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Immunity, Inflammation and Airway Dysfunction in Elite Cross-Country Skiers and Ice Hockey Players: A Systematic Review

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ABSTRACT

Strenuous exercise in elite sports impacts the immune system, leading to high rates of upper respiratory tract infections and airway dysfunction, such as asthma and exercise-induced bronchoconstriction (EIB). Cross-country (XC) skiers and ice hockey (IH) players are particularly affected due to their training environments and sports disciplines. This systematic review (SR) evaluates immune and inflammatory responses and the risk of developing airway dysfunction in these athletes. Original articles focusing on immune response, systemic inflammation, and airway dysfunction in competitive XC skiers and IH players were retrieved from MEDLINE/Ovid, EMBASE, and the Cochrane Library. Risk of bias was assessed using the Cochrane Risk of Bias Tool. Of 3582 studies screened, 50 met the inclusion criteria. Both elite XC skiers and IH players exhibit increased cortisol levels and altered systemic immune cell compositions in response to training and competition. Both groups show neutrophilic or mixed neutrophilic/eosinophilic airway inflammation, in contrast to the primarily eosinophilic inflammation associated with allergic asthma. Both XC skiers (27%) and IH players (14%) had a high prevalence of physician-diagnosed asthma. This SR highlights the notable burden of airway dysfunction in elite winter athletes, with elevated rates of asthma and EIB. The observed inflammatory

Abbreviations: AMP, adenosine monophosphate; BHR, bronchial hyperresponsiveness; CD4/8, cluster of differentiation 4/8; CO, carbon monoxide; CRP, C-reactive protein; DC, dendritic cell; ECM, extracellular matrix; EIB, exercise-induced bronchoconstriction; Endotype, subtype of a disease condition defined by a distinct pathophysiological mechanism; EVH, eucapnic voluntary hyperventilation; FeNO, fractional exhaled nitric oxide; FIS, International Ski Federation; ICS, inhaled corticosteroid; IFN, interferon; IgA/G/M, immunoglobulin A/immunoglobulin G/immunoglobulin M; IH, ice hockey; IL, interleukin; IOC, International Olympic Committee; MPO, myeloperoxidase; NK, natural killer (cells); NO, nitric oxide; NO_2, nitrogen dioxide; Phenotype, observable characteristic of a disease, with no implication of any mechanism; RCT, randomized controlled trial; sIgA, secretory immunoglobulin A; SR, systematic review; TNF-α, tumor necrosis factor-alpha; URTI, upper respiratory tract infection; XC, cross-country.

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patterns support the concept of a "sport asthma" endotype, which may be a result of chronic exposure to cold, dry air. Effective management may benefit from refined diagnostic criteria, the identification of specific biomarkers, and tailored prevention and treatment strategies for asthma and EIB.

1 | Introduction

Exercise impacts the immune system depending on the type of sport, frequency, duration, and intensity, particularly in elite winter athletes who face unique environmental and physiological challenges [1, 2]. Competitive athletes undergo prolonged, intensive training, which, combined with factors like performance pressure, sleep disruption, long-haul travels, stress, pollutants, weather, and socioeconomic conditions, can weaken immunity and increase infection risk [1, 3–6]. High training loads elevate the risk of systemic inflammation by increasing susceptibility to oxidative stress [7] and upper respiratory tract infections (URTIs) [1, 2, 5]. During exercise, there is an immediate increase in minute ventilation, which increases exposure to inhalant allergens, pollutants, irritants, and challenging environmental conditions (e.g., cold, dry air in winter sport athletes), depending on the training environment and intensity. Regular strenuous exercise, particularly in cold or noxious environmental conditions, has been linked to asthma development [8, 9].

Asthma is a chronic disease characterized by symptoms such as coughing, wheezing, shortness of breath, and chest tightness [10]. These symptoms are associated with airway obstruction and inflammation. Bronchial hyperresponsiveness (BHR) is a common accompanying symptom in asthmatics, but is not a necessary criterion for diagnosis [10]. Transient narrowing of the lower airways in response to exercise, known as exercise-induced bronchoconstriction (EIB), is common in individuals with or without asthma [11]. EIB is highly prevalent in healthy athletes, children, atopic individuals, and those recovering from respiratory infections [12–15]. It is also a common feature of uncontrolled asthma [16]. However, prevalence comparisons of asthma, BHR, and EIB across studies are limited by varying definitions and methods.

Disease heterogeneity is being increasingly recognized as essential for personalized asthma management. Several asthma phenotypes and endotypes have been described, with two major phenotypes prevalent in athletes: atopic asthma (with allergic rhinitis) and sports-induced asthma (respiratory symptoms and BHR without allergic features) [17, 18]. Allergic asthma typically develops in childhood, with wheezing as a prominent symptom, whereas non-allergic asthma in athletes emerges during late adolescence or early adulthood, manifesting as coughing, shortness of breath, wheezing, and sputum production [18, 19]. However, significant overlap between these phenotypes is common [18].

Chronic inflammation observed in asthma is typically classified into Type 2 and non-Type 2 endotypes, according to the different immune responses mediated by cluster of differentiation 4+ (CD4+) T cells [20, 21]. Repeated exposure to substances that damage the airway epithelium or to very high ventilation—especially in dry conditions—can impact airway barrier integrity, increasing susceptibility to respiratory pathogens [22–25]. In athletes exposed to cold, dry air over prolonged periods, this repeated cycle of airway injury and repair within the small airways may lead to chronic inflammation, potential remodeling, and an increased risk of EIB [22, 23]. The overlap between immunity and airway function, and the way each influences the other, is crucial for understanding the pathophysiology of respiratory diseases such as asthma and EIB [26].

Diagnosing asthma and EIB/BHR in athletes is challenging due to inconsistent diagnostic criteria and a lack of clear guidelines [27, 28]. Diagnosis often relies on self-reported symptoms and objective assessment of airway responsiveness to direct (e.g., methacholine) or more appropriate indirect challenges (exercise, eucapnic voluntary hyperpnea (EVH), and mannitol), with varying testing protocols and cutoff values [27, 28].

Inhaled corticosteroids (ICS), combined with short- and long-acting β-agonists (SABA and LABA) and/or leukotriene antagonists, are typically used to treat asthma and EIB [29]. However, the use of these medications in athletes raises questions about their necessity, as a clear diagnosis of asthma or exercise-induced bronchoconstriction (EIB) is often lacking. While the World Anti-Doping Agency (WADA) [30] allows the use of inhalers, including ICS and β-agonists, for legitimate medical purposes, it is essential to ensure that athletes are not misusing these medications and that their use is justified by a proper medical diagnosis [30, 31]. Non-pharmacological approaches, such as extended warm-up and cool-down, avoiding extreme weather conditions, and targeted training plans with sufficient breaks, can offer short-term benefits complementary to pharmacological treatment [32]. Furthermore, changes in diet, such as fish oil supplements, low salt, or high doses of caffeine, have been suggested to reduce the severity of EIB [32]. While most athletes across various sports with asthma/EIB/BHR respond to these treatments, they are insufficiently or not effective at all in around 15% of cases [33].

Ice hockey (IH) players and cross-country (XC) skiers had the highest incidence of respiratory illness among all participating disciplines in the first Winter Youth Olympic Games in 2012 [34]. In terms of airway dysfunction, including asthma and EIB/BHR, elite athletes of different winter sports show a prevalence of 30% [15]. Furthermore, endurance athletes show a higher prevalence of physician diagnosed asthma (21.4%), compared to 7.2% in the general population [35]. The high incidence is linked to repeated ventilations of large volumes of cold, dry air during high-intensity training and competitions, with XC skiers facing temperatures as low as −20°C [27, 36]. Dehydration and cooling of the airways due to cold air exposure and airway injury resulting from high ventilation volumes during intense exercise are thought to lead to

hyperosmolar airway fluid and microvascular leakage. These changes can further lead to airway smooth muscle sensation with contraction and airway edema caused by the release of histamine, prostaglandins, and cysteine leukotrienes by activated airway inflammatory cells [17, 22, 23]. Indoor pollutants in poorly ventilated wax rooms and ice arenas, such as CO, NO, NO_2, and (ultra) fine particulates from internal combustion fossil-fueled ice resurfacing machines further aggravate airway dysfunction [8, 24, 36, 37].

Despite the well-documented effects of intense physical exercise and environmental factors on respiratory health, there is limited understanding of how systemic and airway inflammation manifest in elite athletes exposed to cold air and pollutants. Current research is hampered by inconsistent diagnostic criteria, a lack of performance sport-specific guidelines, and insufficient research into immune responses in these populations. However, several studies have explored airway inflammation in winter athletes, including the work by Karjalainen et al. and Sue-Chu et al., which have shown that neutrophilic inflammation is common among exercising athletes [38, 39]. In addition, research on systemic inflammation in winter athletes may provide further insight into the role of different types of inflammation. That said, it is important to note that research in this area is still incomplete, and much of it remains speculative. Further studies on both acute and chronic inflammation in athletes are necessary to deepen our understanding of the complex mechanisms behind respiratory disease in elite athletes.

This systematic review (SR) aims to (1) report the prevalence of systemic inflammation and immunity (based on C-reactive protein [CRP], interleukins (IL), immunoglobulins, CD4/CD8 T cell ratio, and leukocytes cell counts); (2) report the prevalence and type of airway inflammation based on fractional exhaled nitric oxide (F_ENO) data, sputum, and biopsy; and (3) report the prevalence of respiratory symptoms, asthma medication, and self-reported and physician-diagnosed airway dysfunction (based on exercise challenge tests and provocation

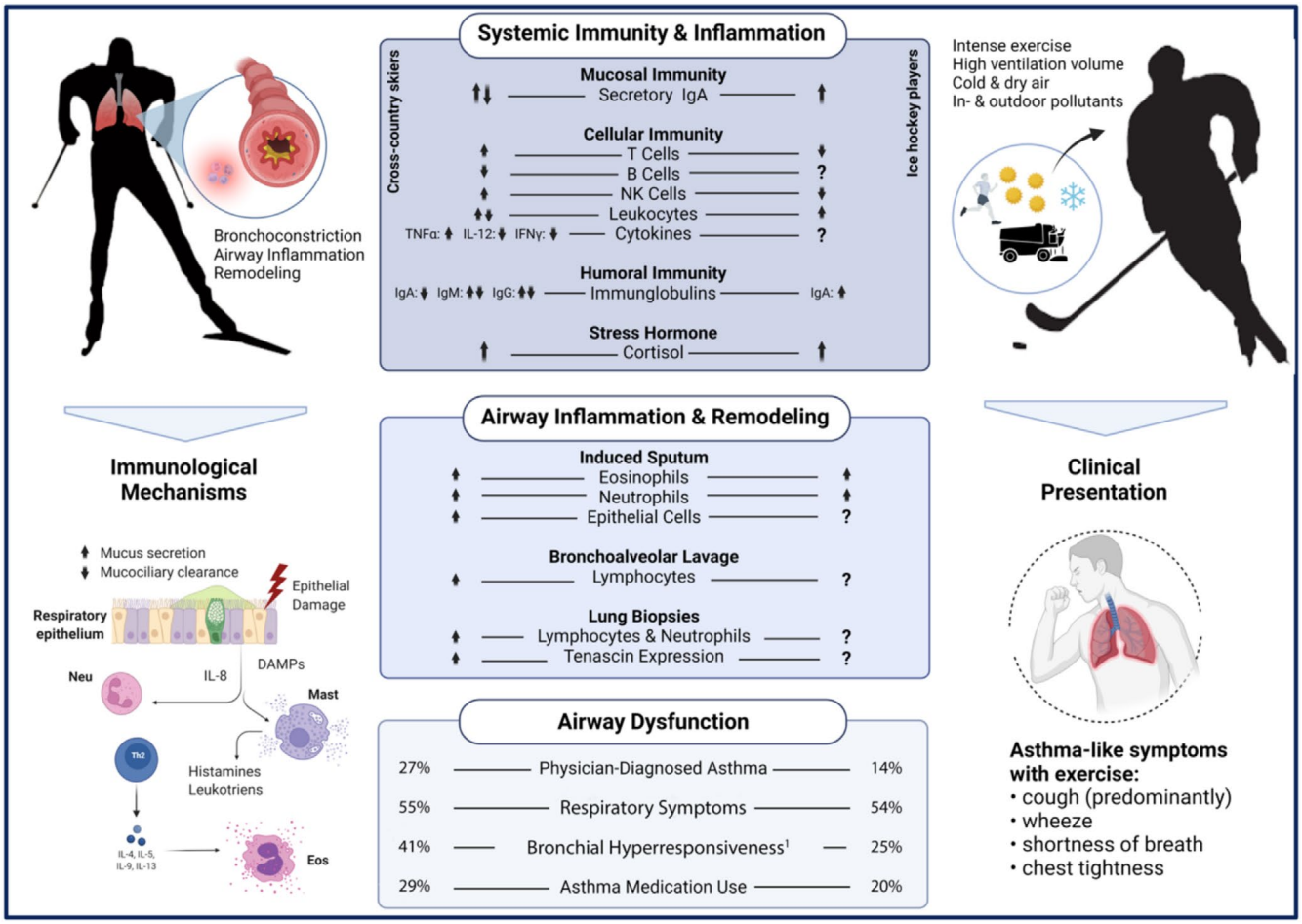

FIGURE 1 | Overall comparison of findings in cross-country skiers and ice hockey players. Elite winter athletes' airways are exposed to high volumes of cold, dry air during intense exercise, leading to bronchoconstriction and respiratory symptoms. Indoor and outdoor pollutants (e.g., pollen, carbon/nitrogen oxides, and particulate matter) further contribute to acute and chronic bronchial hyperresponsiveness and inflammation. Mechanisms include airway epithelial injury, alarmin release (DAMPs), cytokine secretion (e.g., IL-8), and immune cell activation. Triggers, mechanisms, and symptoms are shown separately for XC skiers and IH players for simplicity but apply to both groups. [1]Bronchial hyperresponsiveness assessed using methacholine, mannitol, or exercise provocation test. Eos, eosinophils; IFN-γ, interferon gamma; IgA/IgG/IgM, immunoglobulin A/G/M; IL, interleukin; mast, mast cells; Neu, neutrophils; NK, natural killer (cells); TNF-α, tumor necrosis factor-alpha. Figure created with BioRender.com; "Immunological Mechanisms" adapted from "Allergic Airway Inflammation," by BioRender.com (2021). Retrieved from www.app.biorender.com/biorender-templates.

tests) in elite XC skiers and IH players (Figure 1). The term "airway dysfunction" encompasses asthma and/or EIB and/or BHR throughout this SR, with specific findings highlighted as appropriate [10].

2 | Methods

This SR was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines [40, 41]. The SR protocol was included in the PROSPERO registry (Registration Number: CRD42022308854).

2.1 | Search Strategy and Selection Process

Figure 2 shows the study selection process. The literature search included original articles published up to July 11, 2024, that could be retrieved from MEDLINE/Ovid, EMBASE, and the Cochrane Library. A medical librarian applied a broad literature search approach to identify relevant publications based on the following search terms (applied in different combinations and using synonyms): "asthma" OR "bronchoconstriction" OR "hyperresponsiveness" OR "systemic inflammation" AND "sport" OR "athlete" OR "cross-country" OR "Olympic" OR "ice hockey". To ensure methodological consistency, only studies published after 1990 were included. Detailed search strategies and results are presented in File S1. Following initial study selection, references from selected publications were manually screened to identify additional studies that met the inclusion criteria. Duplicates were removed semi-automatically or by manual deduplication.

Screening of titles and abstracts was performed independently by four authors (E.J., D.J.M., M.V., and A.W.), applying the following inclusion criteria: participants were elite, that is, nationally

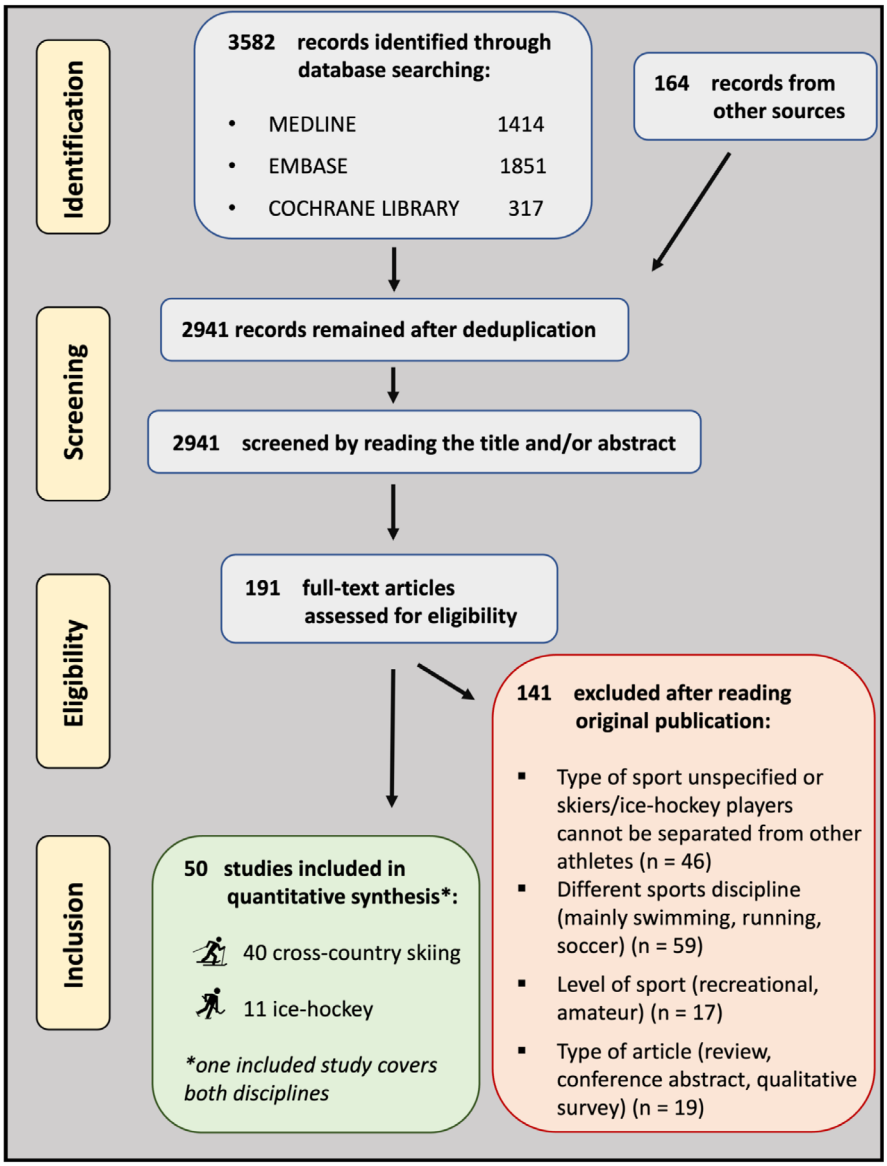

FIGURE 2 | Flowchart depicting the study selection process. Records were identified through searching in three different databases (MEDLINE, EMBASE, and Cochrane Library). Following initial screening, full texts were assessed for eligibility. Studies complying with the inclusion criteria were used for the qualitative and quantitative synthesis.

or internationally competitive IH players or XC skiers (including biathletes, Nordic combined athletes, or ski-orienteers), ensuring participants were engaged at a high-performance level. The included studies were original articles focusing on the immune system, systemic and local (airway) inflammation, and airway dysfunction in the English language. Study participants' mean age was required to be at least 16 years. Studies were excluded if the reported data were not in the format of an original full article (e.g., case reports, reviews, and conference abstracts), if the study included a heterogeneous sample of athletes where data for IH players and XC skiers could not be extracted separately, or if the study population was only recreationally active. No geographic restrictions were applied, although study locations indirectly influence environmental factors, such as air temperature and humidity. Disagreements regarding study inclusion or exclusion were discussed and resolved by third-party consensus.

2.2 | Data Extraction

From each selected study, we collected first author, year of publication, country, study design, population, characteristics of subjects, sports discipline, annual hours of training, test protocols, data on immune system markers, systemic and local (airway) inflammation, prevalence of physician-diagnosed asthma, prevalence of EIB/BHR (based on exercise challenge tests and provocation tests), and respiratory symptoms such as coughing, wheezing, shortness of breath, and chest tightness, and asthma medication usage. Data were independently extracted by three researchers (E.J., D.J.M., and M.V.) and reviewed reciprocally.

2.3 | Study Quality Assessment

The Cochrane Risk of Bias Tool was independently used by four authors (E.J., D.J.M., W.A., and M.V.) to assess risk of bias in all studies included in the review [42]. Risk of bias was rated as very high, high, moderate, low, or unclear. Ratings were discussed and agreed upon. Results of the risk of bias assessment can be found in File S2.

3 | Results

3.1 | Included Studies and Quality Characteristics

Included studies detailing population, location, and study design are summarized in Table 1. No studies were excluded based on the risk of bias assessment, as none were rated with a very high risk. Of the studies, 52% were considered low risk, 38% moderate risk, and 10% high risk. The studies categorized as high risk exhibited issues such as group heterogeneity, incomplete outcome data, and selective reporting. These limitations may have influenced the reported prevalence of airway dysfunction, particularly where data were missing or inconsistently measured. Such biases highlight the need for standardized methods and improved study designs to strengthen the reliability of findings. Results of this assessment are available in File S2. Fifty studies were included in this review: 39 on XC skiers (comprising 14 on biathletes, 5 on speed-skaters, and 3 on ski-orienteers), 10 including IH players, and 1 including both XC skiers and IH players. The designs included 2 randomized controlled trials, 41 observational cross-sectional studies, and 7 (prospective) longitudinal studies. Cohort sizes ranged from 10 to 351. Training volume was reported in 27 studies: IH players trained between 580 and 685 (mean: 632.5) hours per year, while XC skiers trained between 400 to 1191 (mean: 605.5) h/year (weekly training hours were multiplied by 52).

3.2 | Systemic Inflammation, Cellular, Humoral, and Mucosal Immunity in XC Skiers and IH Players

Table 2 summarizes the seven included studies on systemic inflammation and immune responses in XC skiers and IH players. CRP, a marker for systemic inflammation, did not increase in XC skiers following a 30-day training period or immediately after a long-distance race [7, 43]. Furthermore, CRP levels showed no association with performance progress in young XC skiers, did not differ between competitive and moderately trained skiers, and were not elevated in illness-prone IH players with three or more URTI episodes during the competitive season [3, 5, 44]. In contrast, serum cortisol levels increased immediately after a long-distance XC race in both females (1.5-fold) and males (2-fold) compared to pre-race level [43]. IH players also showed elevated serum cortisol during training camp, though saliva cortisol levels remained stable throughout the competitive season [3, 4].

For cellular immunity, total leukocyte counts—especially granulocytes and NK cells—were elevated in both female and male XC skiers immediately post-race [43]. Comparing immune cell counts between well-trained XC skiers and untrained controls in general, male XC skiers showed lower leukocyte and lymphocyte counts, with especially lower B cell counts during the off-season [45]. The CD4/CD8 T cell ratio was higher in well-trained XC skiers than in moderately trained or untrained controls, both during competitive and off-season periods [44, 45]. In IH players, T cells and NK cells decreased within 1 h post-training or post-game, whereas lymphocytes and dendritic cells (DCs) increased immediately after physical training [2, 46]. Pro-inflammatory TNF-α levels increased immediately after maximal exercise in XC skiers, though IL-1β remained unchanged [8]. At rest, IL-12 and IFN-γ were reported to be lower in competitive XC skiers compared to moderately trained XC skiers [44].

Regarding humoral immunity, resting immunoglobulin A (IgA) levels were lower in competitive XC skiers compared to non-aerobic sport athletes, moderately trained XC skiers, and untrained controls [44, 45, 47, 48]. IgM and IgG at rest were lower in competitive XC skiers compared to non-aerobic athletes (wrestlers) but were increased compared to boxers [47, 48].

Secretory IgA (sIgA), an important mediator in mucosal immunity, was measured in saliva upon waking and found to be either decreased in XC skiers both immediately and 2 weeks after a high-altitude training camp [49] or increased after 6 days of training [50]. In IH players, sIgA was higher in in-season soccer players compared to off-season soccer players [1] and both sIgA1 and sIgA2 were increased after a 13-day training camp [4]. No difference in sIgA during the competitive season was observed between healthy and illness-prone IH players [3].

TABLE 1 | Demographics of included studies.

Year	Author	Country	Study type	Study population (*n*)	Sex (*n*)	Age (mean ± SD or mean (range))	Training
1993	Larsson et al. [106]	Sweden	Cross-sectional	42 cross-country skiers	6 F: 36 M	24 (16–50)	406 h/year
1994	Heir [107]	Norway	Longitudinal	8 biathletes 14 cross-country skiers	22 M	20.1 (19–21)	N/A
1994	Heir and Oseid [19]	Norway	Cross-sectional	153 cross-country skiers	47 F:106 M	25.5 (20–38)	N/A
1994	Larsson et al. [108]	Sweden	Cross-sectional	299 cross-country skiers	127 F:172 M	18.5 ± 2.4	424 h/year
1995	Heir and Larsen [89]	Norway	Longitudinal	19 cross-country skiers	19 M	19–21	N/A
1996	Pottkämper et al. [46]	Germany	Cross-sectional	15 ice-hockey players	15 M	N/A	N/A
1996	Sue-Chu et al. [62]	Sweden/Norway	Cross-sectional	171 cross-country skiers (53 SWE/118 NOR)	SWE: 17 F:36 M NOR: 28 F:90 M	SWE: 18.4 ± 1.4 NOR: 17 ± 1.1	SWE: 428 h/year NOR: 400 h/year
1998	Leuppi et al. [61]	Switzerland	Cross-sectional, prospective	26 ice-hockey players	26 M	24 (18-35)	N/A
1998	Sue-Chu et al. [62]	Sweden/Norway	Cross-sectional	44 cross-country skiers	31 M:13 F	17.6 (16-22)	426 h/year
1999	Sashenkov [47]	Russia	Cross-sectional	201 cross-country skiers	201 M	N/A	N/A
1999	Sue-Chu et al. [57]	Norway	Cross-sectional	30 cross-country skiers	23 M:7 F	17.3 (16–20)	435 h/year
2000	Karjalainen et al. [109]	Finland, Norway, Estonia	Cross-sectional	40 cross-country skiers	8 F:32 M	17.5 (16–20)	434 h/year
2000	Langdeau et al. [59]	Canada	Cross-sectional	1 biathlete 13 cross-country skiers 13 speed-skaters	9 F:16 M	23.9 ± 1.7	1191 h/year[a]
2000	Sue-Chu et al. [109]	Norway	RCT	13 cross-country skiers[b]	4 F:9 M	18 (16–20)	468 h/year
2000	Wilber et al. [64]	USA	Cross-sectional, prospective	34 biathletes 14 cross-country skiers 26 ice-hockey players	N/A	N/A	N/A
2001	Mueller et al. [44]	Switzerland	Cross-sectional	10 competitive cross-country skiers	N/A	25.8 (18–42)	N/A
2002	Michalak et al. [110]	France	Cross-sectional	180 biathletes and cross-country skiers	bia/xc 59 F:121 M	18 ± 2	572 h/year[a]
2003	Lumme et al. [36]	Finland	Cross-sectional	88 ice-hockey players	88 M	18.1 ± 0.9	580 h/year
2004	Helenius et al. [55]	Finland	RCT	16 ice-hockey players	16 M	18 (1.0)	685 h/year

(Continues)

TABLE 1 | (Continued)

Year	Author	Country	Study type	Study population (*n*)	Sex (*n*)	Age (mean ± SD or mean (range))	Training
2004	Ronsen et al. [43]	Norway	Cross-sectional	16 cross-country skiers	6 F:10 M	F: 22–32 M: 23–32	N/A
2004	Rundell [63]	USA	Longitudinal	14 ice-hockey players	14 F	22.9 ± 3.0	N/A
2004	Rundell et al. [37]	USA	Cross-sectional	43 ice-hockey players	43 F	22.9 ± 3.6	N/A
2005	Pohjantähti et al. [65]	Finland	Cross-sectional	20 cross-country skiers	6 F:14 M	F: 22.9 ± 3.8 M: 23.7 ± 2.2	N/A
2005	Tiollier et al. [49]	France	Cross-sectional/ cohort study	7 biathletes 2 cross-country skiers 2 Nordic-combined skiers	6 F:5 M	20.6 ± 0.8 (sea-level training group) 23.2 ± 1.6 (high-altitude training group)	N/A
2007	Stensrud et al. [66]	Norway	Cross-sectional	24 cross-country skiers	8 F:16 M	25.7 ± 4.1	N/A
2009	Bougault et al. [23]	Canada	Cross-sectional	5 biathletes 16 cross-country skiers 11 speed skaters	6 F:14 M	19 ± 2	832 h/year[a]
2010	Bougault et al. [58]	Canada	Cross-sectional	7 biathletes 22 cross-country skiers 16 speed-skaters	19 F:26 M	22 ± 2	780 h/year[a]
2010	Stenfors [88]	Sweden	Cross-sectional	46 cross-country skiers	22 F:24 M	21 (19–31)	593 h/year
2010	Suchanek et al. [2]	Czech Republic	Cross-sectional	18 ice-hockey players	18 M	N/A	N/A
2010	Sue-Chu et al. [51]	Norway	Cross-sectional	58 cross-country skiers	22 F:36 M	18.1 ± 1.7	426 h/year
2012	Turmel et al. [111]	Canada	Cross-sectional	10 biathletes 34 cross-country skiers	bia 5 F:5 M xc 10 F:24 M	19 ± 2 18 ± 2	Biathletes: 780 h/year[a] Cross-country skiers: 624 h/year[a]
2012	Turmel et al. [54]	Canada	Longitudinal	25 cross-country skiers 9 biathletes 19 speed-skaters	19 F:34 M	19 ± 3	780 h/year
2015	Norqvist et al. [83]	Sweden	Cross-sectional, prospective	Group 1: 166 skiers[c] Group 2: 72 skiers[d]	Group 1: 80 F:86 Group 2: 34 F:38 M	Group 1: 15–19 Group 2: 20–34	Group 1: 520 h/year[a] Group 2: 780 h/year[a]
2015	Zebrowska et al. [8]	Poland	Cross-sectional	12 biathletes and cross-country skiers	12 F	22.3 ± 2.1	N/A
2016	Born et al. [50]	Sweden	Cross-sectional/ cohort study	2 biathletes 15 cross-country skiers	6 F:12 M	F: 24 ± 5 M: 30 ± 9	N/A

(Continues)

TABLE 1 | (Continued)

Year	Author	Country	Study type	Study population (*n*)	Sex (*n*)	Age (mean ± SD or mean (range))	Training
2016	Kennedy et al. [22]	Canada	Prospective longitudinal	18 cross-country skiers	18 F	25 ± 9	528 h/year
2017	Kuchin et al. [45]	Russia	Cross-sectional	22 cross-country skiers	10 F:12 M	19–22	N/A
2017	Lamb et al. [1]	USA	Cross-sectional	10 ice-hockey players	10 F	18–20	N/A
2017	Orysiak [3]	Poland	Cross-sectional	27 ice-hockey players	27 M	16.5 ± 0.5	N/A
2018	Eriksson et al. [17]	Sweden	Cross-sectional	49 biathletes 171 cross-country skiers 24 ski-orienteers	117 F:127 M	17.6 ± 1.1	520 h/year[a]
2018	Melnikov et al. [48]	Russia	Cross-sectional	33 cross-country skiers	N/A	N/A	N/A
2018	Stang et al. [53]	Norway	Cross-sectional	20 asthmatic athletes[e] 19 healthy athletes[e]	Asthmatics: 7 F:13 M Healthy: 5 F:14 M	Asthmatics: 20.3 ± 2 Healthy: 18.6 ± 1	Asthmatics: 946 h/year[a] Healthy: 962 h/year[a]
2019	Blume & Wolfrath [5]	Germany	Controlled, prospective, longitudinal cohort study	77 cross-country skiers	40 F:37 M	F: 16.1 ± 1.4 M: 15.7 ± 1.2	F: 608 h/year[a] M: 551 h/year[a]
2019	Orysiak [4]	Poland	Cross-sectional	12 ice-hockey players	12 M	17.7 ± 0.5	N/A
2020	Irewall et al. [60]	Sweden	Prospective	81 biathletes 279 cross-country skiers 47 ski-orienteers	279 F:312 M	17 (16–20)	520 h/year[a]
2020	Perrone et al. [7]	Italy	Cross-sectional/ cohort study	20 cross-country skiers (10 international, 10 national)	20 M	International: 26.5 ± 3.2 National: 28.1 ± 2.8	International: ±700 h/year National: ±460 h/year
2021 2023a 2023b[f]	Mäki-Heikkilä et al. [87, 112, 113]	Finland	Cross-sectional	351 cross-country skiers	204F:147 M	18.8 ± 6.1	F: 520 h/year[a] M: 551 h/year[a]
2023	Bernhardsen et al. [52]	Norway	Cross-sectional	32 cross-country skiers	N/A	Cross-country 26.2 ± 4.7	N/A

Note: Gray highlighted parts: Ice-hockey specific.
[a]Training hours originally reported as "per week"; value was multiplied by 52 to assess training hours per year.
[b]Only the placebo group of this RCT was included for our analysis.
[c]Group 1 included adolescent athletes aged 15–19 years; "skiers" include cross-country skiers, biathletes, and ski-orienteers.
[d]Group 2 included athletes aged 20–34 years; "skiers" include cross-country skiers, biathletes, and ski-orienteers.
[e]Athletes include both cross-country skiers (10 asthmatics and 9 healthy) and swimmers; specific data other than demographics could be extracted separately for skiers.
[f]All three papers were based on the same population.

3.3 | Airway Inflammation in XC Skiers and IH Players

Table 3 summarizes all 13 studies that assessed airway inflammation in elite XC skiers and IH players. The assessments were performed either noninvasively by measurement of F_ENO ($n = 4$ studies) and/or examination of induced sputum ($n = 6$ studies) or invasively by bronchial biopsy or bronchoalveolar lavage (BAL) ($n = 3$ studies).

No difference in resting F_ENO levels was observed between healthy XC skiers and healthy non-athletes, nor between XC skiers with and without ski asthma or BHR [8, 51–53].

Four studies examined induced sputum in skiers at rest [22, 23, 53, 54]. Overall, they fail to show a common finding: while one study found a high degree of epithelial cell shedding (reflected in the percentage of bronchial epithelial cells in sputum) [23], another reported no difference between athletes and non-athletes [53]. In one study, sputum eosinophils and lymphocytes were found to be significantly increased during the XC skiing competitive season (winter) compared to spring [22], while other studies found no or only minimal [23] airway inflammation in cold air athletes. Sputum IL-8 was higher in athletes compared to non-athletes, and sputum neutrophils correlated with IL-1β and IL-8 [53].

Two studies including IH players assessed airway inflammation by induced sputum analysis at rest [36, 55]: one only included athletes with respiratory symptoms and found they had a mixed type of eosinophilic and neutrophilic airway inflammation [55]. Similarly, the other study showed that IH players had significantly higher eosinophil and neutrophil numbers compared to control subjects, while there was no difference between symptomatic and asymptomatic athletes or between athletes with and without BHR [36].

Three studies used invasive methods to assess airway inflammation in XC skiers with or without asthma [38, 56, 57]. Generally, skiers exhibited higher numbers of lymphocytes and inflammatory cells in BAL fluid or bronchial mucosa compared to controls, with many displaying respiratory symptoms and/or BHR [57]. Non-asthmatic skiers showed increased lymphocyte counts compared to controls and higher neutrophil counts versus asthmatic non-athletes [38]. Additionally, increased expression of tenascin was observed in the bronchial basement membrane of non-asthmatic skiers [38].

3.4 | Prevalence of Physician-Diagnosed Asthma in XC Skiers and IH Players

Table 4 shows studies reporting the prevalence of physician-diagnosed asthma in the examined athlete groups. Nineteen of the studies assessed the self-reported prevalence of physician-diagnosed asthma in skiers using questionnaires. Asthma prevalence ranged from 0% to 52% in skiers, with a mean of 27%, including studies with speed-skaters [23, 54, 58, 59] and ski-orienteers [17, 60]. Mean prevalence was lower in studies before 2010 (22%, $n = 8$) than after 2010 (30%, $n = 11$). Among IH players, only two studies reported physician-diagnosed asthma, with prevalences of 19% [61] and 9% [36], resulting in a mean prevalence of 14%.

3.5 | Respiratory Symptoms in XC Skiers and IH Players

Twenty-two studies (Table 4) assessed the prevalence of respiratory symptoms in winter athletes using questionnaires. Nine studies that investigated the occurrence of such symptoms, including wheezing, shortness of breath, coughing, and chest tightness in general, found their prevalence to range from 16% to 86% (mean 55%) among elite skiers (including biathletes, XC skiers, and ski-orienteers). The most prevalent symptom in skiers was exercise-induced cough, ranging from 9% to 76%, with a mean of 48%. A study that compared elite skiers from Sweden and Norway found the prevalence of cough with exercise in winter to be 64% in Swedish and 42% in Norwegian athletes, while other respiratory symptoms occurred at similar rates [62]. Three studies assessed the prevalence of any respiratory symptom in a population of IH players, finding that 54% (range 40%–71%) experienced symptoms [36, 55, 63]. While reports on respiratory symptoms in IH players are scarce, the available data suggest that, like skiers, cough (mean 49%) is the most prevalent symptom [37, 63]. Overall, single respiratory symptoms were comparable between skiers and IH players (wheeze: mean 35% vs. 20%; coughing: mean 48% vs. 49%; chest tightness: mean 35% vs. 35% in XC skiers and IH players, respectively).

3.6 | Prevalence of EIB and BHR in XC Skiers and IH Players

In the referenced studies, BHR was assessed using direct provocation methods (methacholine, histamine, and adenosine monophosphate [AMP]) or indirect methods (EVH and mannitol), as well as through exercise challenge tests to evaluate EIB. Table 4 lists 14 studies assessing EIB and/or BHR in XC skiers, reporting a mean prevalence of 41% (range: 0%–80%). Four studies used exercise tests, finding a mean EIB prevalence of 23% [51, 64–66]. One study found a higher incidence of EIB in female XC skiers (57%) compared to male athletes (43%) [64]. BHR assessed via methacholine provocation tests showed a higher prevalence in XC skiers (mean 45%). Interestingly, one study found a considerable difference in EIB prevalence between Norwegian and Swedish XC skiers; while only 14% of the Norwegian cohort were EIB positive, 43% of Swedish skiers living and training in a significantly lower outdoor temperature showed EIB [62].

Four studies assessed EIB and/or BHR in IH players, reporting a mean prevalence of 25% (range: 15%–29%). Three studies on IH players found a mean EIB prevalence of 22%, using exercise tests [37, 63, 64], while one study using methacholine provocation reported a higher BHR prevalence of 35% [61].

3.7 | Asthma Medication Use in XC Skiers and IH Players

Asthma medication use among XC skiers was evaluated through questionnaires and reported in 20 studies (Table 4). On average,

TABLE 2 | Systemic inflammation, cellular, humoral, and mucosal immunity in XC skiers and IH players.

Year	Author, country	Main findings regarding systemic inflammation	Training characteristics	Sample timing	Sample fluid
2001	Mueller et al. [44], Switzerland	↔ **CRP levels** in healthy competitive and healthy moderately trained XC skiers	2 months during the competitive season	At the start, in the middle, and at the end of the 2-month period (between 7 and 8 a.m.)	Blood
2004	Ronsen et al. [43], Norway	↔ **CRP levels** but ↑ **cortisol levels** in females (1.5× increase) and males (2× increase) compared to pre-race levels	World Cup 50-km M and 30-km F XC ski race	60 min before (prior to warm up) and within 1 min of race completion	Blood
2005	Tiollier et al. [49], France	↔ **Saliva cortisol levels** over an 18-day training camp period of elite XC skiers and 2 weeks after the training camp in both control and high-altitude groups	18-day training camp (with high endurance training load) followed by a 2-week period of active recovery. High-altitude group was in hypoxic rooms (2 h during the afternoon and 9 h during nighttime)	Before the training camp, after each 6-day stage (2500, 3000 and 3500 m) and after a 2-week period of active recovery (between 7 and 8 a.m.)	Saliva
2017	Orysiak et al. [3], Poland	↔ **CRP and saliva cortisol levels** between healthy and illness-prone (≥ 3 episodes of URTI) high school IH players	21-week competitive season	Eight times every 3–4 weeks for 21 weeks (between 7 and 9 a.m., > 12 h after the last training)	Blood (CRP) and saliva (cortisol)
2019	Blume and Wolfarth [5], Germany	**No correlation** between **CRP levels** and performance progress of young XC skiers	1-year competitive season with 10.6 training h/week	Initial sampling in June, second sampling 1 year after	Blood
2019	Orysiak et al. [4], Poland	↑ **Cortisol** at Day 9 of a 17-day training camp of healthy IH players **but return** to baseline levels at Day 13	17-day period of a training camp (days 1–8 high loads, days 9–17 progressive reduction of loads)	Start of training camp (after 1 day of rest), on the ninth day and on the 13th day of the training camp	Blood
2020	Perrone et al. [7], Italy	↔ **CRP levels** in national XC skiers before and after a 30-day training load period	30 days of intense training	At days 0 and 0 (in the morning at rest)	Blood

(Continues)

TABLE 2 | (Continued)

Year	Author, country	Main findings regarding cellular immunity	Training characteristics	Sample timing	Sample fluid
1996	Pottkämper et al. [46], Germany	↓ **Counts of pan T cells, suppressor/cytotoxic T and NK cells** and **activities (HLA/DR-positive T cells) of peripheral blood lymphocytes** after a training session or match in professional IH players compared to a relaxation period	Intensive sport activity (a training session or match in professional IH players)	After 48 h without training and within 1 h after training or match	Blood
2001	Mueller et al. [44], Switzerland	↑ **Ratios of CD16/CD3** and **CD4/CD8** in healthy competitive XC skiers compared to healthy moderately trained XC skiers during 2 months of competitive season. ↓ **Inducible IL-12 and IFN-γ levels** in healthy competitive XC skiers during 2 months of competitive season	2 months during competitive season	At the start, in the middle, and at the end of the 2-month period (between 7 and 8 a.m.)	Blood
2004	Ronsen et al. [43], Norway	↑ **Total leukocytes count** with a 5× increase in granulocytes in both female and male XC skiers after a ski race compared to pre-race levels. ↑ **NK cells** in females (2× increase) and males (1.5) compared to pre-race levels	World Cup 50-km M and 30-km F XC ski race	60 min before (prior to warm up) and within 1 min of race completion	Blood
2010	Suchanek et al. [2], Czech Republic	↑ **Leukocyte numbers**, with a predominance of the DC and lymphocyte population, after physical load in professional healthy IH players. ↑ **Myeloid and plasmacytoid DCs** after physical load	Intensive 60 min training session on ice (winter, prior to play-off season)	Before the start of training (after 15 min of rest) and immediately (< 1 min) after the end of the training session	Blood
2015	Zebrowska et al. [8], Poland	↑ **tnf-α levels** after exercise and remained elevated after 15 min of recovery in elite female XC skiers. ↔ **IL-1β levels** after exercise compared to rest levels but were ↑ **after a 15-min recovery** in elite female XC skiers	Graded exercise test until exhaustion. Prior to the study, 6 weeks of training in cold or hypobaric hypoxic conditions were conducted	In the morning at rest (between 8:00 and 9:00 a.m.), immediately after exercise and after 15 min of post-exercise recovery	Blood
2017	Kuchin et al. [45], Russia	↓ **Leukocyte and lymphocyte count** in male XC skiers compared to non-athletic male controls. ↑ **CD4/CD8 ratio** in female XC skiers compared to non-athletic female controls. ↓ **B cell numbers ($CD3^-$ $CD19^+$)** in male XC skiers compared to non-athletic male controls		In June and May comparing non-athletic controls to XC skiers (one time sampling)	Blood

(Continues)

TABLE 2 | (Continued)

Year	Author, country	Main findings regarding humoral immunity	Training characteristics	Sample timing	Sample fluid
1999	Sashenkov et al. [47], Russia	↓ **iga, igm and igg levels** in XC skiers, compared to non-aerobic sport athletes		In autumn-winter comparing non-aerobic controls (wrestlers) to XC skiers during 2–3-day rest from training and competitions (one time sampling)	Blood
2001	Mueller et al. [44], Switzerland	↓ **iga/igm ratio** in healthy competitive XC skiers compared to healthy moderately trained XC skiers during 2 months of competitive season	2 months during competitive season	At the start, in the middle, and at the end of the 2 months period (between 7 and 8 a.m.)	Blood
2017	Kuchin et al. [45], Russia	↓ **Serum iga levels** in female and male XC skiers from the middle Ob region (Russia) compared to non-athletic controls		In June and May comparing non-athletic controls to XC skiers (one time sampling)	Blood
2018	Melnikov et al. [48], Russia	↓ **Serum iga levels** in XC skiers, compared to acyclic-sport athletes. ↑ **igm and igg levels** of XC skiers compared to boxers		During the wintertime (one time sampling) with no training and competitive loads comparing XC skiers to acyclic-sport athletes (wrestlers and boxers)	Blood

Year	Author, country	Main findings regarding mucosal immunity	Training characteristics	Sample timing	Sample fluid
2005	Tiollier et al. [49], France	↓ **siga** in elite XC skiers over an 18-day training camp period on high altitude	18-day training camp (with high endurance training load) followed by a 2-week period of active recovery. High-altitude group was in hypoxic rooms (2 h during the afternoon and 9 h during nighttime)	Before the training camp, after each 6-day stage (2500, 3000, and 3500 m) and after a 2-week period of active recovery (between 7 and 8 a.m.)	Saliva
2016	Born et al. [50], Sweden	↑ **Secretion of siga** in XC skiers after 6 days of training compared to 1 day after training in the case of repeated sprint training in hypoxia but not in normoxia	2 weeks with a total of 6 days of training (repeated sprinting on a double-poling ergometer) in either normobaric hypoxia or normoxia	First sample after normal aerobic training, on the sixth day of training, and > 3 days after the final session (immediately after waking up)	Saliva

(Continues)

TABLE 2 | (Continued)

Year	Author, country	Main findings regarding mucosal immunity	Training characteristics	Sample timing	Sample fluid
2017	Lamb et al. [1], USA	↑ **Salivary iga/total protein ratio** in "in-season" IH players compared to "off-season" soccer players		In the IH hockey competitive season (e.g., winter) comparing IH players to off-season soccer players. All sampling took place between 2 and 6 p.m. on the same day (one time sampling). IH players did not compete 2 days prior to study	Saliva
2017	Orysiak et al. [3], Poland	↔ **siga** between healthy and illness-prone young IH players (≥ 3 episodes of URTI) during the 24-week competitive season	21-week competitive season	Eight times every 3–4 weeks for 21 weeks (between 7 and 9 a.m. and > 12 h after the last training)	Blood (CRP) and saliva (cortisol)
2019	Orysiak et al. [4], Poland	↑ **siga1 and siga2** in IH players on Day 13 of a training camp compared to Day 1 (iga1) and Day 9 (iga1 and iga2) sampling	17-day period of a training camp (Days 1–8 high loads, Days 9–17 progressive reduction of loads)	Start of training camp (after 1 day of rest), on the ninth day and on the 13th day of the training camp	Saliva

Note: Gray highlighted parts: Ice-hockey specific.

Abbreviations: ↑, increase; ↓, decrease; ↔, unchanged/no difference; CD, cluster of differentiation; CRP, C-reactive protein; DC, dendritic cells; HLA/DR, human leukocyte antigen/antigen D-related; IFN-γ, interferon-gamma; IgA, immunoglobulin A; IgG, immunoglobulin G; IgM, immunoglobulin M; IH, ice hockey; IL, interleukin; N/A, not applicable; NK, natural killer; sIgA, secretory immunoglobulin A; sIgA1, secretory immunoglobulin A1; sIgA2, secretory immunoglobulin A2; TNF-α, tumor necrosis factor-alpha; URTI, upper respiratory tract infections; XC, cross-country.

TABLE 3 | Airway inflammation in XC skiers and IH players.

Non-Invasive

Year	Author, country	Main findings from measurements of F_ENO at rest
2010	Sue-Chu et al. [51], Norway	No significant difference of F_ENO between XC skiers with and without bronchial hyperresponsiveness to methacholine (resting F_ENO: median 7.3 vs. 6.5 ppb)
2015	Zebrowska et al. [8], Poland	F_ENO values within normal range in all female XC skiers (< 25 ppb)
2018	Stang et al. [53], Norway[a]	**XC skiers exhibited increased F_ENO (21.7 ppb) compared to swimmers (15.1 ppb)**. Athletes with asthma had significantly higher F_ENO levels than non-athletes (21.3 vs. 13.6 ppb)[a] but did not differ significantly from healthy athletes[a] (21.3 vs. 15.5 ppb). No significant difference was found between atopic (19.5 ppb) and non-atopic subjects (15.0 ppb)[b]
2023	Bernhardsen et al. [52], Norway	Mean FENO levels were within normal reference values across all sports (14.4–22.6 ppb). **XC skiers had a mean FENO of 22.6 ppb**. Among XC skiers, speed skaters, and rowers/paddlers, the confidence intervals for mean F_ENO measurements were wide

Year	Author, country	Main findings from induced sputum
2003	Lumme et al. [36], Finland[c]	**Significantly higher sputum eosinophil and neutrophil count** in ice-hockey players compared to control subjects; sputum eosinophilia (> 2%) in 15% of the athletes (control subjects: 0%). Similar sputum eosinophil and neutrophil counts in symptomatic and symptom-free ice-hockey players, those with and without BHR, and atopic and non-atopic athletes.
2004	Helenius et al. [55], Finland	Sputum eosinophilia in 3 (19%) ice-hockey players with respiratory symptoms at baseline. Overall, a **mixed type of neutrophilic and eosinophilic airway inflammation** was observed. No effect of montelukast (10 mg orally over 4 weeks) on eosinophil or neutrophil sputum cell count
2009	Bougault et al. [23], Canada[c,d]	Minimal or no airway inflammation in cold air (CA) athletes (except for those with BHR: slight increase in eosinophil count). **High bronchial epithelial cell count**, indicating persistent epithelial cell shedding (less in CA athletes vs. swimmers)
2012	Turmel et al. [54], Canada[c,e]	Sputum eosinophils and neutrophils within the normal range. No correlation between cough reflex sensitivity and sputum cell counts

(Continues)

TABLE 3 | (Continued)

Year	Author, country	Main findings from induced sputum
2016	Kennedy et al. [22], Canada[c,f]	**From the start of training in spring to the peak XC competitive season, sputum eosinophils and lymphocytes significantly increased**. Total yearly training time correlated with changes in total cell count, neutrophil percentage and absolute count, as well as absolute macrophage count
2018	Stang et al. [53], Norway[c]	**Higher sputum IL-8 in athletes** compared to non-athletes. **Correlation of IL-1β and IL-8 with sputum neutrophils**. No significant differences between the groups (healthy and asthmatic swimmers, XCskiers, and non-athletes) regarding bronchial epithelial and total sputum cell count. No correlations between weekly exercise (h) or years of sport participation and sputum neutrophils or epithelial cells. No differences regarding leukocytes between subjects with and without BHR. Nonatopic subjects showed similar cell counts as atopic subjects

Year	Author, country	Main findings from bronchial biopsies	Main finding from bronchoscopy or BAL
1998	Sue-Chu et al. [56], Norway	In 64% of XC skiers vs. 25% of control, **lymphoid aggregates** (of > 50 cells) were identified.	N/A
1999	Sue-Chu et al. [57], Norway[g]	N/A	Bronchoscopy: **Mild-to-moderate macroscopic inflammation of proximal airways** in XC skiers. Higher macroscopic inflammatory index in XC skiers vs. controls (3.1 vs. 1.3, $p = 0.008$). BAL: **More lymphocytes (%) and less macrophages (%) in "ski asthma"** subjects vs. healthy controls. **Higher level of TNF-α and MPO in skier BAL fluid**. No increase in fibroblastic activity (fibronectin and hyaluron levels comparable)
2000	Karjalainen et al. [38], Finland/Norway/Estonia[h,i]	**Higher numbers of T-lymphocytes, eosinophils and macrophages in XC skiers** vs. controls. Lower eosinophil, macrophages, and mast cell numbers in non-asthmatic XC skiers vs. asthmatic subjects. Higher counts of neutrophils in non-asthmatic XC skiers vs. asthmatic subjects. **Increased tenascin expression in bronchial basement membrane of non-asthmatic skiers**, which could indicate an association to airway remodeling.	N/A

Note: Gray highlighted parts: Ice-hockey specific.
Abbreviations: BAL, bronchioalveolar lavage; CA, cold air; F_ENO, fractional exhaled nitric oxide; IL, interleukin; MPO, myeloperoxidase; N/A, not applicable; ppb, parts per billion; TNF-α, tumor necrosis factor–alpha.
[a]Including swimmers.
[b]Including swimmers and nonathletes.
[c]No exercise > 12 h prior to examination.
[d]Cold-air group: including speed-skating, measurements done in autumn.
[e]Including speed-skating.
[f]Measurements taken from T1 (May–June) and T3 (January–March).
[g]The procedure was performed in late autumn for skiers and in late autumn and winter for controls. Skiers were in daily training for the competitive season but refrained from training on the day of bronchoscopy.
[h]Competitive skiers without prior diagnosis of asthma.
[i]Bronchoscopy in the autumn, at the peak of the preseason training program.

TABLE 4 | Prevalence of physician-diagnosed asthma, EIB prevalence, (exercise-induced) respiratory symptoms, and asthma medication in XC skiers and IH players.

Year	Author, country	Physician-diagnosed asthma, *n* (%)	EIB[†]/BHR[‡] prevalence, *n* (%)	(Exercise-induced) respiratory symptoms					Asthma medication, *n* (%)
				Any (at least one symptom)	Wheeze, *n* (%)	Shortness of breath, *n* (%)	Cough, *n* (%)	Chest tightness, *n* (%)	
1993	Larsson et al. [106], Sweden	13 (31%)	N/A	32 (76%)	32 (76%)	17 (40%)	27 (64%)	24 (57%)	15 (36%) *13 B2agonist,* *13 steroids,* *2 sodium cromoglycate*
1994	Larsson et al. [108], Sweden	45 (15%)	N/A	117 (39%) w/exercise	54 (18%)	72 (24%)[a]	N/A	N/A	55 (18%)
1994	Heir [107], Norway	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2 (11%) *2 B2agonist*
1994	Heir and Oseid [19], Norway	22 (14%)	N/A	131 (86%) w/exercise	11 (7%)[b] 39 (25%)[c] w/exercise	10 (7%)[b] 47 (31%)[c] w/exercise	25 (16%)[b] 85 (56%)[c] w/exercise	13 (8%)[b] 45 (29%)[c] w/exercise	34 (22%) *32 B2agonist* *10 Sodium cromoglycate* *14 Steroid inhalation* *17 Anticholinergic* *1 Theophylline* *1 Prednisolone*
1995	Heir and Larsen [89], Norway	None	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1996	Sue-Chu et al. [62], Sweden/Norway	NOR: 10%, SWE: 26%	NOR: 14%[‡,d] SWE: 43%[‡,d]	NOR: 46% SWE: 51%	NOR: 53 (45%) SWE: 25 (47%)	NOR: 35 (30%), w/exercise SWE: 14 (26%), w/exercise	NOR: 50 (42%), w/ exercise in winter SWE: 34 (64%), w/ exercise in winter	NOR: 46 (39%), w/exercise SWE: 20 (38%), w/exercise	NOR: 16%, SWE: 38%
1998	Leuppi et al. [61], Switzerland	5 (19%)	9 (35%)[‡,e]	N/A	N/A	N/A	N/A	N/A	4 (15%) *4 B2agonists,* *0 ICS*
1998	Sue-Chu et al. [56], Sweden/Norway	N/A	35 (80%)[‡,d]	26 (59%) (W, SOB, CT)	N/A	N/A	N/A	N/A	11 (25%) *(only B2agonist reported)*

(Continues)

TABLE 4 | (Continued)

Year	Author, country	Physician-diagnosed asthma, *n* (%)	EIB[†]/BHR[‡] prevalence, *n* (%)	(Exercise-induced) respiratory symptoms					Asthma medication, *n* (%)
				Any (at least one symptom)	Wheeze, *n* (%)	Shortness of breath, *n* (%)	Cough, *n* (%)	Chest tightness, *n* (%)	
1999	Sue-Chu et al. [57], Norway	N/A	19 (63%)[‡,d]	12 (40%) (W, SOB, CT)	N/A	N/A	N/A	N/A	N/A
2000	Karjalainen [38], Finland	None	30 (75%)[‡,d]	26 (65%)	N/A	N/A	N/A	N/A	6 (15%) *6 B2agonist, 0 theophylline*
2000	Langdeau [59], Canada	CA[f]: 7 (28%)	18 (72%)[‡,g]	19 (76%), w/exercise	12 (48%) (W, SOB, CT)	12 (48%) (W, SOB, CT)	19 (76%), w/exercise	12 (48%) (W, SOB, CT)	6 (24%) *3 B2agonist 1 ICS 2 SABA + ICS*
2000	Wilber et al. [64], USA	N/A	xc: F 57%[†,h] M 43%[†,h] bia: F/M 0 (0%)[†,h] ih: F 4 (15%)[†,h]	N/A	N/A	N/A	N/A	N/A	N/A
2002	Michalak et al. [110], France	xc/bia: 14 (8%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2003	Lumme et al. [36], Finland	8 (9%)	21 (24%)[i]	46 (52%)	N/A	N/A	N/A	N/A	5 (6%)[j] *3 B2agonists, 2 ICS*
2004	Helenius et al. [55], Finland	N/A	N/A	16 (100%)[k]	N/A	N/A	N/A	N/A	N/A
2004	Rundell [63], USA	N/A	4 (29%)[†,h]	10 (71%), w/exercise	3 (21%), w/exercise	N/A	9 (64%) w/exercise	6 (43%) w/exercise	4 (29%) *1 sodium cromoglycate 1 sodium cromoglycate + ICA + montelukast 1 B2agonists 1 ICS*

(Continues)

TABLE 4 | (Continued)

Year	Author, country	Physician-diagnosed asthma, *n* (%)	EIB[†]/BHR[‡] prevalence, *n* (%)	(Exercise-induced) respiratory symptoms					Asthma medication, *n* (%)
				Any (at least one symptom)	Wheeze, *n* (%)	Shortness of breath, *n* (%)	Cough, *n* (%)	Chest tightness, *n* (%)	
2004	Rundell et al. [37], USA	N/A	9 (21%)[†,h]	17 (40%), w/exercise	8 (19%), w/exercise	N/A	14 (33%), w/exercise	11 (26%) w/exercise	13 (30%) *2 LABA + SABA + ICS + Montelukast + sodium cromoglycate* *10 B2agonists* *1 ICS*
2005	Pohjantähti et al. [65], Finland	10 (42%)	2 (10%)[†,h]	N/A	N/A	N/A	N/A	N/A	N/A
2007	Stensrud et al. [66], Norway	9 (38%)	9 (38%)[‡,l] 2 (8.3%)[†,h]	N/A	N/A	N/A	N/A	N/A	8 (33%) *3 ICS + LABA*, *2 ICS + LABA + LTA*, *1 ICS + LTA*, *2 LTA alone*
2009	Bougault et al. [23], Canada	CA[f]: 6 (19%)	9 (28%)[‡,g]	20 (63%) w/exercise	N/A	N/A	N/A	N/A	9 (28%)[j] *6 B2agonist*, *3 ICS*
2010	Bougault et al. [58], Canada	CA[f]: 13 (29%)	8 (18%)[‡,m]	N/A	15 (33%), w/exercise	N/A	29 (64%), w/exercise	13 (29%), w/exercise	16 (36%)[j] *10 B2agonist*, *6 ICS*
2010	Sue-Chu et al. [51], Norway	10 (17%)	**Total: 25 (43%)** 3 (9%)[n] 23 (40%)[‡,o] 3 (5%)[p] 5 (8%)[q] 6 (18%)[†,h]	26 (45%) (W, SOB, CT)	N/A	N/A	N/A	N/A	17 (47%)[j] *11 B2agonist*, *6 ICS*
2010	Stenfors [88], Sweden	24 (52%)	**Total: 8 (17%)** 6 (13%)[n] 2 (4%)[‡,r] 3 (7%)[p]	N/A	17 (37%), anytime	2 (4%), at rest 8 (17%), w/exercise	N/A	N/A	17 (37%)

(Continues)

TABLE 4 | (Continued)

Year	Author, country	Physician-diagnosed asthma, *n* (%)	EIB[†]/BHR[‡] prevalence, *n* (%)	(Exercise-induced) respiratory symptoms					Asthma medication, *n* (%)
				Any (at least one symptom)	Wheeze, *n* (%)	Shortness of breath, *n* (%)	Cough, *n* (%)	Chest tightness, *n* (%)	
2012	Turmel et al. [111], Canada	xc: 7 (35%) bia: 1 (10%)	**Total:** **xc: 10 (50%)** **bia: 6 (60%)** xc: 7 (21%)[n] bia: 6 (60%)[n] xc: 5 (25%)[‡,g] bia: 4 (40%)[‡,g]	xc: 14 (41%) bia: 8 (80%) (W, CT, C), w/exercise	N/A	N/A	N/A	N/A	N/A
2012	Turmel et al. [54], Canada	N/A	N/A	N/A	N/A	N/A	CA[f]: Summer: 9% Fall: 18% Winter: 18% w/exercise	N/A	N/A
2015	Norqvist [83], Sweden	48 (29%)[s] 25 (35%)[t]	N/A	32 (20%)[s] 19 (26%)[t]	44 (27%)[s,u] 24 (33%)[t,u]	27 (17%)[s] w/exercise 7 (19%)[t] w/exercise	N/A	N/A	42 (25%)[s] 20 (28%)[t]
2016	Kennedy et al. [22], Canada	2 (11%)	N/A	N/A	N/A	N/A	N/A	N/A	4 (22%) *2 Montelukast* *2 ICS*
2018	Eriksson [17], Sweden	65 (27%)	N/A	37 (16%)	N/A	N/A	N/A	N/A	53 (22%)
2020	Irewall et al. [60], Sweden	98 (24%)	N/A	N/A	73 (18%)	59 (12%), w/exercise	N/A	N/A	110 (19%)[v]
2021	Mäki-Heikkilä et al. [112], Finland	91 (26%)	N/A	N/A	N/A	N/A	N/A	N/A	123 (35%) *38 ICS* *43 ICS + LABA* *73 SABA*

(Continues)

TABLE 4 | (Continued)

Year	Author, country	Physician-diagnosed asthma, *n* (%)	EIB[†]/BHR[‡] prevalence, *n* (%)	(Exercise-induced) respiratory symptoms					Asthma medication, *n* (%)
				Any (at least one symptom)	Wheeze, *n* (%)	Shortness of breath, *n* (%)	Cough, *n* (%)	Chest tightness, *n* (%)	
2023	Bernhardsen et al. [52], Norway	cs: 22 (69%)	**xc: 15 (47%)**[‡,l] xc: 12 (38%)[‡,w] xc: 8 (25%)[‡,x]	xc: 25 (83%) w/exercise	xc: 13 (41%) w/exercise	N/A	xc: 24 (75%) w/exercise	xc: 12 (38%) w/exercise	xc: 23 (72%)[y] *28 ICS* *20 Ipratropium bromide* *17 SABA* *16 LABA* *5 Leukotriene antagonists*

Note: Bold indicates values used for the total EIB/BHR calculation when multiple testing methods are presented. Gray highlighted parts: Ice hockey specific.

Abbreviations: B2agonists, β2-adrenergic agonist; BHR, bronchial hyperresponsiveness; bia, biathlon; C, cough; CA, cold air group; CT, chest tightness; def, definition; EIB, exercise-induced bronchoconstriction; EVH, eucapnic voluntary hyperventilation; FEV1, forced expiratory volume in the first second; ICD, inhaled corticosteroids; ih, ice hockey; LABA, long-acting β-agonist; N/A, not applicable; NOR, Norway; PC20/PD20, provocation concentration/dose (the concentration/dose causing a 20% fall in FEV1); SABA, short-acting β-agonist; SOB, shortness of breath; ss, speed skating; SWE, Sweden; W, wheeze; w/, with; xc, cross-country.

[†]EIB assessed with an exercise challenge test.

[‡]BHR assessed with a methacholine challenge test.

[a]With or without wheeze and/or cough.

[b]Regular symptoms (not further defined).

[c]Occasional symptoms (not further defined).

[d]PD20 FEV1 ≤1800 μg methacholine, defined as the dose causing a 20% reduction in FEV1.

[e]PD20 FEV1 ≤2 mg methacholine, defined as the dose causing a 20% reduction in FEV1.

[f]Cold air group (CA) included biathletes, cross-country skiers, and speed skaters.

[g]PC20 ≤16 mg/mL methacholine, defined as the concentration causing a 20% reduction in FEV1.

[h]Reduction of FEV1 > 10% with exercise.

[i]PD15 FEV1 ≤1.6 mg histamine diphosphate, defined as the dose causing a 15% reduction in FEV1.

[j]Prevalence might be overrated, as no specific medication data were available (it is possible that athletes used both B2 agonists and ICS).

[k]Inclusion criteria: Only athletes with symptoms included.

[l]PD20 FEV1 ≤8 μmol methacholine, defined as the dose causing a 20% reduction in FEV1.

[m]PC20 FEV1 ≤4 mg/mL methacholine; for athletes with ICS: PC20 ≤16 mg/mL methacholine, defined as the concentration causing a 20% reduction in FEV1.

[n]Reduction of FEV1 > 10% with EVH.

[o]PD20 FEV1 ≤1814 μg methacholine, defined as the dose causing a 20% reduction in FEV1.

[p]PD15 FEV1 ≤635 mg mannitol, defined as the dose causing a 15% reduction in FEV1.

[q]PD20 FEV1 ≤50.5 mg adenosine 5′-monophosphate, defined as the dose causing a 20% reduction in FEV1.

[r]PD20 FEV1 ≤1812 μg methacholine, defined as the dose causing a 20% reduction in FEV1.

[s]Group 1 included adolescent athletes aged 15–19 years.

[t]Group 2 included athletes aged 20–34 years.

[u]With breathlessness.

[v]Including orienteers.

[w]PD20 FEV1 ≤4 μmol methacholine, defined as the dose causing a 20% reduction in FEV1.

[x]PD20 FEV1 ≤2 μmol methacholine, defined as the dose causing a 20% reduction in FEV1.

[y]May be underestimated.

29% of skiers used at least one form of asthma therapy (range: 11%–72%), with β2-agonists being the most utilized. Notably, three studies [23, 51, 58] did not specify whether athletes used multiple medications concurrently, potentially leading to an overestimation of prevalence, while one study reported medications individually, which may have led to an underestimation [52]. Additionally, four studies assessed asthma medication use among IH players [36, 37, 61, 63]. The reported prevalence of asthma medication use (primarily β2-agonists) was 20%, with a range of 6%–30%. Again, one study [36] did not provide specific medication data, which potentially leads to an overestimated prevalence.

4 | Discussion

In this SR, we summarized the available aspects of immune response, inflammation, and airway dysfunction in elite XC skiers and IH players from 50 studies that were published from 1993 to 2024, which in total included 3553 athletes competing in either one of the winter sports disciplines of interest (XC, biathletes or Nordic combined athletes, ski-orienteering $n = 3258$, IH $n = 295$).

Exercise serves as a potent immunological stimulus, triggering immune cell proliferation, differentiation, and cytokine secretion [67]. This effect is particularly pronounced in elite XC skiers and IH players, who, in addition to high aerobic training loads, are also exposed to cold and dry air. The included studies demonstrated that elite XC skiers and IH players exhibit distinct systemic immune responses during training sessions and competitions, as well as at rest, compared to moderately trained or untrained controls. In elite XC skiers, exercise immediately increases leukocyte numbers and pro-inflammatory TNF-α levels in the blood [8, 43]. However, during resting states, leukocyte counts and pro-inflammatory cytokines, such as IL-12 and IFN-γ, are decreased compared to untrained or moderately trained individuals [44, 45]. Similarly, elite IH players showed an increase in lymphocytes and DCs following physical exertion, while a decrease in T cells and NK cells was observed [2, 46]. Lymphocytopenia, noted after high-intensity or prolonged exercise, has been proposed as a biomarker for the "open window" of increased susceptibility to infections [68]. It is believed that exercise stimulates the migration of immune cell subsets to peripheral tissues, leading to a temporary increase in lymphocyte, leukocyte, neutrophil, and NK counts in the blood [69]. Consequently, lymphocyte counts in XC skiers and IH players may vary depending on the sampling time point. However, the link between transient immune changes and infection risk has recently been questioned [70].

Research on airway inflammation in athletes has predominantly focused on swimmers [71, 72], with studies on winter sport athletes, particularly XC skiers, being overall inconclusive, and IH players being limited. One study indicates that in XC skiers, eosinophil and lymphocyte counts increase during the competitive season more than 7- and 114-fold, respectively, and that higher annual training volume correlates with increased neutrophil counts [22]. Increased neutrophil counts observed after the season in soccer players suggest that this may not necessarily be an adaptation to cold air, but rather a result of endurance training [73]. Compared to non-athletes, XC skiers exhibit higher levels of proinflammatory TNF-α and myeloperoxidase (MPO), a marker of neutrophilic activation, in BAL samples [57]. One study found sputum IL-8 and IL-1β to be higher in athletes compared to non-athletes, and that these cytokine levels correlate with sputum neutrophils [53]. IL-8 is a strong neutrophil chemoattractant, and an increase in proinflammatory IL-1β levels is found in asthma patients, especially in those with neutrophilic inflammation [53].

Local mediators like IL-8 increase airway neutrophils in response to stress on the bronchial epithelium, such as intense exercise or training in cold, dry air [24, 53]. Thus, neutrophilic inflammation may result directly from endurance training, and it has even been suggested that exercise could be a causative factor for airway inflammation in swimmers [71]. Two studies examining airway inflammation in IH players shared a common finding in a mixed type of eosinophilic and neutrophilic airway inflammation [36, 55]. Taken together, studies included in this SR suggest that airway inflammation in XC skiers and IH players is primarily neutrophilic or mixed neutrophilic/eosinophilic, differing from the predominantly eosinophilic inflammation typically seen in allergic asthma [74]. These results are consistent with a recent SR [27] focusing specifically on competitive XC skiers.

Cytokines, such as TNF-α, IL-4, IL-5, and IL-13, play an important role in the regulation of immunity and respiratory function [74, 75]. They are involved in the activation of immune cells, the differentiation of T cells, the regulation of IgE production, and inflammation in the airways [75]. The overlap between immunity and airway function is therefore of great importance for understanding the pathophysiology of respiratory diseases such as asthma and EIB [26]. In this context, airway inflammation can drive remodeling processes in the airway epithelium, which may contribute to adaptive changes in respiratory function [26]. Assessment methods are not standardized and mainly rely on histologic analysis, including epithelial cell shedding, basal membrane thickness, and smooth muscle hypertrophy and hyperplasia [26, 76]. One study assessing XC skiers' BAL fluid found normal fibronectin and hyaluronan levels (both components of the extracellular matrix [ECM]) [76], indicating normal fibroblast activity without any indication of an ongoing remodeling process [57]. However, one study found high bronchial epithelial cell counts in induced sputum samples of cold air athletes and swimmers, indicating persistent epithelial cell shedding [23]. Another study observed elevated tenascin expression in the bronchial basement membrane of non-asthmatic skiers [38]. Tenascin, another ECM component linked to airway remodeling [76], may exhibit increased expression in winter athletes due to the hypothesized ongoing injury-repair cycle in their small airways [38]. It remains debated whether airway remodeling is a primary event, a secondary consequence of inflammation, or if both processes occur concurrently, promoting and sustaining each other [26, 77]. In case of airway dysfunction in elite athletes, the latter is well conceivable—however, most current research on the matter is cross-sectional, which is problematic due to the progressive nature of airway remodeling [76].

Elite-level exercise requires high training loads and high ventilation rates (up to 20–30 times those at rest), which may lead

to or maintain local inflammation and airway dysfunction [9]. Hyperventilation, especially in cold and dry air, leads to dehydration of the airway epithelium and subsequent hyperosmolar cellular stress, which causes the above-mentioned secretion of neutrophilic chemotactic factors, such as IL-8, and a shift in cellular ions, resulting in contraction of airway smooth muscle [9]. Stress on the airway epithelium can be aggravated by environmental agents such as indoor pollutants in ice arenas, which can easily access the lower airways due to the shift from nasal to oral airflow during heavy exercise [9, 78]. The role of various environmental agents' association with airway disorders in elite athletes has very recently been discussed elsewhere [24, 79]. Also, continuous and high-dose exposure to epithelial barrier-damaging substances (e.g., detergents, shampoos, microplastic, and nanoparticles) is of relevance for these athlete groups [24, 80]. The damage to the epithelial barrier triggers inflammatory responses and increases epithelial permeability [75]. A key aspect of this process is that epithelial cells release alarmins, including IL-25, IL-33, and thymic stromal lymphopoietin (TSLP), as well as multiple chemokines in response to allergens and infections [75]. Among these alarmins, TSLP has been identified as a potential biological target for the treatment of severe asthma, leading to the development of a new biologic, tezepelumab (TZP) [75, 81]. By blocking TSLP, and based on positive clinical trial results, TZP appears to offer a promising, safe, and effective treatment [75, 81]. Treatment options, such as anti-TSLP and anti-IL-33, are currently under development [75].

The included studies report a high mean prevalence of physician-diagnosed asthma, at 27% in XC skiers and 14% in IH players, which is in line with previous reports [23, 27, 82, 83]. The mean prevalence reported in studies from before 2010 was lower than that reported afterwards (22% vs. 30%). This upward trend has been shown by several studies in Olympic athletes of various disciplines and is also observable in the general population [10, 84, 85]. The reasons for the rise in asthma prevalence are assumed to be multifactorial, but they remain not fully understood [86]. Exercise-related symptoms have been found to be unreliable predictors of airway dysfunction in elite athletes, as these symptoms can occur even in the absence of objectively measurable asthma, EIB, or BHR [27, 82], as demonstrated in one of the included studies on female IH players [37] and two studies on XC skiers [87, 88].

It has also been reported that even healthy XC skiers, without any diagnosis of airway dysfunction, can experience BHR during the winter season [54, 89]. These observations highlight the difficulty of diagnosing airway dysfunction, particularly asthma, in the athlete population. Common diagnostic tools for detecting BHR—which seem to be more sensitive in detecting asthma than spirometry and bronchodilation tests [27]—include both direct (methacholine challenge) and indirect provocation tests (e.g., exercise challenge, EVH, mannitol, AMP, or histamine) [29, 90]. Although a gold standard is still lacking, indirect testing is recommended for assessing lower airway dysfunction in athletes. While the IOC recommends EVH as the preferred test for identifying EIB in athletes [28], other indirect tests, such as exercise challenge tests tailored to the specific population, may also be effective alternatives [28, 64]. To avoid misdiagnosis in athletes with borderline lung function, repeated or alternative tests should be used due to the variable sensitivity and specificity of provocation tests and the seasonal and training-related variations in asthma and EIB [91].

The included studies reported a mean EIB and/or BHR prevalence of 41% in XC skiers and 25% in IH players, with wide 2s of 0%–80% and 15%–29%, respectively. EIB prevalence was found to be 23% in XC skiers and 22% in IH players. BHR, as assessed by methacholine challenge tests, showed the highest mean prevalence, with 45% in XC skiers and 35% in IH players. Comparing these results is difficult due to varying diagnostic methods, thresholds, and cut-off values, many of which are based on non-athletic populations, complicating the interpretation of prevalence rates [27]. It is important to note that a positive methacholine test result does not necessarily indicate EIB [92, 93]. Indirect respiratory challenges (e.g., EVH, exercise, and mannitol) are more appropriate than the methacholine test for diagnosingf EIB in athletic populations [93]. The use of nine different cut-off doses or concentrations for the methacholine test in the included studies underscores the need for standardized testing protocols.

Current guidelines, such as the GINA recommendations, are not tailored to the specific demands of athletes, leading to inconsistencies in diagnosing airway dysfunction [94]. These variations highlight the need for a standardized, athlete-specific diagnostic framework to ensure comparability across studies and improve the accuracy of prevalence estimates. While such inconsistencies could not be fully resolved in this review, addressing these gaps in future research will be critical for more reliable assessments. Nevertheless, the high prevalence of EIB and/or BHR highlights the significant challenges faced by elite winter sports athletes. Additionally, respiratory symptoms were even higher with reported means of 55% in XC skiers and 54% in IH players. Given these high prevalences among winter athletes, active and regular screenings for asthma and/or EIB and/or BHR should be recommended for certain athletes, especially those in at-risk populations, such as XC skiers and IH players.

Asthma medication use is high in the investigated athlete groups, especially in XC skiers (mean 29%). This is in accordance with a study covering three Winter Olympic Games between 2002 and 2010, where the highest approved usage rate for inhaled β2-agonists was reported for XC skiing (17.2%) [95]. IH players in four included studies also reported high asthma medication usage (mean 20%). However, it is noteworthy that 4 of 19 studies covering XC skiers [23, 51, 52, 58] and 1 of 4 studies on IH players [36] did not provide specific data on whether athletes used more than one drug, which is why the user percentage might be overrated. The mean rate of medication usage for both athlete groups is higher than the reported mean prevalence of asthma (27% for XC skiers and 14% for IH players). Since 2011, WADA has allowed athletes to use inhaled β2-agonists within certain limits without having to prove asthma or EIB [30]. However, if an athlete has a urine value above the decision value for a β2-agonist (e.g., salbutamol), they must demonstrate that they have asthma or EIB to justify the use of the drug [30]. The included studies do not provide conclusive evidence of misuse of medications containing inhaled β2-agonists in elite XC skiers and IH players [95]. However, it remains unclear whether those with physician-diagnosed asthma are the same individuals using asthma medication. One study found that 9% of undiagnosed

XC skiers reported using asthma medication [19]. Still, evidence suggests that neither inhaled β2-agonists nor ICS enhance performance when taken at therapeutic doses for asthma/EIB [95–97]. Although ICS are the first-line treatment for asthma in both athletes and non-athletes, they are underused in the athlete population compared to inhaled β2-agonists [31, 95]. Furthermore, none of the included studies examined whether inhaler technique was used appropriately.

The included studies confirm this trend among XC skiers and IH players, underscoring the need for better education of physicians to optimize airway dysfunction management in athletes. In most cases, asthma and EIB in sports can be effectively managed with preventive measures (e.g., environmental management, health-oriented behavior, and strict competition rules) and standardized inhaler therapy for asthma (e.g., ICS combined with SABA/LABA and additional leukotriene antagonists, if needed, are the standard controller/reliever therapy for symptomatic athletes) allowing elite athletes to compete without symptoms or long-term complications [29]. As outlined in the 2024 GINA Guidelines [94], SABA without ICS as preventive and reliever therapy is no longer recommended and should always be combined with ICS, even in mild asthma, to avoid more severe or even fatal exacerbations, increased AHR, reduced bronchodilator effect, and to prevent the vicious cycle of overuse [29]. For athletes with persistent severe symptoms, the use of anti-IgE or other biologics is still under evaluation [98].

When symptoms are related to environmental factors (cold air, pollution, and allergens), the primary prevention strategy is to minimize exposure [29, 99]. XC skiers should train during the warmest daytime periods in cold weather, reduce intensity, and limit exposure. International competition temperature limits must be strictly followed. IH players should avoid rinks contaminated by ice-cleaning machines. Allergic athletes may benefit from training in allergen-free zones above 1600 m [79]. The use of face masks can also help reduce exposure to cold air, pollen, and particulate matter [79, 100]. In most cases, asthma and EIB/BHR in athletes are well treatable with the above-mentioned preventive measures combined with state-of-the-art medical treatments (ICS combined with SABA/LABA, along with leukotriene antagonists or anticholinergics for symptomatic athletes, and SABA as rescue medication), allowing athletes to participate in elite sports without symptoms or long-term complications [99].

As optimal treatment of airway dysfunction in athletes can only be achieved through careful assessment and diagnosis, it is important to be aware of its main differential diagnoses: While asthma remains the most common respiratory disorder among athletes, exercise-induced respiratory symptoms can arise from a number of other clinical entities, such as vocal cord dysfunction, exercise-induced laryngeal obstruction, URTI, breathing pattern disorders, exercise-induced hyperventilation, exercise-induced arterial hypoxemia, or exercise-induced supraventricular tachycardia [101–104]. Accurate diagnosis is essential for ensuring successful treatment of athletes and preventing interruptions in training [101].

The extracted data on asthma diagnosis, symptoms, and medication use may be subject to information bias, which is a significant limitation of this SR. Often, it is unclear whether diagnoses were based on objective assessments or self-reported indications. Furthermore, the age of asthma onset was often not reported, despite its relevance in distinguishing between allergic asthma and exercise-induced asthma. Additionally, due to information bias, it was not possible to extract data on the potential functional consequences of asthma and airway dysfunction, such as their impact on performance outcomes, training quality, and adherence, as this data were either not reported or not collected. Additionally, 10% of the articles were identified as having a high risk of bias and 38% as moderate risk. This distribution underscores the need to interpret the findings with caution, considering the potential impact of study quality on the overall conclusions.

Another important limitation is the predominance of cross-sectional studies, which limits the ability to determine causal relationships or assess the cumulative effects of high-intensity cold-air exposure on respiratory health. Longitudinal research is crucial to understanding how airway dysfunction evolves over time, particularly in elite athletes exposed to prolonged and intense training conditions. Future studies should prioritize longitudinal designs to capture changes throughout athletes' careers and provide a clearer understanding of the long-term impacts of cold-air training on respiratory function. Moreover, there was insufficient exploration of potential confounding factors, such as high-altitude training, environmental pollutants, and variations in training intensity, all of which could influence respiratory outcomes [39, 105]. Addressing these factors in future studies will offer a more comprehensive understanding of the unique risks faced by winter athletes and help refine the conclusions regarding airway dysfunction.

5 | Conclusions

In summary, this SR reinforces the substantial disease burden and adds to the understanding of immune mechanisms and airway dysfunction in elite winter athletes. XC skiers and IH players exhibit distinct immune patterns, with increased cortisol levels and shifts in immune cell composition during training, competition, and rest compared to control individuals, aligning with previous observations in athletes [38, 39]. Both groups are significantly impacted by airway dysfunction, with 27% of XC skiers and 14% of IH players diagnosed with asthma, along with even higher rates of respiratory symptoms and EIB/BHR. The mixed eosinophilic–neutrophilic airway inflammation supports the context of a “sport asthma” endotype, likely influenced by repeated exposure to cold, dry air. However, optimal treatment—including preventive strategies, appropriate use of ICS, β2-agonists, and advanced medical therapies—can help manage asthma and EIB/BHR in athletes, enabling them to compete in elite sports without symptoms or long-term complications.

Further refinement of diagnostic guidelines and a deeper understanding of underlying immune and airway mechanisms will support improved athlete management. Identifying specific biomarkers for early detection of at-risk athletes, along with tailored prevention and treatment strategies, will be essential for reducing disease burden and improving long-term outcomes for elite winter athletes.

This review emphasizes the significant presence of airway dysfunction and immune responses in elite winter athletes, highlighting the need for more tailored diagnostic and treatment approaches. While there is progress in understanding the immune mechanisms behind conditions like asthma and BHR/EIB, a variety of methods are currently used to assess airway dysfunction in XC skiers and IH players, leading to varying results. A standardized, athlete-specific diagnostic and treatment framework is essential for improving the accuracy of assessments and ensuring comparability across studies. Moreover, further research is necessary to refine prevention strategies and develop more effective treatments. Closing these gaps will enable more effective management of respiratory conditions, leading to improved health outcomes and sustained athletic performance.

Author Contributions

D.J.M., A.W., W.K., B.V., C.A.A., and M.V. defined the topic and outlined the review. E.J., D.J.M., A.W., and M.V. performed the literature search, screening of papers, and data extraction of papers meeting the inclusion criteria. All authors contributed to the interpretation of the results. E.J., D.J.M., A.W., and M.V. wrote the manuscript. W.K., B.V., I.A., M.J., K.N., M.R., M.B., O.J.P., and C.A.A. critically revised the review. All authors read and approved the final manuscript and agree to be accountable for all aspects of the work.

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Disclosure

Disclaimer: The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data generated or analyzed during this review are included in this published article and its Supplementary Files S1 and S2.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.