations and cytokine mRNA expression in leukocytes and muscle diminish over consecutive days (77, 118). By contrast, changes in total leukocyte, neutrophil, and monocyte counts (73, 116, 118), lymphocyte proliferation (79), neutrophil chemotaxis (116), leukocyte IL-1ra mRNA expression (77), plasma myeloperoxidase concentration, and salivary IgA secretion rate (79) do not change over time. Changes in lymphocyte subsets (43, 73), oxidative burst activity (79, 116, 118), salivary IgA secretion rate (60, 77), and NK cell count and cytotoxicity (73, 79) over consecutive days are more variable.

Immune changes associated with overreaching and overtraining. Studies on short periods (2−4 wk) of functional overreaching have reported decreases in resting neutrophil degranulation (95), lymphocyte proliferation, and antibody production (124). Neutrophil count, plasma cytokine concentrations, CD4-to-CD8 T cell ratio, and salivary IgA concentration are more variable (or do not change) in response to functional overreaching (39, 95, 124). Athletes who exhibit signs of nonfunctional overreaching and/or frequent upper respiratory illness present with lower salivary IgA concentration (26, 35, 60); lower cytokine production by monocytes, neutrophils, and dendritic cells (67); and a greater number of activated ($CD25^+$) lymphocytes (29). Changes in differential blood cell counts, lymphocyte subsets, and NK cell count following extended periods of intensified training are variable (29, 35, 61). Studies of athletes exhibiting the hallmarks of overtraining syndrome (including illness) have not revealed any consistent or characteristic immune profile (30, 101).

Sleep Disturbance and Immune Function

Sleep disturbances influence immunity via activation of the hypothalamic-pituitary-adrenal axis and the sympathetic nervous system (46). Chronic sleep disturbance and disruption to the normal circadian rhythm are associated with inflammation and desynchronization of rhythmic immune variables. These responses likely contribute to increased risk of infection, cardiovascular disease, and cancer in shift workers (21, 68). Despite evidence that athletes experience poor sleep patterns compared with nonathletes (16, 55), surprisingly little is known

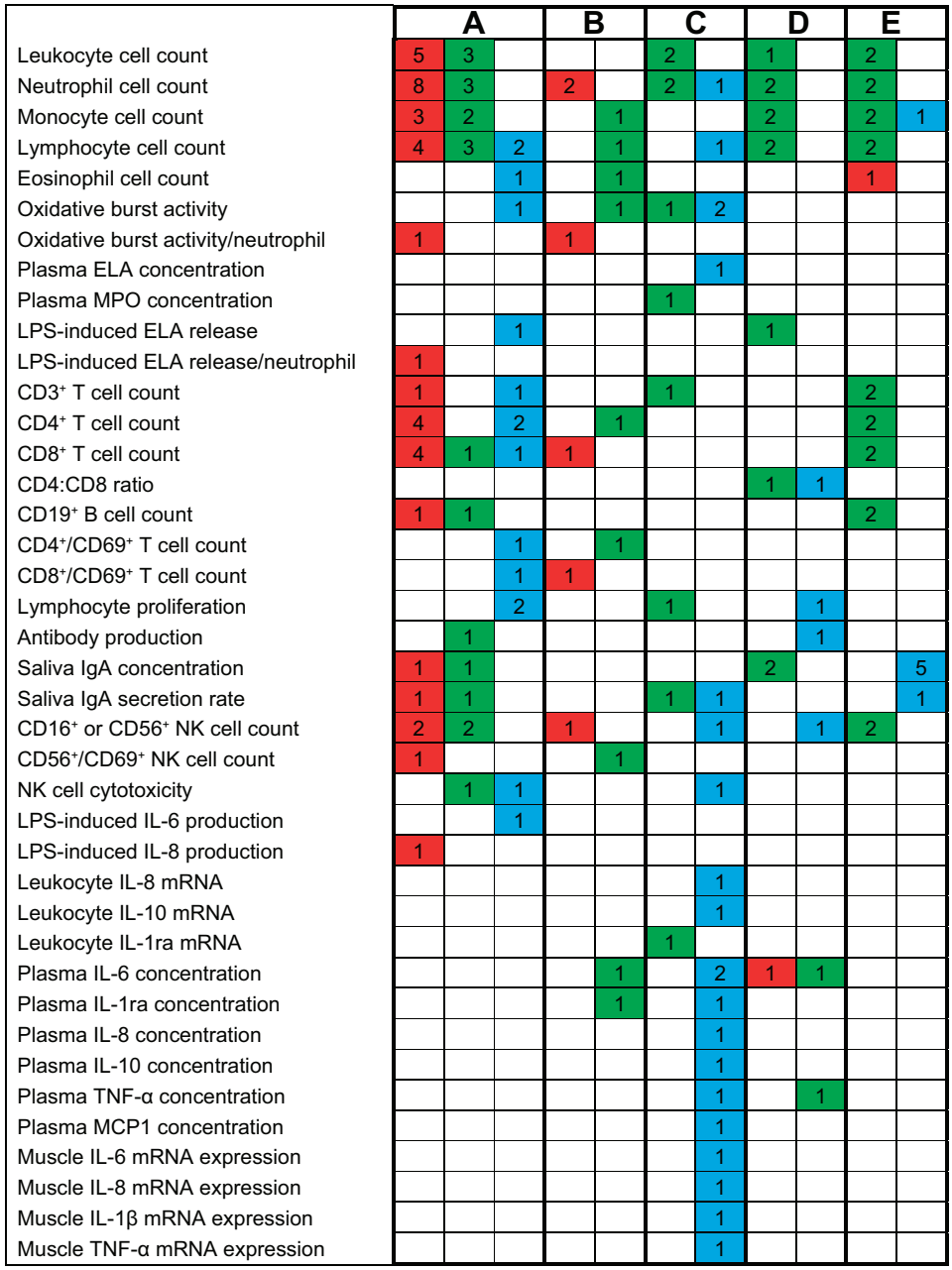

Fig 1. Evidence heat map comparing differences in immune responses to two vs. one exercise bout on the same day (*A*), short vs. long recovery between bouts on the same day (*B*), consecutive days of exercise (*C*), and weeks (*D*) or months (*E*) of intensified training. Numbers represent the number of studies demonstrating an increase/greater change (red), no difference (green), or decrease/smaller change (blue) compared with the first bout of exercise, long recovery, before training, or healthy athletes (refer to text). ELA, elastase; MPO, myeloperoxidase; NK, natural killer; LPS, lipopolysaccharide; MCP1, monocyte chemoattractant protein 1.

about how sleep disturbance influences the immune responses to exercise. Compared with normal sleep, a disrupted night's sleep appears to prime the immune system and enhance immunosurveillance by stimulating total lymphocytes, $CD8^+$ T cells, NK cells, and γδ T cells to leave the blood and migrate to potential sites of infection during the early recovery period after exercise (45). By contrast, other studies indicate that a night without sleep does not influence leukocyte trafficking, neutrophil degranulation, or mucosal immunity at rest or after exercise (31, 93). Subtle immune changes have been observed after a night without sleep, including a shift toward a T helper 2 cytokine profile (46).

It is uncertain whether these subtle immune modifications with acute sleep loss are clinically meaningful. When considering the potential effects of poor sleep on immunity in athletes, it is important to distinguish between acute and chronic sleep disturbance. Chronic sleep disturbance (12 nights, 50% sleep loss) increases the plasma inflammation markers C-reactive protein and IL-6 (38). However, intervening daytime naps can counter this apparent inflammatory response (103). Short sleep duration (<7 h/night for 7 days) decreases the response to hepatitis B vaccination and the likelihood of clinical protection (90). Similarly, a night of wakefulness after hepatitis A vaccination decreases the specific antibody response 2−4 mo later (52). People who experience poor-quality sleep and/or regular sleep deprivation also have a 4−5 times greater risk of developing the common cold (16, 91). Continued research efforts should be directed toward monitoring and improving sleep in athletes and understanding the implications for immune health.

Nutritional Interventions for Restoring Immune Function After Exercise

Research over the last 30 years has investigated whether nutritional strategies counteract exercise-induced immunodepression and systemic inflammation (32, 125). A comprehensive review of the literature on these is beyond the scope of this mini-review; other, more detailed reviews on this topic are available [e.g., Gleeson (32) and Walsh et al. (125)]. Here, we focus on the most effective nutritional strategies (primarily carbohydrate ingestion) for restoring systemic immune function in the first few hours after exercise (9, 10, 19, 51, 65, 76, 78, 82, 83) and over consecutive days (7). We also assess whether the timing of nutritional interventions (i.e., before, during, or after exercise) influences their effectiveness (50, 59).

Carbohydrate supplementation before and/or during exercise. Carbohydrate supplementation during prolonged, intense exercise consistently attenuates exercise-induced increases in circulating cytokines (74, 125) and the redistribution of neutrophils (74, 76, 78), monocytes (76, 82), natural killer cells (78), and lymphocytes (51). The immunomodulatory effects of carbohydrates arise from better maintenance of blood glucose concentrations and blunted release of stress hormones such as catecholamines and glucocorticoids during and after exercise (51, 76, 78, 82, 83). Although the systemic release of IL-6 during exercise is related to muscle glycogen depletion (114), the precise mechanism by which carbohydrate supplementation reduces systemic IL-6 release from contracting muscle during exercise is not clear, because carbohydrate supplementation does not alter muscle glycogen content (75).

In several studies, the immunomodulatory effects of carbohydrate supplementation were observed to "carry over" into the recovery period (i.e., ≥2 h postexercise; 51, 76, 78, 82, 83). Nieman et al. reported that carbohydrate supplementation during 2.5-h high-intensity running reduces the number of neutrophils (immediately and 1.5 h postexercise), monocytes (immediately and 6 h postexercise), and lymphocytes (immediately and 3 h postexercise) (76, 78). Extending carbohydrate ingestion to the postexercise recovery period also reduces neutrophil count (74) and blood granulocyte and monocyte phagocytosis 6 h postexercise (82). Lancaster et al. showed that carbohydrate consumption (30 and 60 g/h) during 2.5-h cycling minimized the suppression of $CD4^+$ and $CD8^+$ T lymphocytes, which express and produce IFNγ, during the 2 h following exercise (51).

Considering that exercise-induced responses of the adaptive immune system are relatively slow (125), it is important to assess whether these effects are maintained over consecutive days of exercise. Carbohydrate ingestion before, during, and after two exercise bouts on 2 consecutive days attenuated the decrease in antigen-stimulated proliferative lymphocyte responses before exercise on the second day (7). Carbohydrate ingestion also enhanced lymphocyte proliferative responses to mitogen stimulation postexercise on the second day (7). These findings suggest that carbohydrates may help to diminish potential cumulative immunodepression over consecutive days of exercise.

The immunomodulatory effects of carbohydrate may depend on the timing of carbohydrate intake. The ingestion of a glucose solution 15 min, but not 75 min, before 1-h high-intensity cycling prevented immunoendocrine perturbations (50). The lack of an effect of carbohydrates ingested 75 min preexercise was potentially associated with an insulin-induced decrease in the plasma glucose concentration before exercise, which, in turn, might have enhanced immunoendocrine responses (50). Carbohydrate ingestion during either the first or the second of two 90-min bouts of cycling on the same day better maintained plasma glucose and attenuated plasma stress hormone responses to the second bout (59). By contrast, carbohydrate ingestion during the 2-h recovery period between these exercise bouts had no such effects (59). These findings suggest beneficial effects of a timely carbohydrate supplementation (i.e., shortly before and/or during exercise) on immune responses to exercise. This may be particularly relevant with more prolonged and/or intense exercise protocols and when the recovery duration between two consecutive exercise bouts is short.

Carbohydrate ingestion does not influence all aspects of the immune system. For example, carbohydrate supplementation does not alter the exercise-induced suppression of natural killer cell function (78) or salivary IgA secretion (18). Importantly, it remains unclear whether the immunomodulatory effects of carbohydrates have clinical relevance for resistance to illness or adaptation of the immune system to regular exercise stress (32, 125). Recent evidence indicates that carbohydrate supplementation during prolonged exercise blunts exercise-induced immune-endocrine perturbations but does not prevent the suppression of in vivo immunity (22). More research is required to examine the effects of carbohydrates (or other nutritional strategies) on in vivo immune function in response to acute and chronic exercise.

Dietary carbohydrate intake after glycogen depletion. Some studies have investigated the effects of dietary carbohydrate intake on immune responses to consecutive days of exercise intended to deplete muscle glycogen (9, 10, 34, 65). A higher carbohydrate intake consistently attenuated certain components of immunodepression well into the recovery period (i.e., ≥2 h postexercise) after the second exercise session (10, 34, 65). Athletic training often involves conditions of low carbohydrate availability, e.g., due to abbreviated recovery periods and/or as part of a "train low-compete high" training regime (41, 42). These investigations therefore have particular practical implications. Compared with a higher carbohydrate intake (8 $g \cdot kg^{-1} \cdot day^{-1}$), very low carbohydrate intake (0.5 $g \cdot kg^{-1} \cdot day^{-1}$) leads to greater perturbation in leukocyte subsets during recovery from exercise (65). These effects may be related to sustained elevation of plasma cortisol concentration (65). Bishop et al. observed that compared with a low-carbohydrate diet (1.1 $g \cdot kg^{-1} \cdot day^{-1}$), a high-carbohydrate diet (8.4 $g \cdot kg^{-1} \cdot day^{-1}$) for 3 days after glycogen-lowering cycling attenuated plasma cortisol and cytokine concentrations and circulating total leukocyte and neutrophil counts following subsequent exercise (10).

Consuming a high-carbohydrate diet (8.5 $g \cdot kg^{-1} \cdot day^{-1}$) also reduces overreaching symptoms during 11 days of intense training, compared with moderate carbohydrate consumption (5.5 $g \cdot kg^{-1} \cdot day^{-1}$; 1). The periodic implementation of "train-low" strategies (e.g., by commencing training with low muscle glycogen stores) may further amplify metabolic adaptations in skeletal muscle (41, 42). When considering their dietary carbohydrate intake, athletes should aim to achieve a balance between minimizing immunodepression and maximizing met-

abolic adaptations in skeletal muscle. In view of the detrimental effects of low carbohydrate availability on the immune system, chronic carbohydrate restriction should be avoided during intense periods of training (32, 41). Additional research is warranted to better understand the effect of long-term training consisting of intermittent train-low sessions on immune function and susceptibility to illness.

Dietary protein intake and postexercise protein supplementation. Recognizing the importance of protein for immunocompetence (15), there are benefits of postexercise protein ingestion (18, 19, 69) or a diet high in protein (128) on immune responses to exercise. On the basis of previous results indicating that exercise-induced lymphocyte trafficking was impaired during high-intensity training, Witard et al. examined whether a high-protein diet can restore these impaired immune responses (128). Consuming a high-protein diet (3 $g \cdot kg^{-1} \cdot day^{-1}$) helped to minimize exercise-induced changes in lymphocyte distribution during a period of intense training (128). Interestingly, an energy- and carbohydrate-matched normal protein diet (1.5 $g \cdot kg^{-1} \cdot day^{-1}$) failed to provide the same benefit (128). The high-protein diet was also associated with fewer self-reported upper respiratory illnesses (128). Another study demonstrated that protein and leucine supplementation for 1–3 h postexercise during 6 days of high-intensity training enhanced neutrophil respiratory burst activity after the last exercise session (69). Consuming a carbohydrate-protein solution immediately, but not 1 h, after exercise prevents a decrease in neutrophil degranulation during the postexercise recovery period (19).

Recent research has shown that the timing, distribution, and amount of postexercise protein intake modulate the blood and tissue availability of protein/amino acids and adaptive responses of skeletal muscle (3, 42). Notably, amino acid-sensitive mammalian target of rapamycin (mTOR) signaling is also a key mechanism underlying leukocyte trafficking (110). More studies are therefore needed to examine whether different postexercise protein feeding patterns influence immune function during recovery from exercise.

Antioxidants and phytochemicals. Except for carbohydrate supplementation, evidence for effective nutritional countermeasures to exercise-induced immune alterations is limited (32, 125). Among other types of nutritional supplements [e.g., probiotics and vitamin D; for reviews, see Gleeson (32) and Walsh et al. (125)], antioxidants and phytochemicals such as quercetin have been studied for their potential capacity to minimize immune perturbations, particularly during exercise recovery (75, 77, 79, 80). Some data point toward beneficial effects of quercetin supplementation on immune health after intense exercise (77, 79). Other findings suggest an increased need for nutritional antioxidants during the first 24 h of recovery from intense exercise lasting several hours such as an Ironman triathlon (71). However, taken together, the present literature is not sufficiently robust to recommend supplementation with phytochemicals or antioxidants to prevent immune suppression and illness in athletes and exercising individuals. Athletes often take high doses of antioxidant/phytochemical supplements in the belief that this will reduce their risk of illness (47). However, high doses of antioxidant/phytochemical supplements can interfere with training adaptations (42, 72). A natural diet rich in fruits, vegetables, whole grains, and nuts delivers antioxidants and phytochemicals in physiologically effective amounts that are most likely sufficient to help maintain immune function following exercise and during exercise training (32, 72, 125).

Other Strategies for Restoring Immune Function After Exercise

In addition to nutritional interventions, other research has examined the efficacy of nonsteroidal anti-inflammatory drugs (NSAIDs) and various physical therapies for restoring immune function after exercise. Some studies (13, 20, 70, 89, 120, 127) have shown effects of NSAIDs, but other human studies have failed to demonstrate any effects of NSAIDs (122, 123), cryotherapy (44), compression garments (5, 37, 92), active recovery (2, 119), or other physical therapies (28) on immune responses during recovery from exercise (Fig. 2). Despite this lack of empirical evidence for the benefits of NSAIDs and physical therapies for restoring immune function after exercise, some of these treatments are associated with positive psychological outcomes and other effects not related to immune function after exercise (4, 17). Therefore, although the physiological effects of these physical treatments are not understood fully at the present time, they may confer some important benefits for athletes, which may involve the immune system, perhaps indirectly.

Theoretical and Practical Considerations

The redeployment of effector lymphocytes from blood to peripheral tissues is seen as an integral part of the physiological stress response and the immune system's response to prepare the body for potential injury by mobilizing its "troops" (cells)

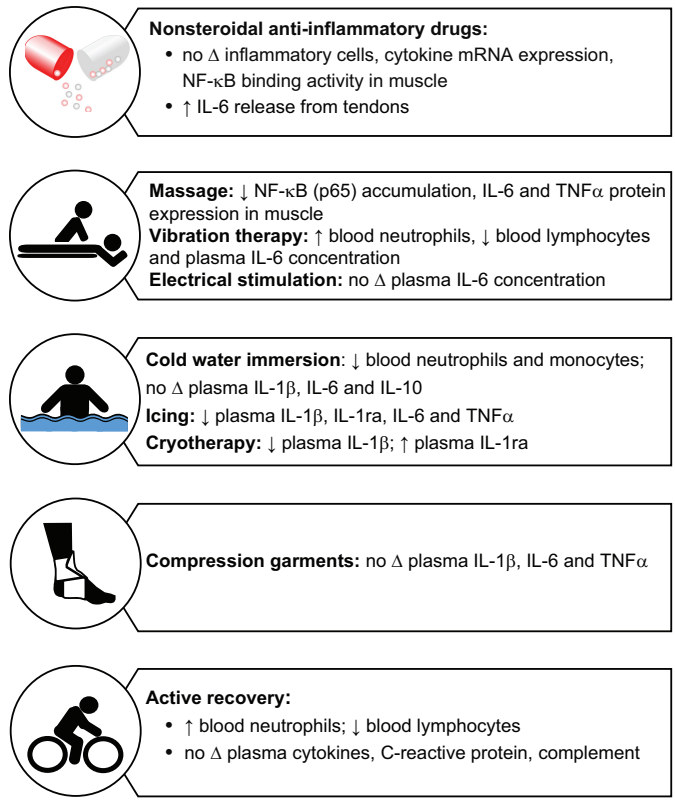

Fig. 2. Summary of the effects of nonsteroidal anti-inflammatory drugs (NSAIDs) and physical therapies on immune changes during recovery from exercise.

to increase immunosurveillance (24). Therefore immune integrity during exercise recovery may be characterized by the host's ability to redeploy effector lymphocytes effectively to the peripheral tissues. Lymphocyte redeployment may be impaired following very prolonged bouts of exercise or in athletes who are overreaching. The redeployment of $CD8^+$ T cells both during and after exercise is significantly reduced after 1 wk of high-intensity training compared with normal training (129). Specifically, the egress of $CD8^+$ T cells was 1.4-fold higher after normal compared with high-intensity training.

Considering other evidence that stress-induced leukocyte redeployment is linked to poor clinical outcomes following surgery (100), immune cell redistribution and infection risk after exercise warrant further investigation. High-volume exercise training may impair the redeployment of viral-specific T cells and NK cells, thereby reducing antiviral "patrolling" during exercise recovery (Fig. 3). Herpes viruses such as EBV and CMV are highly prevalent in the population, and reactivation of these viruses from a latent state is indicative of systemic immunodepression (107). EBV viral DNA is present in saliva from athletes after even short periods of high-intensity training (36), but it is unknown whether this reflects training-induced impairment in the trafficking of virus-fighting lymphocytes.

Cellular immune function in response to exercise is typically assessed in isolated cells ex vivo or at the cell population level in the blood compartment. This approach can make it difficult to interpret changes in immune cell function after exercise because of the massive alterations in the cellular composition of discrete leukocyte subtypes. On the one hand, it seems intuitive to interpret lower immune cell function measured in blood during the early stages of exercise recovery as indicative of immunodepression. On the other hand, it is equally possible that after exercise, the most functional immune cells (i.e., those with effector phenotypes and high tissue-migrating potential) are redeployed to other areas of the body where they are needed. If true, this suggests that systemic immunosurveillance may be enhanced during exercise recovery, despite an apparent depressed profile in the blood compartment.

It is difficult to determine the biological significance of exercise-induced changes in immune cell function when assessed in vitro. This is because cell function is typically assessed relative to the total cell population (e.g., percentage of T cells responding to mitogen stimulation, number of target cells killed per NK cell, oxidative burst activity per neutrophil, etc.) without accounting for exercise-induced changes in the subset composition of these cell populations. For example, the proportion of NK cells expressing the activating receptor, NKG2C, is markedly elevated during exercise recovery (6). As a result, NK cell cytotoxic activity for the total NK cell population increases markedly when an NKG2C-sensitive target cell is used to assess NK cell function (6). Conversely, when an NKG2C-insensitive target cell line (K562) is used, NK cell killing is not affected by exercise (6). Therefore the proportional shifts in the composition of cell subtypes should be considered when interpreting exercise-induced changes in immune cell function at the total cell population level in vitro. Moreover, assessment of in vitro immune cell function using venous blood samples does not account for the complex interactions among immune cells and soluble factors within tissues (e.g., gut, lungs, and skin). However, some evidence suggests that reduced immune cell function in vitro may coincide with changes in vivo and rates of illness (14, 40).

The validity of the original paradigm of cumulative immunodepression with repeated bouts of exercise (87) is somewhat difficult to assess. Months of intense training increase the incidence of illness in elite athletes (26, 30, 35). However, on the basis of these studies, we can only assume, but not assert, that increased incidence of illness results from an imbalance between training and recovery. Research that has systematically manipulated the balance between training and recovery has not identified any immune variables that are consistently depressed as a result of insufficient recovery after exercise. However, with one exception (79), these studies have not tracked the incidence of illness after repeated bouts of exercise.

Reduced salivary IgA concentration and secretion rate (amount of IgA secreted over a fixed period) may predispose athletes to illness in the long term (26, 35). IgA binds micro-

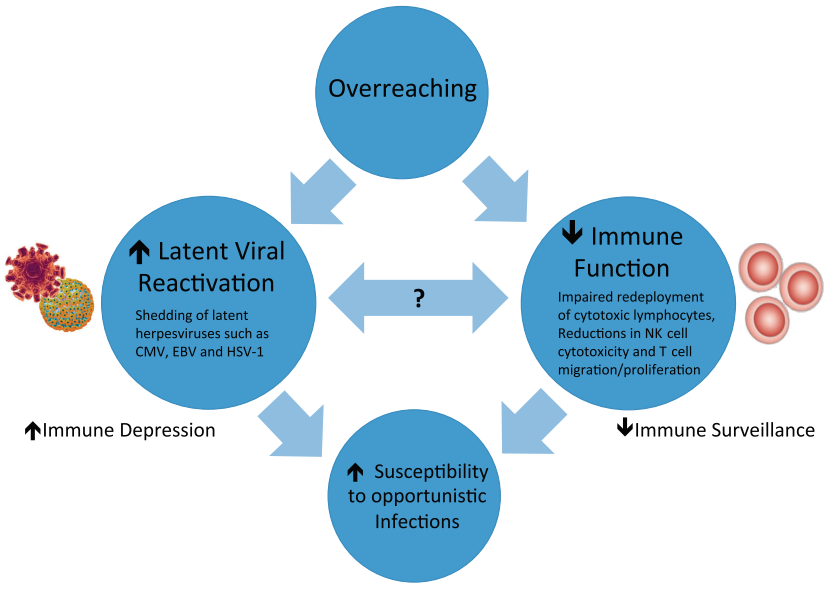

Fig. 3. Overreaching or heavy training is associated with impaired cellular immune function and latent viral reactivation. Reduction in lymphocyte trafficking and function during exercise recovery impairs immune surveillance, which may increase susceptibility to opportunistic infection. Lowered immunity may also allow previously acquired viruses to reactivate from a latent state, which may cause further immunodepression and increase susceptibility to infection. HSV-1, herpes simplex virus type 1.

organisms such as bacteria and viruses in the mucosa so that they can be destroyed by immune cells. However, short-term changes in salivary IgA concentration and secretion rate after repeated bouts of exercise are variable (56, 58, 60, 79). Salivary IgA concentration and secretion rate may decrease incrementally over longer periods. The repeated exercise models used in many of the studies described above induce only acute fatigue (64). Accordingly, smaller exercise-induced changes in immune variables following repeated bouts of exercise may actually represent positive adaptation of the immune system, as opposed to depression of immunity that may lead to illness.

Pedersen et al. (87) suggested that there is a critical threshold for exercise intensity and duration that determines the risk of immunodepression after repeated bouts of exercise. However, no studies have systematically determined the effects of repeated exercise bouts of different intensity and duration. There are also no data on the effects of repeated bouts of anaerobic or resistance/strength exercise, or a combination of different types of exercise on the same day. The large gaps in Fig. 1 show that much remains to be learned about the effects of repeated bouts of exercise on the immune system.

Among various nutritional interventions that have been studied to counteract immunodepression during exercise recovery, carbohydrate supplementation has proven the most effective. A balanced and well-diversified diet that meets the energy demands in athletes and exercising individuals is certainly a key component to maintain immune function in response to strenuous exercise and intense periods of training. Additional research is warranted to investigate how the timing and pattern in the ingestion of nutrients, particularly carbohydrates and protein/amino acids, influence recovery of the immune system after exercise.

Sleep disturbances can depress immunity, increase inflammation, and promote adverse health outcomes in the general population. However, the limited data available on how sleep disturbances influence immune responses to exercise are inconsistent. Physical treatments that are used after exercise (e.g., hydrotherapy and massage) may enhance the athlete's sense of well-being and should be considered as adjunct therapies for maintaining immune health.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

J.M.P. and R.J.S. prepared figures; J.M.P., O.N., N.P.W., and R.J.S. drafted manuscript; J.M.P., O.N., N.P.W., and R.J.S. edited and revised manuscript; J.M.P., O.N., N.P.W., and R.J.S. approved final version of manuscript.

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