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THEMED REVIEW

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Lifestyle and the Respiratory Health of Children

Abstract: *This article offers a review of the potential influences of personal lifestyle on respiratory health in children, looking at both healthy individuals and those with respiratory disorders. As with many aspects of health, regular physical activity, an appropriate diet, and avoidance of obesity and cigarette smoke all contribute to optimal development of the healthy child. An active lifestyle is associated with greater static and dynamic lung volumes, greater efficiency of the ventilatory process, and an optimization of breathing patterns. The risk of upper respiratory infections is also reduced in those maintaining a moderate level of physical activity. Maternal smoking during pregnancy, as well as active and passive smoking, all have an adverse influence on lung function in the child, the largest effects being on dynamic lung volumes. The risk of developing asthma seems reduced in children who maintain a normal body mass and are physically active. A program of graded physical activity is of therapeutic value in a number of established respiratory conditions, including asthma, cystic fibrosis, and ventilatory impairment from neuromuscular disorders. Exercise carries a slight risk of fatalities from*

asthma and anaphylactic reactions. In designing an optimal physical activity program, it is also important to guard against the hazards of deep oronasal breathing, including the precipitation of bronchospasm by the inhalation of cold, dry air and pollens; an increased exposure to atmospheric pollutants (reducing and oxidant smog, fine and ultra-fine particulates, and carbon monoxide); and possible long-term dangers from chlorine derivatives in the atmosphere of indoor swimming pools.

Keywords: physical activity; physical fitness; obesity; asthma; cystic fibrosis; neuromuscular disorders; exercise-induced bronchospasm; air pollutants

In keeping with the mandate of this journal, the aim of the present review is to examine the impact of personal lifestyle on respiratory health in children, looking both at healthy individuals and those with various respiratory disorders. Lifestyle factors that are examined include the control of body mass, the optimization of diet, the avoidance of cigarette smoke and other air pollutants, and especially the impact of habitual physical activity, including general and specific respiratory training. Outcomes that

are discussed include changes in static and dynamic lung volumes, ventilatory efficiency, breathing pattern, and susceptibility to upper respiratory infections. Particular consideration is given to the possible roles of physical inactivity and obesity in precipitating asthma and related respiratory disorders. The possible value of increased physical activity in the treatment of certain respiratory conditions such as asthma, cystic fibrosis, and neuromuscular disorders is also explored. Finally, note is taken of some potential disadvantages of an active lifestyle, commenting on how such problems may be minimized.

Information on these various topics has been sought through the HealthStar OVID and PubMed databases (to January 2010), the author's extensive personal files, and a scan of reference lists in articles selected from these 3 sources. Particularly in studies dealing with disease states, there are many limitations to the available data, often including small participant numbers, weak definition of exercise programs and disease severity, and a lack of appropriate control groups. Detailed description of the studies has thus been provided, rather than attempting a formal and arbitrary ranking of studies in terms of their quality.

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Associations Between Lifestyle and Respiratory Health

Level of Habitual Physical Activity

Until recently, most large-scale studies of habitual physical activity and respiratory health have relied on questionnaire assessments of physical activity patterns. Such assessments have limited accuracy, particularly in children. During the past few years, epidemiologists have made increasing use of simple and inexpensive uniaxial electronic pedometers/accelerometers to determine habitual activity patterns.¹ If observers allow for seasonal effects² and monitor participants for a sufficiently long period,³ the precision of physical activity assessment is greatly increased in older adults, where the main source of physical activity is usually walking. However, uniaxial electronic pedometer/accelerometers respond mainly to vertical accelerations, and they are thus less effective monitoring devices in children, where much of the total daily activity may be taken on a bicycle.

Many studies point to an association between regular physical activity and the development of above-average lung volumes—both static volumes such as vital capacity and dynamic lung volumes such as the forced expiratory volume in 1 second. Nevertheless, evidence is as yet insufficient to posit causality; indeed, a child with a large vital capacity is likely to be successful and thus a regular participant in some sports, particularly swimming. Regular physical activity also leads to an optimization of breathing patterns and an increase of ventilatory efficiency. Finally, regular moderate physical activity appears to reduce the risk of upper respiratory infections, although excessive physical activity can have the opposite effect.

Static and Dynamic Lung Volumes

Early investigators considered vital capacity an important indicator of an individual's physical fitness.^{4,5} Subsequent studies established modest but statistically significant correlations between static

lung volumes and cardiorespiratory fitness⁶; however, it was argued that if an increase of physical activity were to have any substantial influence on lung volumes, then such activity must be initiated at an early age.⁷

Cross-sectional differences of static or dynamic lung volumes between athletic and sedentary children⁸⁻¹⁰ cannot be interpreted causally because greater lung volumes might be the cause of enhanced athletic prowess rather than an effect of sport participation. Moreover, socioeconomic status, access to health care, and the smoking behavior of parents frequently differ between athletes and sedentary groups. Finally, although reported differences have reached statistical significance, the advantage in the athletic children has generally been too small to have any major clinical significance. One relatively large quasi-experimental study tested the effects of 5 additional hours of physical education per week on the lung volumes of a community-wide sample of primary school students in grades 1 through 6; a small but statistically significant advantage of both vital capacity (VC) and 1-second forced expiratory volume (FEV_{1.0}) was found in the experimental classes.¹¹ The VC was enhanced by an average of 3.2%, the effect being larger in boys than in girls, and largest in the final 3 years of the 6-year program. There was little effect on the FEV_{1.0} except in the sixth year, when the experimental students had an advantage of 7.0%. The advantage in lung volumes did not reflect any difference of growth between experimental and control children, and the most likely explanation seemed a strengthening of the chest muscles by the additional physical education; this would have allowed the experimental students to make a more forceful expiration, with greater compression of the rib cage, and a larger expulsion of blood from the pulmonary venous reservoir.

Cross-sectional comparisons by other investigators have confirmed these effects. A recent survey of 2537 Norwegian students aged 9 to 10 years compared those reporting activity less than once a week with those who were

active more than 4 times per week.¹² After adjusting for confounding variables, the more active students had a small (70 mL) advantage of both forced vital capacity (FVC) and FEV_{1.0}. The longitudinal Amsterdam growth and development study also noted that increases in physical activity were positively correlated with changes in FVC.¹³ Larger effects of similar type have been described in children involved in intensive swim training,¹⁴⁻¹⁶ although perhaps because success in swimming depends in part on lung volumes, differences between athletes and sedentary students have been less clear cut for participants in other sports.

Extensive studies of Canadian Inuit children provide further information on this topic. When the community of Igloodik, NWT, was first evaluated in 1969-1970, almost all of the population was very active. With acculturation to a southern Canadian lifestyle, levels of habitual activity decreased progressively over the next 20 years, although at least in the children energy expenditures remained higher than in many urban environments. The VC and FEV_{1.0} of the Inuit students in all 3 surveys were substantially higher than suggested by either the prediction equations of Cotes¹⁷ or our own more recent urban norms,¹¹ with no substantial differences of average VC or FEV_{1.0} between the surveys for 1969-1970, 1979-1980, and 1989-1990.^{18,19} Moreover, as the children grew, the VC developed with a height exponent of almost exactly 3.0, substantially greater than that seen in most urban communities.¹⁸ There are, of course, differences of body build, diet, and socioeconomic conditions between the Inuit and urban Canadians, complicating standardizations based on standing height, and such factors rather than vigorous daily physical activity may explain the advantage of static and dynamic lung volumes in the Inuit children. In support of this view, their advantage over urban Canadians has shown little change as the community has acculturated to a more sedentary urban lifestyle.

Obesity seems to have the opposite effect to a high level of habitual physical activity, reducing lung function. Studies of obese adults have shown a decrease

in total respiratory compliance and an increase in the oxygen cost of breathing.²⁰ A report from Mexico City²¹ found that in children aged 8 to 10 years, body mass was positively correlated with FVC and FEV_{1.0}. However, the relationship had an inverted U-form, so that children who were obese had subnormal lung volumes.

Optimization of the Breathing Pattern

In adults, it is well recognized that specific training of the respiratory muscles can allow a faster inspiration,²² thus permitting a slower expiration and reducing the risk of expiratory collapse of the airways; this is generally helpful to ventilation during exercise, although it is also important to guard against vocal cord dysfunction and extrathoracic airway obstruction as a consequence of rapid inspiration. The smaller relative size of the airways²³ and a greater relative respiratory minute volume²⁴ make the optimization of breathing pattern more of an issue in children than in adults. Cross-sectional comparisons in small groups of prepubertal children have suggested that high-intensity intermittent running¹⁰ and involvement in aerobic sports⁹ are both associated with increased maximal respiratory flow rates. Biofeedback and self-hypnosis techniques may be helpful in optimizing breathing patterns, particularly in anxious athletes.²⁵⁻²⁷

Avoidance of airway collapse through a reduction of expiratory flow rate has been suggested as important in chronic respiratory conditions such as asthma,²⁸ cystic fibrosis,^{29,30} and various neuromuscular disorders.^{31,32} By training the respiratory muscles, it becomes possible for the affected individuals to take a faster inspiration and a slower expiration, thus reducing the risk of airway collapse.

Ventilatory Efficiency

Children adopting an active lifestyle show various manifestations of enhanced ventilatory efficiency. In addition to increases in static and dynamic lung volumes,⁹⁻¹¹ dead space ventilation is decreased,¹⁰ and the ventilatory cost of achieving a given oxygen

intake is reduced.¹⁰ These changes most likely reflect some combination of a better matching of ventilation to perfusion within the lungs, consequent upon a greater peak cardiac output, and a strengthening of the peripheral muscles, with a resultant increase in the aerobic threshold and less accumulation of lactate during vigorous effort.³³ The idea that growth of the lungs differs between active and sedentary children is more speculative, although in the case of swimmers, some developmental effects may arise from frequent pressure loading of the thoracic cage.

One cross-sectional comparison found a lower ventilatory efficiency in obese children than in those of normal weight; the authors of this report suggested that the accumulation of abdominal fat had restricted normal thoracic movements.³⁴ Others have found similar ventilatory efficiencies for obese children and their normal-weight peers.^{35,36} A small controlled trial in overweight children (age 11 years, average body mass index [BMI] 30 kg/m², body fat 44%) reported that 8 weeks of cycle ergometer exercise (30 minutes, 4 times per week, at 50%-60% of maximal oxygen intake) led to a substantial decrease in ventilatory equivalent, although because of the short-term nature of the intervention, there was no decrease in body fat content.³⁷ Any enhancement of efficiency in this study could not be attributed to an easing of thoracic movement; rather, benefit must have arisen from factors similar to those that operate with training of the non-obese child.

Upper Respiratory Infections

In adults, it is now well established that regular moderate physical activity decreases vulnerability to upper respiratory infections.³⁸⁻⁴⁰ Active individuals learn by experience the amount of training that they can undertake without compromising respiratory health. The issue has received less attention in children. One early report⁴¹ noted an apparent association between recent participation in intensive exercise and an increase in the incidence of pneumonia among pupils at a boys' school; however, it

is difficult to be certain that exposure to infection had not somehow been increased by participation in the activity. More recently, Klentrou and associates⁴² examined 256 average Canadian adolescents with an average age of 14.3 years. In the boys, but not in the girls, higher levels of reported physical activity and a higher score on a 20-meter shuttle run estimate of aerobic fitness were both associated with fewer reported incidents of upper respiratory infection.

In very young children, on the other hand, swimming in poorly maintained pools can increase exposure to microorganisms and thus increase the risk of upper respiratory infections.⁴³

Cigarette Smoke

The effects of cigarette smoke on children are difficult to disentangle from associated differences of socioeconomic status between parents who are smokers and those who are nonsmokers. In the case of passive exposure, adverse effects are most likely to become apparent where dwellings are small and overcrowded; there is also a risk, even in young children, that those passively exposed to cigarette smoke may themselves be at least occasional smokers. Finally, maternal smoking during pregnancy may have adverse effects on fetal development.

Active Effects of Smoking

The adverse long-term effects of cigarette smoking on the lungs of adults are well documented; they include a progressive deterioration of interstitial collagen, a collapse of alveolar walls, an increased secretion of mucus, and vulnerability to neoplasia.

There have been fewer studies in children. Children and adolescents are not particularly concerned about long-term health sequelae, but they may be deterred from smoking by immediate consequences for their physical performance, including an increase in the oxygen cost of breathing⁴⁴ and a decrease in the oxygen-carrying capacity of the blood.⁴⁵

A cross-sectional comparison from India found that active smokers aged 12 to 18 years had a significantly smaller

VC than nonsmokers of the same age.⁴⁶ Likewise, Spanish adolescents aged 14 to 20 years had a poor VC, FEV_{1.0}, peak expiratory flow rate (PEF), and maximal mid-expiratory flow rate (MMEF) relative to nonsmokers in the same age group.⁴⁷

Passive Exposure to Cigarette Smoke

Reports from various parts of the world have indicated a reduction in expiratory flow rates and an increased susceptibility to upper respiratory infections among children who are passively exposed to cigarette smoke.⁴⁸ A series of more recent reviews has emphasized that although adverse effects are incontrovertible, there remains a need for studies to determine critical periods of exposure in utero, in the neonatal period, and later during infancy.⁴⁹ At least a part of the effect is clearly environmental because function is affected not only by maternal smoking, but also by paternal smoking.^{50,51}

The decrease in dynamic flow rates probably reflects an irritant effect of the smoke. In Turkey, children aged 9 to 13 years showed lower values for peak flow and mid-expiratory flow if their fathers were smokers.⁵⁰ A study of Indian adolescents⁴⁶ found that passive smokers had a low FEV_{1.0}/FVC ratio and a low MMEF relative to controls. In Spanish adolescents also, passive smoking was associated with lower values for peak flow and FEV_{1.0},⁴⁷ and in rural China, passive smokers showed small but statistically significant deficiencies in FVC and FEV_{1.0} relative to controls.⁵² Similar if less dramatic trends have been observed among children living in Los Angeles⁵³ and primary school students in various parts of Britain.⁵⁴ A pooled analysis of 21 studies in school-aged children found that parental smoking was associated with a 1.4% disadvantage in FEV_{1.0}, a 5.0% reduction in MMEF, and a 4.3% reduction in end-expiratory flow rate.⁵⁵ The peak flow rate also seems to be more variable if the parents are smokers, but any apparent slight trend to bronchial hyperresponsiveness with passive smoke exposure probably reflects a publication bias.⁵⁶ A review of 51 relevant publications through 1997 concluded that

maternal smoking increased the risk of wheezing illness (by 31% up to the age of 6 years, but less markedly in older children). Cook and Strachan⁵¹ have conducted several other meta-analyses. With maternal smoking, school-age children showed increases in cough (odds ratio [OR] = 1.40), phlegm (OR = 1.35), and breathlessness (OR = 1.31). The odds ratio for the development of asthma was 1.41 if either parent smoked, although it was suggested that tobacco smoke was probably serving as a cofactor, provoking wheezing attacks in a child with a tendency to asthma.⁵⁷

In addition to adverse effects on dynamic lung volumes, an Italian study found evidence of an increased residual volume and a decreased lung-diffusing capacity in 16-year-old boys who had been passively exposed to cigarette smoke.⁵⁸ Passive exposure to cigarette smoke is also associated with increased susceptibility to upper respiratory infections, although it is less clear how far this is a result of socioeconomic factors and how far it is a direct effect of smoke exposure. In one review,⁴⁹ the odds ratios for susceptibility to upper respiratory infections in passive smokers were in the range of 1.2 to 1.6. The effect was greatest in young children and was larger with maternal than with paternal smoking. In early life, the odds ratio for acute lower respiratory illness was 1.57 if either parent smoked and 1.72 if the mother smoked.⁵⁹ The risk of sudden death syndrome was also doubled if the mother was a smoker, and parental smoking increased the risk of hospital admission for children with cystic fibrosis.⁴⁹

In Utero Exposure

A number of reports have suggested that maternal smoking during pregnancy has an adverse effect on respiratory outcomes in the young child, although with the exception of studies made shortly after birth, it has been difficult to separate the effects of in utero exposure to tobacco products from subsequent exposure of the neonate to high concentrations of environmental cigarette smoke.

Lodrup-Carlsen and associates⁶⁰ assessed respiratory function an average of 2.7 days after birth; they reported adverse effects on tidal flow/volume loops and overall pulmonary compliance proportional to the mother's daily consumption of cigarettes during pregnancy. A second study examined respiratory function immediately following preterm delivery (average 33 weeks); infant cotinine levels averaged 458 ng/mL if the mothers had smoked, compared with <4 ng/mL in the children of nonsmoking mothers.⁶¹ In this second study, maternal smoking had an adverse effect on both MMEF and time to peak tidal expiratory flow as a proportion of the total expiratory time. A third report examined infants an average of 4 weeks following delivery; after covarying for smaller body size and exposure to environmental cigarette smoke, the infants of mothers who had smoked during pregnancy still showed a significant disadvantage in terms of forced expiratory flow rates.⁶² Studies of infants aged 2 to 24 months found a reduced drive to breathe and a blunted response to hypoxia if the mother was a smoker.⁶³ Even at the age of 8 to 12 years, forced expiratory flow rates remained lower if the mother was a smoker, and this effect appeared largely attributable to smoking during pregnancy, rather than subsequent environmental exposure.⁶⁴

Other Air Pollutants

The influence of other air pollutants on respiratory health is discussed in the section on potential disadvantages of a physically active lifestyle.

Diet

An excessive overall food intake, possibly linked to a preference for snack and junk food with a high content of refined sugar, saturated fat, and/or salt, can lead to obesity, with adverse effects on respiratory function, as discussed elsewhere in this review.

Specific effects of polyunsaturated fatty acids, vitamin supplements, caffeine, and alcohol have been suggested, both in terms of increasing lung volumes and in protecting the individual against airway inflammation, exercise-induced

bronchospasm, and asthma. However, the evidence of benefit is conflicting, in part because of difficulties in ensuring a full covariate analysis for habitual physical activity, active and passive smoking history, allergen exposure, and socioeconomic factors. The timing of supplement administration may also be important; 1 recent Scandinavian study suggested that the administration of fish oils to the mother late in pregnancy was helpful in reducing the risk of asthma in her offspring.⁶⁵

Polyunsaturated Fatty Acids

Changes in respiratory function induced by an increased intake of polyunsaturated fatty acids (PUFA), particularly the omega-3 unsaturated fats found in fish oil, have attracted considerable attention in recent years. One possible mode of action may be to inhibit the cyclooxygenase conversion of arachidonic acid in inflamed airways.⁶⁶ However, the evidence of benefit from PUFA is conflicting; a Cochrane review⁶⁷ concluded that 2 studies of children and 7 studies of adults provided no consistent evidence of change in any of the analyzable respiratory outcomes: FEV_{1.0}, peak flow rate, asthma symptoms, use of asthma medications, or bronchial hyperreactivity.

PUFA intake was positively correlated with lung volumes in a longitudinal study of Dutch teenagers.¹³ Other authors have suggested that PUFA supplements can protect against exercise-induced bronchospasm (EIB). A double-blind crossover trial in 10 elite athletes⁶⁸ found that daily administration of 3.2 g eicosapentaenoic acid (EPA) and 2.2 g docosahexaenoic acid (DHA) for a 3-week period reduced the exercise-induced decrease in FEV_{1.0} (as measured 15 minutes following exercise) from 17.3% to 3.5%. Further trials by the same group of investigators confirmed that EIB dropped below the diagnostic threshold after administration of fish oil supplements.⁶⁹

A cross-sectional study of 2112 twelfth-grade US and Canadian students found an association between a low dietary intake of n-3 fatty acids and chronic bronchitic symptoms (odds ratio [OR] = 1.37; 95% confidence interval [CI]: 1.05-1.81),

wheezing (OR = 1.34; 95% CI: 1.06-1.69), and asthma (OR = 1.68; 95% CI: 1.18-2.39).⁷⁰ Nagakura and associates⁷¹ kept 29 asthmatic children in a long-term treatment hospital where diet and allergen exposure were closely controlled; under these conditions, a 10-month double-blind trial showed that treatment with EPA (84 mg/d) and DHA (36 mg/d) decreased respiratory symptom scores and acetylcholine responsiveness. Other positive results have included a small double-blind trial on 17 adults with atopic asthma (where the asthmatic response to allergens was reduced by daily administration of 3.2 g EPA and 2.2 g DHA),⁷² and a double-blind study in 12 adult asthmatics (where there was a small increase of FEV_{1.0} after taking fish oil supplements for 9 months).⁷³ The first US National Health and Nutrition Examination Survey related FEV_{1.0} to reported intakes of fish oil in 2526 adults, finding a weak positive association that was increased when current smokers were excluded from the analysis.⁷⁴ However, the second US National Health and Nutrition Examination Survey found no relationship between respiratory symptoms and dietary fish intake.⁷⁵

Many other studies have found no benefit from PUFA supplements. A double-blind 10-week trial compared 12 children with mild asthma who received a daily dose of 3.2 g of EPA and 2.2 g of DHA with 8 asthmatic children who received a placebo.⁷⁶ The fish oil supplements reduced neutrophil activity relative to control participants but had no effect on either clinical condition or the airway response to a histamine challenge. Likewise, a 6-month double-blind trial of omega-3 and omega-6 fatty acids in 39 asthmatic children aged 8 to 12 years found that the supplements decreased plasma levels of tumor necrosis factor but did not affect symptoms, peak flow rates, or medication use.⁷⁷ The daily administration of 15 to 20 mL of evening primrose oil to 29 adult asthmatics had no therapeutic benefit,⁷⁸ and a parallel, double-blind, placebo-controlled trial in 25 adults with pollen allergies found that 3.2 g/d of EPA had no influence on bronchial reactivity, peak expiratory flow rates, nocturnal cough, wheezing, nasal

symptoms, or use of medications.⁷⁹ A single-blind sequential trial on 10 aspirin-intolerant adult patients even found that during the 6 weeks when fish oil supplements were provided, peak flows decreased, and the patients needed to use bronchodilators more frequently.⁸⁰

Vitamin and Mineral Supplements

A randomized controlled trial tested the value of vitamin A supplements (450 µg/d) in 147 Australian preschool-age children with a history of frequent respiratory infections.⁸¹ Over an 11-month period, children receiving the supplement had 19% fewer infectious episodes than control participants, although plasma retinol levels were not increased by the supplement. The decrease in risk of infection was most apparent in children with a prior history of asthma or lower respiratory illness. A second trial of vitamin A supplementation involved some 2000 children aged 1 to 5 years; this sample was living in a developing country (Indonesia),⁸² and 8% of children initially had low plasma retinol levels. According to a stratified, randomized, and placebo-controlled design, 200 000 IU of vitamin A was administered at 6-month intervals. The duration of respiratory infections was slightly shorter in the experimental participants, but the treatment had no effect on either the incidence or the severity of respiratory infections.

In a cross-sectional study of US and Canadian adolescents,⁷⁰ low dietary fruit intake was associated with a low FEV_{1.0} (−1.3% of predicted; 95% CI: −2.4% to −0.2% of predicted) and increased odds of chronic bronchitic symptoms (OR = 1.36; 95% CI: 1.03-1.73). The odds ratio for respiratory symptoms among students who were smokers was also greater in those who had a low dietary intake of vitamin C. However, a linkage between the purchase of fruit and socioeconomic status may have contributed to these findings.

The second National Health and Nutrition Examination Survey⁷⁵ surveyed US adults aged >30 years. Respiratory symptoms were negatively associated with serum vitamin C, niacin, and the

serum zinc/copper ratio but positively associated with the sodium/potassium ratio; moreover, the benefits from vitamin C and niacin were apparently independent of smoking history.⁷⁵

A deficiency of vitamins A and C has been reported in infants with cystic fibrosis.⁸³ Twenty of 39 infants newly diagnosed with this condition had low serum retinol levels, and 9 of 38 had low alpha-tocopherol levels. Both deficiencies were corrected by providing supplements of vitamins A and E, but low initial levels of these vitamins did not appear to be correlated with the extent of airway inflammation.⁸³

Caffeine

Data from the second US National Health and Nutrition Examination Survey⁸⁴ found that asthma symptoms were 29% less likely in adults who drank coffee on a regular basis; moreover, there was a dose-response relationship between the consumption of coffee and protection against asthma. It was thus suggested that the methyl xanthines in coffee served as bronchodilators. However, it is a little curious that the same survey found no such association for tea drinking.

Alcohol

Multivariate analysis of longitudinal data for 233 Dutch male adolescents found positive relationships between lung volumes (FVC and FEV_{1.0}) and alcohol consumption.¹³ This may possibly reflect a common relationship of sports participation to both lung volumes and alcohol consumption. Cross-sectional and longitudinal studies in 1067 adult men found no such relationship between alcohol consumption and lung volumes.⁸⁵ Indeed, those consuming substantial amounts of alcohol have shown poorer lung function and an increased prevalence of respiratory symptoms, although the associated adverse effect of cigarette smoking has been larger.⁸⁶

Lifestyle and Vulnerability to Asthma

Several important lifestyle issues arise when considering the asthmatic child.

Have obesity, an inappropriate diet, insufficient physical activity, a low level of aerobic and anaerobic fitness, and/or passive exposure to cigarette smoke contributed to development of the condition? Can normal participation in sport and physical activity be recommended for those affected, and (as discussed in the following section) will an increase of habitual physical activity improve the child's clinical status?

Obesity

A number of cross-sectional studies have pointed to an association between obesity and predisposition to asthma.⁸⁷⁻⁹³ An association between BMI and asthma-like symptoms in girls (but not in boys) was reported in a longitudinal questionnaire

in some of the large surveys, both the estimation of BMI and the diagnosis of asthma have been based on parental reports rather than physician diagnoses. Finally, asthma may have led to inactivity and obesity, rather than the converse.

Habitual Physical Activity

An association between asthma and a low level of habitual physical inactivity might make intuitive sense, given that (depending on age) the child or the parents may see exercise as precipitating bouts of asthma and thus avoid bouts of exercise whenever possible.^{87,97,98} There have certainly been suggestions that asthmatic adults are inactive. However, in children, the evidence is less clear cut (Table 1), and any differences between

Several important lifestyle issues arise when considering the asthmatic child.

study.⁹⁴ Parent-reported responses found no link between the BMI at age 6 and wheezing at any age, but the reporting of new asthma symptoms was 7 times more likely in girls who became overweight between ages 6 and 11 than in their peers. A longitudinal investigation from California included many covariates.⁹⁵ The relative risk of new cases of physician-reported asthma in a 4-year follow-up of 4th-, 7th-, and 10th-grade pupils was 1.52 in overweight pupils, this adverse effect of excess body mass on risk being more marked in the boys than in the girls.

A causal association would not be altogether surprising. Adipose tissue is known to be biologically active and is associated with systemic markers of inflammation. There are also linkages between obesity and sleep-disordered breathing.⁹² However, in many of the reports, it is difficult to rule out the influence of confounding factors such as parental smoking, greater exposure to pollutants, and lesser access to medical care associated with a low socioeconomic status.⁹⁶ Moreover,

asthmatic students and their peers seem to be relatively small. There have been at least 8 reports, but with one exception,⁹⁹ information on physical activity has been limited to questionnaire data. Four of the 8 studies suggested no difference of physical activity between asthmatic and control groups. One report actually found more frequent bouts of exercise in asthmatic children,¹⁰⁰ although noting that the students with asthma were more anxious about exercising; this may have led them to report bouts of activity that other children or parents would not have considered. There is plainly a need for more objective studies of children in various age groups and with varying severity of the disease process because 1 small questionnaire study and 1 accelerometer study⁹⁹ (in children aged 3-5 years) noted that bouts of vigorous activity were less frequent and maintained for shorter periods in those with asthma.

Aerobic Fitness

Some authors have suggested that physical fitness can be assessed more

Table 1.

Physical Activity and Physical Fitness in Children With Asthma

First Author	Test Mode	Sample	Findings
Physical Activity			
Weston ¹⁰⁰	Questionnaire	408 children aged 11-13 years (16% asthmatic)	Reported preexercise anxiety but higher frequency of exercise than nonasthmatic children
Nystad ²⁴⁵	Questionnaire	4585 children aged 7-16 years (9.5% with asthma)	No difference in exercise frequency from controls
Kitsantas ²⁴⁶	Questionnaire	38 high school girls	Less vigorous activity than controls
Wong ¹⁰⁴	Questionnaire	1427 children aged 8-12 years	Physical activity low in all participants but unrelated to asthma and other respiratory diseases
Welsh ²⁴⁷	Questionnaire	28 asthmatics aged 11-15 years	No difference of physical activity from controls (abstract only)
Firincieli ⁹⁹	Accelerometer	54 children aged 3-5 years	Less prolonged bouts of physical activity if history of wheezing
Jones ⁹²	Questionnaire	13 553 high school students	No difference in compliance with recommendations for moderate and vigorous physical activity if asthmatic
Nystad ²⁴⁸	Questionnaire	80 asthmatic children aged 6-16 years, 80 controls	12% vs 10% exercise <1 h/wk; 35% vs 38% exercise >4 h/wk Bronchial responsiveness inversely related to h/wk exercise
Aerobic Fitness			
Bevegard ²⁴⁹	Maximum cycle ergometer	20 M; aged 8-13 years, asthmatics	Normal maximal oxygen intake
Hedlin ²⁵⁰	Maximum and submaximum cycle ergometry	10 M, 6 F; aged 10-14 years	High ventilatory equivalent but similar peak power output to Swedish norms even in severely asthmatic group
Fink ²⁵¹	Maximum cycle ergometry	27 M, 22 F; aged 9-16 years	Maximal oxygen intake of asthmatic children matched that of control group with similar physical activity
Varray ^{101,102}	Maximum cycle ergometry	9 M, 2 F; aged 11-12 years	Lower maximal oxygen intake than controls
Thio ²⁵²	Treadmill to peak effort	17 M, 11 F; aged 6-13 years	Normal peak oxygen intake in 22 cases, low in 6 physically inactive cases; no correlation with low FEV _{1.0}
Santuz ²⁵³	Treadmill to peak effort	60 M, 20 F; aged 7-15 years	Low peak oxygen intake in asthmatics and controls; no difference in asthmatics if matched with controls for habitual activity

(continued)

Table 1. (continued)

First Author	Test Mode	Sample	Findings
Aerobic Fitness			
Rasmussen ¹⁰³	Cycle ergometer	757 children aged 9.7 years, 10.5-year follow-up	Risk of developing asthma in adolescence –7% per W/kg advantage of peak power
Welsh ²⁴⁷	6-minute run	18 M, 10 F; aged 10-15 years	No difference of distance run versus 200 controls
Strunk ¹¹⁴	9-minute run	42 M, 34 F; aged 9-17 years	91% had performance below 50th percentile for healthy controls Abdominal strength and flexibility normal Skinfolds often increased
Wong ¹⁰⁴	Léger Shuttle run	43 M; aged 14 F; aged 8-12 years	Reduced predicted maximal oxygen intake if respiratory disease or asthma was present
Kukafka ²⁵⁴	1-mile run	19 M; aged 14-18 years	Asthmatics 10% slower than controls
Riedler ²⁵⁵	5-minute run	number not specified; aged 13-15 years	Asthmatics ran 10% slower than controls
Anaerobic Fitness			
Boas ²⁵⁶	Wingate test	22 M; aged 7-15 years, asthmatics	No differences of anaerobic power or capacity from controls
Buttinfant ²⁵⁷	Wingate test	19 M; aged 15 years	No difference in mean or peak anaerobic power from controls
Counil ²⁵⁸	Vandewalle force-velocity test	19 M; aged 11.6-15.1 years	Reduced capacity for anaerobic work; low lean body mass relative to controls

readily than habitual physical activity and may thus provide a more reliable indication of a child's activity. This is particularly true when making inferences from grouped data, where genetic influences on an individual's level of fitness are largely factored out. However, it is less certain that fitness tests will provide an accurate picture of physical capacity in asthmatic children because many of the tests of both aerobic and anaerobic power require all-out effort, and it may be more difficult to elicit maximal effort from an asthmatic child than from a child with normal respiratory function. Indeed, one group of observers concluded that the main factor influencing a child's peak oxygen intake was the perceived competence of the individual.⁹⁷

There are at least 12 reports on aerobic fitness and asthma (Table 1). Six studies used a cycle ergometer or treadmill to determine peak oxygen intake, and with

one exception, values for asthmatic children were considered normal, at least if compared with control participants who were engaging in a comparable amount of habitual physical activity.^{101,102} Rasmussen and associates¹⁰³ followed 757 students initially aged 9.7 years prospectively for 10.5 years; they noted a small decrease in the risk of developing asthma during adolescence in those who had a higher prepubertal peak power output (7% decrease in risk per W/kg of peak power output). The remaining investigators used various field performance tests based on all-out running; 4 of the 5 studies in this group concluded that the peak performance of asthmatic children was impaired, although in 1 of these studies, asthma was not distinguished clearly from other forms of respiratory disease.¹⁰⁴

Possibly, it is easier to elicit a true maximal effort from an asthmatic participant

when testing is conducted in a laboratory. In this situation, the participants are more likely to have received any necessary pre-medication, and they are unlikely to visit the laboratory if there has been an acute exacerbation of their condition. However, most laboratory studies have been small scale, limiting their power to demonstrate an effect, and in some cases, the appropriateness of the comparison group can be questioned. Finally, a shortness of breath attributable to the poor physical condition of a child is too often misinterpreted as a bout of exercise-induced bronchospasm.¹⁰⁵ These various factors could account for the absence of any association between asthma and aerobic power as measured in the laboratory.

Given the discrepancy between field and laboratory tests, it is at present difficult to reach any strong conclusions about low aerobic fitness and predisposition to asthma.

Anaerobic Fitness

A few investigators have tested associations between anaerobic fitness and susceptibility to asthma, using either the Wingate test or the Vandewalle force-velocity test (Table 1). Again, the findings are unfortunately conflicting. Two reports indicate normal performance, and one shows some impairment of anaerobic fitness in asthmatic students.

Conclusions

The likelihood of finding an association between indicators of a poor lifestyle (obesity, lack of habitual physical activity, and subnormal aerobic and anaerobic fitness) and asthma seems dependent on both the severity of the disorder and any restrictions on habitual activity imposed by anxious parents or the affected child. Those individuals who remain active appear to have relatively normal levels of aerobic function. It is safe and reasonable for the asthmatic child to engage in regular sport and physical activity, given adequate preparation¹⁰⁶ and appropriate warm-up.¹⁰⁷ Moreover, adequate levels of physical activity will avoid setting the stage for many chronic conditions during adult life.¹⁰⁸ Thus, children with asthma should be encouraged to reach their potential by maintaining as normal an activity schedule as possible.

Physical Activity as Therapy for Respiratory Disorders

Programs of graded exercise and/or localized training of the respiratory muscles are helpful in the treatment of children with a variety of chronic conditions, including asthma, cystic fibrosis, certain neuromuscular disorders, and sleep apnea. Some of the benefits observed with training programs have reflected the well-known general positive effects of increased regular physical activity.¹⁰⁸ However, there is also evidence that exercise programs bring about more specific improvements in clinical status.

Asthma

Exertional dyspnea has long been recognized as a factor contributing to restriction of physical activity and a poor level of

fitness in asthmatic children.¹⁰⁹ There were initially fears that attempts to normalize the fitness levels of asthmatic children by a vigorous training program might be hazardous, unless the activity was performed in an indoor pool,¹¹⁰ where a warm and humid atmosphere would reduce the risk of provoking bronchospasm. However, many investigators have now examined the effects of a wide variety of exercise programs in children with asthma (Table 2). The response has been examined both in terms of an improved physical capacity and an enhancement of clinical status.

Physical Work Capacity

Opinions remain divided as to whether exercise programs can enhance the physical capacity of an asthmatic child. There are a number of reasons for discordant results. In some cases, the test measures have been relatively simple: field performance tests,¹¹¹ distance runs,¹¹²⁻¹¹⁵ or a shuttle run.¹¹⁶ The scores on such tests tend to increase with time, because of growth of the child. Moreover, with one exception,¹¹⁶ the studies using such measures have not included a control group. Apparent gains of performance could therefore reflect test learning and habituation rather than a true training response, with increments of score being seen mainly in the form of exercise practiced during training.¹¹⁷ Thus, Nickerson and associates¹¹² reported an 11% increase in 12-minute run distance but no change of cycle ergometer performance or pulmonary function following a training program that involved 4 runs of up to 3.2 km per week for 6 weeks. In some studies, the prescribed dose of exercise has lacked the frequency^{109,118} or the intensity^{119,120} at which a training response might reasonably be anticipated. A further important interstudy variable has undoubtedly been the initial physical condition of the children, long recognized as an important determinant of the training response.¹²¹ Some children (generally those with more severe asthma) have entered trials with a very low level of fitness, giving them much scope for training, but a response has inevitably been less likely in comparison groups who began with a fairly normal

level of fitness.¹²²⁻¹²⁴ Finally, the response to almost all testing of physical capacity depends in part on the motivation of the participant; the confidence of the asthmatic children may have been enhanced and their medication optimized as a result of participation in a training program, thus boosting their final test scores.

Several authors have underlined the potential to normalize exercise performance in children with severe asthma. Ludwick and associates¹²⁵ reported that 12-minute cycle ergometer sessions carried to peak power and repeated 2 to 6 times per week for 2 to 17 weeks brought 84% of 47 severe cases of asthma to a normal ergometer physical work capacity. Likewise, Strunk et al¹¹⁴ noted that although the 9-minute run score was initially below the 50th percentile in 91% of their asthmatic children, scores for three quarters of the group improved by an average of some 10% over a 1- to 12-month running program. van Veldhoven et al¹²⁶ noted gains in maximal oxygen intake and a lower heart rate in submaximal work following training, and Counil et al¹²⁷ reported increases in both aerobic and anaerobic power in response to their program. Other reported physiological benefits have included an increase in ventilatory efficiency following 3 months of biweekly swim training,¹²⁸ an increase in oxygen pulse,^{116,129} a faster heart rate recovery,¹¹³ a greater power output at the anaerobic threshold, and a small decrease in blood lactate concentrations immediately following exercise.¹³⁰⁻¹³² Several studies that reported no response to land-based training probably used an inadequate intensity and/or frequency of training sessions.¹¹⁸⁻¹²⁰ The most puzzling study is that of Fitch and colleagues,¹³³ who found no effect from running, although they had previously observed a response to swim training.¹¹⁰

A meta-analysis using the Cochrane database¹³⁴ was based on 8 randomized controlled trials of exercise in asthma, involving 226 participants >8 years of age. The type of training was not specified, and the minimum volume accepted for inclusion (>20 minutes, 2/wk) was less than optimal. Resting lung volumes and episodes of wheezing were unchanged by this dose of activity, but

(text continues on page 19)

Table 2.

Therapeutic Response to Exercise Training in Asthmatic Children

First Author	Measure	Sample	Training	Observed Response
Physical Capacity				
Petersen ¹¹¹	Field performance tests	18 M; aged 8-13 years	3 h gym training/wk for 8 months	Increased scores (but no controls, growth of child)
Hyde ¹⁰⁹	FEV _{1.0}	35, ? sex; aged 6-14 years	Abdominal, flexibility, and endurance exercises 1 h/wk for 9 months	Lung function improved in a few cases but worsened in others
Vavra ¹²⁰	Cycle ergometer	9 M, 7 F; aged 12-14 years	Three 1-h sessions/wk for 3 months (games and gymnastics)	No gain in peak oxygen intake
Fitch ¹¹⁰	Treadmill	46, ? sex, aged 9-16 years (moderate-severe)	Swim training 3-5/wk for 5 months	Increase of work rate at 170 beats/min
Leisti ¹²⁴	Cycle ergometer	8 M, 8 F; aged 9-14 years	60-minute various exercises 2/wk for 4 months	Physical work capacity +11% (most if unfit)
Graff-Lonnevig ¹¹⁹	Cycle ergometer	20 M; aged 9-14 years	1 h moderate gym training 2/wk for 2 years + skiing	No change of peak oxygen intake
Henriksen ^{130,131}	6-minute treadmill run	25 M, 17 F; aged 8-13 years	2/wk 90-min aerobic exercise for 6 weeks	Postexercise lactate shows small decrease
Schnall ¹⁴⁰	Postexercise heart rate	23 M, 8 F; aged 5-16 years	10 weeks swim, dry land, or combination training	Reduced postexercise HR with dry land or combined
Svenonius ¹³⁷	Cycle ergometer	37 M, 14 F; aged 8-17 years	Interval training and swimming 60 minutes 2/wk, for 3-4 months	11%-21% increase of work capacity No change in controls
Nickerson ¹¹²	12-minute run cycle ergometer	12 M, 3 F; aged 7-14 years (severe)	Running increasing to 3.2 km, 4/wk for 6 weeks	Run +11% (but no change in pulmonary function or cycle ergometer performance)
Orenstein ¹⁴⁴	Cycle ergometer	14 M, 9 F; aged 6-16 years (13 controls)	30-minute run 3/wk for 4 months	Peak power +9%, peak oxygen intake +15% relative to controls
Ramazanoglu ¹²⁹	Cycle ergometer	7 M, 16 F; aged 6-15 years	15 weeks of training, 4.5 h/wk	22% increase of physical work capacity (greatest in unfit participants)
Ludwick ¹²⁵	Peak power cycle ergometer	40, ? sex, aged 8-17 years (severe)	2-17/weeks 12-minute cycle to peak power 2-5 times/wk	84% participants improved to normal peak power

(continued)

Table 2. (continued)

First Author	Measure	Sample	Training	Observed Response
Physical Capacity				
Fitch ¹³³	Treadmill	?	3 months running	No change of maximal oxygen intake
Szentagothai ¹¹³	12-minute run	82 M, 39 F; aged 5-14 years	4 h/wk of run, swim, and gymnastics for 1 year	Final 12-minute run scores as in normal children
Strunk ¹¹⁴	9-minute run	42 M, 34 F; aged 9-17 years (moderate-severe)	2/wk 90-min aerobic training for 6 weeks	75% of group improved distance run by >10%
Edenbrandt ¹¹⁸	Cycle ergometer	12 M, 8 F; aged 7-13 years	Physiotherapy + 1 h/wk endurance activities	No gains of peak power
Varray ¹³⁹	Cycle ergometer	6 M, 1 F; aged 9-13 years	30-minute aerobic training 2/wk for 3 months	Gain of peak oxygen intake relative to controls
Ahmaidi ¹¹⁶	Shuttle run Cycle ergometer	28 M, 20 F; aged 10-17 years (mild-moderate)	3 × 10-minute run, 3/wk for 3 months	16% gain of maximal oxygen intake; no change in controls
Varray ¹²⁸	Cycle ergometer	7 M, 2 F; aged 9-12 years	30-minute swim 2/wk for 3 months at individual ventilatory threshold	Increased ventilatory efficiency relative to controls
Matsumoto ¹³⁸	Cycle ergometer Swim ergometer	7 M, 1 F; aged 9-12 years (mild-moderate)	Swim at 125% lactate threshold 2 × 15 minutes, 6/wk for 6 weeks	Peak power +15% relative to controls; also gains on swimming ergometer
Neder ¹²³	Maximal oxygen intake cycle ergometer prediction FEV _{1.0}	15 M, 11 F; aged 8-16 years (moderate-severe) ? Intensity	2 months cycle ergometer 30 minutes thrice/wk	+5.5% (but to +16% in unfit)
van Veldhoven ¹²⁶	Treadmill run Cycle ergometer	34 M, 13 F; aged 8-13 years (light-moderate)	2/wk 60-minute aerobic sessions for 3 months, 1/wk 20-minute home training	7% gain in peak oxygen intake, treadmill endurance time +50%, lung volumes unchanged
Counil ¹²⁷	Cycle ergometer	7 M; aged 8-13 years (7 controls) (mild-moderate)	3/wk 45-minute cycle ergometry for 6 weeks	Maximal oxygen intake +9%, peak power +12%
Basaran ¹¹⁵	Cycle ergometer 6-minute walk	31; 10.4 years (31 controls)	8-week basketball training	Gains, not in controls
Fanelli ¹³²	Treadmill	21; ? sex, aged 7-15 years	1-hour endurance 2/wk for 16 weeks	Peak oxygen intake +11% Power at anaerobic threshold increased; no change in controls

(continued)

Table 2. (continued)

First Author	Measure	Sample	Training	Observed Response
Clinical Benefits				
Petersen ¹¹¹	Clinical status	18 M; aged 8-13 years	3-hour gym training/wk for 8 months	Fewer asthma attacks, reduced absenteeism
Sly ¹⁴²	Clinical status	9 M, 3 F; aged 9-13 years	Three 2-hour sessions/wk for 13 weeks; swimming, running, and gym training	Reduced wheezing Improved mood state
Fitch ¹¹⁰	EIB Use of medication	46, ? sex; aged 9-16 years (moderate-severe)	Swim training 3-5/wk for 5 months	No change Decreased
Henriksen ^{130,131}	FEV _{1.0} , peak expiratory flow postexercise	2 M, 5 F	2/wk 90-minute aerobic exercise for 6 weeks	Decrease in FEV _{1.0} halved, 27% smaller drop in peak flow
Svenonius ¹³⁷	EIB after treadmill run	37 M, 14 F; aged 8-17 years	Interval training and swimming 60 min 2/wk, for 3-4 months	Decreased
Nickerson ¹¹²	Clinical status, EIB	12 M, 3 F; aged 7-14 years (severe)	Running increasing to 3.2 km, 4/wk for 6 weeks	No change
Ramazanoglu ¹²⁹	EIB	7 M, 16 F; aged 6-15 years	15 weeks of training, 4.5 h/wk	No change
Orenstein ¹⁴⁴	Symptoms	14 M, 9 F; aged 6-16 years (13 controls)	30-minute run 3/wk for 4 months	No change
Fitch ¹³³	Clinical status	?	3 months running	No change in asthma severity but confidence improved
Szentagothai ¹¹³	Clinical status	82 M, 39 F; aged 5-14 years	4 h/wk of run, swim, and gym for 1 year	Decrease of symptoms, medications, absenteeism, and hospitalization
Huang ¹⁴³	Clinical status	33 M, 12 F; aged 6-12 years	3 × 1-hour swimming/wk for 3 months	Less wheezing, asthma; fewer medications; less hospitalization and absenteeism
Olivia ¹⁴⁷	Clinical status	10 M, 2 F; aged 9-14 years	12-day camp; 2 months weekly swimming	Improved morale and confidence
Wardell ¹⁴⁶	Clinical status	38 M, 35 F; ? ages	Weekly swim for 2.4 years	Less absenteeism, fewer doctor visits, less hospitalization
Engstrom ¹⁴⁵	Clinical status	10 M; aged 9-12 years	45-minute swim or gym 2/wk for 8 months	Fewer medications, less hospitalization; enhanced mood state

(continued)

Table 2. (continued)

First Author	Measure	Sample	Training	Observed Response
Clinical Benefits				
Varray ¹³⁹	Clinical status	6 M, 1 F; aged 9-13 years	30-minute aerobic training 2/wk for 3 months	Less wheezing, fewer asthmatic attacks, less medication
Matsumoto ¹³⁸	EIB	7 M, 1 F; aged 9-12 years (mild-moderate)	Swim at 125% lactate threshold 2 × 15 minutes, 6/wk for 6 weeks	Decreased
Neder ¹²³	Clinical score, EIB Medication use	15 M, 11 F; aged 8-16 years (moderate-severe)	2 months cycle ergometer 30 minutes thrice/wk ? Intensity	No change Reduced, especially if gain of maximum oxygen intake, but no controls
van Veldhoven ¹²⁶	EIB	34 M, 13 F; aged 8-13 years (light-moderate)	2/wk 60-minute aerobic sessions for 3 months	No change
Basaran ¹¹⁵	Quality of life	31 participants, 10.4 years (31 controls)	8-week basketball training	Gains, not in controls
Fanelli ¹³²	EIB, quality of life	21 participants, ? sex; aged 7-15 years	1 hour, 2/wk endurance training for 15 weeks	EIB reduced; quality of life increased

Question marks indicate that the data are unavailable. HR, heart rate; EIB, exercise-induced bronchospasm.

maximal oxygen intake was increased by about 10% (5.6 mL/[kg·min]).

Bronchospasm is less likely to be induced by swimming than by running or cycling,^{135,136} and this may favor a response to pool training. Some of the advantage of swimming probably comes from the warm and humid air in an indoor pool, although Inbar and associates¹³⁶ also found less bronchospasm in swimmers even after matching for these factors. Certainly, 6 of 7 studies that evaluated swim training reported gains of aerobic performance.* The one dissident report noted improved performance on a treadmill test only when swimming was combined with running training.¹⁴⁰ The response to swimming is highly dependent on the learning of technique, and this could explain the decrease of

postexercise heart rate reported by Schnall and associates¹⁴⁰ and the increase in 9-minute swimming distance seen by Fitch and colleagues,¹¹⁰ although not the gains of treadmill or cycle ergometer performance seen in other studies.

Although the above findings would seem to encourage the inclusion of swim training in any conditioning program for asthmatic children, there remains a possible long-term risk to the development of the lungs from the chlorine derivatives used to disinfect pools (see below).¹⁴¹ This aspect of swim training merits further study.

Clinical Status

Although physiologists have tended to focus on gains in exercise performance, from the viewpoint of the asthmatic child

and his or her parents, the enhancement of clinical status is usually of greater concern (Table 2). Reported clinical benefits following training have included fewer symptoms, particularly wheezing (noted by some researchers^{113,139,142,143} but not by others¹⁴⁴), fewer attacks of asthma or exercise-induced bronchospasm (reported by about a half of studies[†] but not other studies[‡]), a reduced use of medications,[§] less absenteeism from school,^{111,113,143,146} fewer visits to the doctor and less need for hospitalization,^{113,143,145,146} and an enhanced mood state or quality of life.^{||}

Mechanisms of Benefit

Asthma is strongly influenced by the psyche. Thus, if training brings an asthmatic child to a level of physical ability that matches that of his or her peers,

*References 110, 113, 128, 137-139.

†References 111, 130-132, 137-139, 143.

‡References 112, 123, 126, 129, 133.

§References 110, 113, 123, 139, 143, 145.

||References 115, 132, 133, 142, 145, 147.

confidence will be increased, and attacks will be less likely. A strengthening of the peripheral muscles will also decrease the likelihood of lactic acid production and thus the ventilation induced by any given rate of working. This, in turn, will decrease the likelihood of mouth breathing and the attendant effects of cold dry air and air pollutants on the bronchi.¹²² Strengthening of the chest muscles will also allow a faster inspiration and a slower expiration, with a reduced risk of airway collapse during expiration. Indirect benefits may arise from the psychosocial effects of involvement in an exercise class, together with incidental advice on medication and management of the condition from those operating the programs. Neder and associates¹²³ found that a reduced use of both oral and inhaled steroids was most apparent in those individuals who had improved their maximal oxygen intake.

Some authors have found evidence that training reduces susceptibility to exercise-induced bronchospasm, but any benefit is not necessarily reflected in a reduced sensitivity to histamine or other triggering irritants. This might indicate that training had caused some specific desensitization of the airways,^{138,146} but it is also possible that because of an increase in aerobic fitness, a comparable submaximal work rate generates a smaller respiratory minute volume and thus reduces the risk of exercise-induced bronchospasm.

Cystic Fibrosis

In part because of breathlessness and resulting restriction of vigorous physical activity, and in part because of poor nutrition and chronic infection, children with cystic fibrosis tend to have a limited muscle mass, with associated low levels of aerobic and anaerobic fitness,¹⁴⁸ as well as poor scores on field tests such as a 6-minute walk test.¹⁴⁹ Nevertheless, an appropriate program of aerobic training seems beneficial. Sputum clearance is enhanced, physical condition is improved, lean body mass is increased, and muscle strength is enhanced (Table 3).

In one early study, Godfrey and Mearns¹⁵⁰ examined a sample of 41 participants aged 5 to 21 years, finding that

in the more severe cases, the peak aerobic power was less than 70% of that seen in healthy individuals of comparable age. A low peak oxygen intake was associated with a 3-fold increase of mortality over an 8-year prospective study.¹⁵¹ It remains to be established whether this simply reflects disease severity or whether a program designed to increase peak oxygen intake could have enhanced prognosis for the children concerned. The peak anaerobic power is also compromised in cystic fibrosis.¹⁵² Boas and associates¹⁵³ found that in children with cystic fibrosis aged 11 to 18 years, the peak anaerobic power was 11% less than that seen in controls.

There is a growing consensus that regular exercise can enhance both cardiac and respiratory function in children with cystic fibrosis. A small observational study by Stanghelle and colleagues¹⁵⁴ reported that children who elected to exercise regularly showed gains in maximal oxygen intake and FVC relative to those who did not. Orenstein and associates¹⁵⁵ carried out uncontrolled trials of either stepping or upper body exercise in 67 patients aged 8 to 18 years. After 3 sessions per week for 1 year, lifting ability was much improved, particularly in the group that had undertaken strength training. Aerobic training sustained maximal aerobic power (although this declined over the study in the group who received strength training). However, static and dynamic lung volumes remained unchanged in either group. An uncontrolled trial of home cycle ergometry (20-minute sessions, 5 times per week for 6 months) in 14 patients aged 14 years noted increased leg strength, a reversal of the loss of maximal oxygen intake seen in an initial 6-month period without training, and a gain of perceived competence; nevertheless, pulmonary function scores remained unchanged.¹⁵⁶ A controlled trial in 66 children aged 8 to 16 years¹⁵⁷ confirmed that aerobic training (30 minutes, 5 times per week) had a greater impact on oxygen transport (+22%), whereas resistance training for the upper and lower limbs had more effect on strength (+18%); both regimens improved the FEV_{1.0} and the quality of life relative to a control group. The authors thus recommended adopting

a combined aerobic and strength training program for children with cystic fibrosis. A small controlled trial of anaerobic exercise (short bursts of activity for 30–45 minutes, twice per week for 12 weeks) also improved aerobic power (+6%), anaerobic power (+12%), and health-related quality of life relative to controls; however, in this study, FEV_{1.0} remained unchanged.¹⁵⁸

Despite reports of inspiratory muscle fatigue, it remains to be determined how much benefit cystic fibrosis patients can derive from a specific training of the inspiratory muscles. One small controlled study²⁹ applied inspiratory threshold loading (up to 40% of maximal inspiratory pressure) for 20 minutes per day, 5 days per week, over a 6-week period. At the end of the trial, the 8 experimental patients (average age 17 years) showed an increase of inspiratory endurance, but nevertheless, there was no change in their pulmonary function, dyspnea, fatigue, or exercise capacity relative to controls. Other investigators reached similar conclusions.^{159,160} Twenty-five minutes of normocapnic hyperventilation 5 days per week increased ventilatory muscle endurance by 52%, comparable with that achieved by 4 weeks of swimming and canoeing at a summer camp, but there were no other improvements in pulmonary function.¹⁶⁰ One trial of 10 children adopted a larger stimulus (resistance equivalent to 60% of maximal inspiratory pressure) for 30 minutes per day over 10 weeks; this group showed not only gains in inspiratory muscle endurance but also improvements in pulmonary function and exercise capacity.³⁰

Now that modern treatment is prolonging survival, inadequate bone mineral accrual is an important late complication of cystic fibrosis; regular weight-bearing physical activity can play an important role in alleviating this problem.¹⁶¹

Neuromuscular Disorders

Weakness and/or poor coordination of the respiratory muscles can become an important factor limiting physical activity in a variety of chronic neuromuscular disorders such as Duchenne muscular dystrophy and cerebral palsy. Interest has thus been shown in the possibility

Table 3.

Functional Status and Response to Training in Cystic Fibrosis

First Author	Sample	Findings
Nixon ¹⁴⁸	18 M, 12 F; CF 7-17 years; 17 M, 13 F controls	BMI 98% vs 112% prediction Cycle ergometer $\dot{V}O_{2max}$ 36.5 vs 41.4 mL/[min] Vigorous activity 2.0 vs 3.7 h/wk
Gruber ¹⁴⁹	286 CF, aged 6-18 years	Poor 6-minute walk (676 ± 74 m) Score increased 4.4% with training (45 minutes, 5/wk for 4-6 weeks)
Godfrey ¹⁵⁰	41 CF, aged 5-21 years	Cycle ergometer maximal power output decreased with disease severity Grade 1: 97% predicted; grade 2: 82% predicted; grade 3: 69% predicted
Nixon ¹⁵¹	109 CF, aged 7-35 years	8-year survival dependent on $\dot{V}O_2$ peak: 83% survival if >82% predicted, 51% survival if 59%-81% predicted, 28% survival if <58% predicted
Boas ¹⁵³	41 M CF, aged 11-18 years; 37 M controls	Wingate test: mean anaerobic power 350 vs 425 W, 8.9 vs 9.6 W/kg; peak power: 525 vs 666 W, 13.4 vs 15.0 W/kg
Stanghelle ¹⁵⁴	9 M CF, aged 16 years	Patients who elected to exercise had gains of $\dot{V}O_{2max}$ and forced vital capacity relative to those who did not
Orenstein ¹⁵⁵	67 CF, aged 8-18 years	12 months training on stair-stepping machine or 12 months resistance exercise (3/wk). Increased lifting ability, but no gains of $\dot{V}O_{2max}$ or FEV _{1.0}
Gulmans ¹⁵⁶	9 M, 5 F CF; aged 14 years	Cycle ergometry 20 minutes, 5/wk for 6 months increased leg strength, reversed loss of $\dot{V}O_{2max}$, and enhanced perceived competence. No changes of vital capacity or FEV _{1.0}
Selvadurai ¹⁵⁷	66 CF, aged 8-16 years	22 treadmill or cycle ergometer training (30 minutes, 5/wk), 22 non-isokinetic resistance training, 22 controls; study duration unclear. Aerobic training $\dot{V}O_{2peak}$ +22%, FEV _{1.0} +7%, body mass +3%, quality of life +4%. Resistance training FEV _{1.0} +10%, lower limb strength +18%, body mass +7%; controls FEV _{1.0} +3%, body mass +3%
Klijn ¹⁵⁸	20 CF, 13.6 ± 1.3 years (9 as controls)	Anaerobic training (20- to 30-second bursts for 30-45 minutes, 2/wk for 12 week. Aerobic power +6%, anaerobic power +12%, relative to controls. No change of FEV _{1.0}

CF, cystic fibrosis; BMI, body mass index.

of alleviating such problems by a specific training of the respiratory muscles, using such approaches as periods of maximal voluntary ventilation or breathing through a narrow aperture or against a loaded inspiratory valve.¹⁶²

Duchenne Muscular Dystrophy

There has been much research on the value of inspiratory loading in Duchenne muscular dystrophy¹⁶³ (Table 4).

Training of such children is best begun in the early stages of the disease. A crossover

trial on 22 boys aged 9 to 14 years found no gains of FVC, FEV_{1.0}, or peak expiratory flow rate in response to performing 20 inspirations per day for 18 days, using a "triflow spirometer" where resistance increased with the rate of inspiration.¹⁶⁴ Several other authors also failed to induce gains of lung volumes in response to such training.¹⁶⁵⁻¹⁶⁸ Possibly, the training period was too short. Winkler and associates³² had 16 patients with neuromuscular dystrophy (13 with Duchenne dystrophy) undertake 9 months of home training, using a variable inspiratory

resistance. Ages ranged quite widely from 8 to 29 years. At the end of the 9 months, there were significant gains in both the maximal inspiratory pressure and the 12-second maximal voluntary ventilation relative to the control participants (where there had been a substantial functional decline), although gains were seen only in those individuals whose VC had declined by less than 10% in the year preceding the trial.

Even if training can increase respiratory endurance,^{165,166} the clinical value of such gains remains debatable. In 1 investigation,

Table 4.

Functional Status and Response to Inspiratory Muscle Training in Myopathies

First Author	Sample	Findings
Duchenne Muscular Dystrophy		
Rodillo ¹⁶⁴	22 M, aged 9-14 years	Crossover trial. No gains of FVC, FEV _{1.0} , or peak expiratory flow rate with 18 days of 20 inspirations/d against inspiratory resistance
Smith ¹⁶⁷	8 participants aged 8-10 years	Crossover trial. No significant changes in maximal voluntary ventilation, vital capacity, or maximal static inspiratory pressure with 5 weeks of inspiratory resistance training (10-15 min/d)
Vilozni ¹⁶⁸	15 participants	Respiratory muscle training using video games 10 min/d for 23 days. Maximal voluntary ventilation +12%, maximal hypercapnic ventilation +53%, duration of isocapnic hyperventilation +57% in moderately impaired patients
Winkler ³²	13 Duchenne, 3 spinal muscular atrophy, aged 8-29 years	Inspiratory muscle training for 9/12. Gains of maximal inspiratory pressure and MVV but only in patients whose vital capacity decreased by <10% in previous year
Wanke ¹⁶⁹	30 Duchenne (15 as controls) 13.6 years	Inspiratory muscle training for 6/12 (10 one-minute loaded cycles/d + 10 max inspiratory efforts/d). No gains of VC, FEV _{1.0} , or MVV but gains of peak inspiratory pressure in 10/15 patients with less severe disease
Topin ¹⁷⁰	16 Duchenne (8 as controls) 14.7 years	Inspiratory resistance training 6 weeks, 2 × 10 min/d at 30% maximum inspiratory pressure; 46% increase in endurance time breathing against specified load
Cerebral Palsy		
van den Berg-Emons ¹⁷¹	8 CP 8.8 years	Peak aerobic and anaerobic power measurements reliable (test/retest $r = 0.72-0.96$). Isokinetic tests less reliable in CP
Hoofwijk ¹⁷³	9 CP 13.5 years, 9 controls	Treadmill $\dot{V}O_{2max}$ 72% of control, ventilatory equivalent for oxygen 123% of control
da Silva ²⁵⁹	16 CP (athletes), 12 controls age 25 years	Patients with CP show tachypnea during exercise, reduced MVV, normal $\dot{V}O_{2max}$
Parker ¹⁷⁴	29 M, 20 F CP; aged 6-14 years	Peak and mean anaerobic power 2-4 SD less than norms, even when adjusted for body mass (dependent on disease severity)
Bar-Or ¹⁷²	26 CP aged 15-22 years (9 did not exercise)	12 months mild aerobic conditioning (2 hours, 2/wk). Initial $\dot{V}O_{2max}$ 21.3 mL/[kg×min], 8.5% gain of $\dot{V}O_{2max}$, 5.9% gain of maximal ventilation
Hutzler ¹⁷⁹	46 CP (kindergarten)	6 months, 30-minute sessions swimming (2/wk) + gymnastics (1/wk) or physiotherapy. Vital capacity initially low in both groups but increased 65% with exercise, 23% with physiotherapy
Verschuren ¹⁸⁰	65 CP 7-18 year (33 controls)	Circuit training (aerobic + anaerobic) for 45 minutes 2/wk for 8 months. Gains in shuttle run, sprint, and agility relative to controls

FVC, forced vital capacity; VC, vital capacity; MVV = maximal voluntary ventilation; CP, cerebral palsy.

Wanke and associates¹⁶⁹ trained 15 patients with an average age of 13.6 years daily for 6 months; they used a variable inspiratory resistance (10 one-minute loaded cycles/d, plus 10 maximal inspiratory efforts/d), offering a video game reward to encourage compliance. No gains of VC or maximal voluntary ventilation were seen, although the maximum inspiratory and expiratory pressures and respiratory endurance were all substantially increased relative to control participants. Gains in respiratory endurance were largely retained 6 months after ceasing training. In another controlled study, a relatively light loading was chosen to encourage compliance. Eight children of an average age of 14.7 years undertook 6 weeks of resisted breathing (10 minutes, twice per day) against an inspiratory valve that opened at 30% of maximal inspiratory pressure.¹⁷⁰ This program did not increase the strength of the respiratory muscles, as gauged by the individuals' maximal inspiratory pressure, but it was sufficient to increase the endurance time of the children by 46% when they were breathing against a specified load; the performance of the control group remained unchanged over the same period.

Cerebral Palsy

A study of children with cerebral palsy (average age 8.8 years) showed that despite their disability, it was possible to make reliable measurements of peak aerobic and anaerobic power (test/retest correlation, $r = 0.72-0.96$).¹⁷¹ Because of logistic problems, observations on such children have generally used a cycle ergometer or an arm ergometer rather than a treadmill. Oxygen transport values have generally been peak rather than maximal in type but nevertheless have been low relative to normal children (Table 4).^{172,173} The reported anaerobic power has also been less than in control participants.¹⁷⁴ However, in most children with cerebral palsy, performance is probably limited more by mechanical inefficiencies caused by muscle spasm than by the maximal oxygen intake or anaerobic performance per se.¹⁷⁵⁻¹⁷⁷

One recent review found that children with cerebral palsy benefited from training programs that were directed at either

muscular strength or cardiorespiratory fitness.¹⁷⁸ Hutzler and associates¹⁷⁹ examined 46 kindergarten children with cerebral palsy; they were assigned to either standard physiotherapy or a 6-month program of swimming (twice per week) and gym training (once per week). Initially, both groups had poor lung function, but at the end of the training period, the VC of the exercise group had increased by 65%, compared with only 23% in the group receiving standard physiotherapy. A trial in 32 children aged 7 to 18 years found that 45 minutes of circuit training twice per week for 4 months enhanced aerobic and anaerobic capacity, strength, agility, and quality of life relative to controls.¹⁸⁰ Twelve months of mild conditioning in adolescents and young adults noted small gains in both maximal oxygen intake (+8.5%) and maximal ventilation during exercise (+5.9%).¹⁷²

Sleep Apnea and Obesity

The prevalence of sleep apnea in children is currently around 2%,¹⁸¹ although the problem may be becoming more common in parallel with the obesity epidemic. Mass loading decreases compliance of the chest wall in an obese person, but even in participants with a BMI of 40 kg/m², the mechanical problems of ventilation do not seem to be the main factors limiting physical exercise.¹⁸² Nevertheless, sleep apnea is commonly linked with a poor lifestyle, particularly obesity, a low level of physical activity, and choice of an atherogenic diet.¹⁸³⁻¹⁸⁶ Often there seems to be a favorable clinical response to some combination of dieting and increased energy expenditure,^{184,187-190} although there remains a need for more careful controlled trials.¹⁹¹

Much of the research has been conducted in adults rather than in children. Nevertheless, the risk factors noted in children (obesity and physical inactivity) are generally similar to those reported in adults.^{181,192-194} In 41 children and adolescents with morbid obesity (average 208% of their ideal weight), all snored at night, and frank apnea was seen in 32% of the group.¹⁹² In a sample of 383 adolescents aged 11 to 16 years, the risk of sleep disturbance increased by 80%, and

daytime physical activity decreased by 3% for each hour of lost sleep.¹⁹³ A controlled trial of high- versus low-dose exercise was undertaken in 100 randomly assigned children aged 7 to 11 years; the BMI of the group was at or above the 85th percentile.¹⁹⁵ Twenty or 40 minutes of aerobic exercise were provided 5 days per week for 13 weeks. Snoring improved in both high- and low-dose groups relative to control students. The greater response was seen in students given the higher dose of exercise (40 minutes per day), although weight loss was similar for the 2 groups, suggesting that some other factor such as appetite-regulating hormones may have contributed to the improvement in clinical status. Verhulst and associates¹⁹⁶ had obese teenagers with sleep disorders attend a residential treatment center. An average weight loss of 24 kg was achieved in 31 participants, and in most cases, there was a substantial associated improvement in their sleep disorder.

Potential Disadvantages of an Active Lifestyle and Their Avoidance

Having considered the beneficial effects of physical activity on respiratory health, we must now look carefully at some potential disadvantages. Physical activity inevitably increases the volume of inspiration, sometimes by a factor of 20 relative to the resting respiratory minute volume. The resting pattern of predominantly nasal breathing is thus replaced by oronasal or oral breathing. This bypasses the normal filtering, warming, and moisturizing functions of the nasal turbinate bones.¹⁹⁷⁻²⁰⁰ In adults, the transition from nasal to oronasal ventilation typically occurs at 4 to 5 times the resting respiratory minute volume.²⁰¹ The switching point has not been examined in children; because the head is larger relative to the rest of the body, a somewhat larger relative switching point might be envisaged in healthy children. However, the transition will occur early if the nose is blocked by a chronic allergic rhinitis; in some such children, mouth breathing may even be present at rest, although

this tendency can be helped by specific training of the inspiratory muscles.²⁰²

Both the large volumes of air inspired during vigorous exercise and the change of breathing pattern expose the individual to increased doses of allergens and air pollutants, along with the cold dry air that can precipitate bronchospasm and (rarely) severe anaphylactic reactions. Specific problems can also arise from the chlorine compounds used to disinfect swimming pools. In adults, very prolonged endurance exercise such as an ultra-marathon run can cause pulmonary edema^{203,204}; children are unlikely to compete over such distances, but there do not appear to have been any studies of lung water content in children following prolonged exercise. Finally, in adults, prolonged exercise such as a marathon run or a period of very heavy competitive training can increase an individual's vulnerability to upper respiratory infections.³⁸⁻⁴⁰ It has been claimed that such problems can be alleviated by taking large doses of vitamin C,²⁰⁵ although the relevant study relied on self-reports of infection, and it has been criticized because of an unusually high incidence of infections in both experimental and control groups. It is unlikely that children will compete at the levels causing problems in adults, and as yet there have been no reports that prolonged exercise has increased the risk of upper respiratory infections in children.

Allergens and Bronchospastic Reactions

In addition to the ventilatory factors noted above, some forms of outdoor physical activity increase an individual's exposure to allergens such as ragweed. Severe anaphylactic reactions are rare and are limited mainly to individuals who react adversely to other allergens such as specific foods.

Pollen

A study of 12 boys and 4 girls aged 8 to 15 years with mild asthma showed a substantially greater decrease of FEV_{1.0} following a treadmill challenge when pollen concentrations were high.²⁰⁶ Likewise, a study of adults found that exercise-induced bronchospasm was exacerbated in individuals who were allergic to birch

pollen.²⁰⁷ On the other hand, a 10-year prospective survey of 2429 participants initially aged 5 to 14 years found significantly higher rates of hay fever among those who were inactive than in those who were active, both at baseline and at follow-up.²⁰⁸

Exercise-Induced Bronchospasm

Bronchial spasm precipitated by running has been documented in children as young as 3 years old.²⁰⁹ Vigorous exercise is a precipitant of bronchospasm in a substantial minority of children. Usually, the attacks are no more than a nuisance, with a 10% to 20% decrease in forced expiratory volume.²¹⁰ Athletic performance is impaired, but attacks resolve spontaneously within a few minutes of ceasing the activity. One 8-year study identified 81 incidents where US athletes were thought to have died of a severe attack of asthma during or immediately following sports participation; most of the deaths were in the age group of 10 to 20 years.²¹¹

The primary cause of exercise-induced bronchospasm is usually the inhalation of large quantities of cold and/or dry air, combined with oronasal breathing.^{201,212-214} The prevalence of exercise-induced bronchospasm thus tends to be greater in sports that take place in cold environments (eg, skating, cross-country skiing, and ice hockey).²¹⁵ One laboratory trial demonstrated a halving of exercise-induced bronchospasm when the ambient humidity at 20°C was increased from 40% to 95%.²¹⁶ In some areas, problems may be compounded by seasonal increases in the airborne concentration of allergenic pollens. Problems in vulnerable children can be minimized by reducing mouth breathing and avoiding sports that require a cold environment. Alternatively, a face-mask can be used to warm and humidify the inspired air. One small controlled trial suggested that the incidence of bronchospasm could be reduced by a daily dose of fish oil (3.2 g EPA, 2.2 g DHA).²¹⁷

Anaphylactic Reactions

Major anaphylactic reactions to vigorous exercise have been recognized

since 1980,²¹⁸ although they are quite rare. Usually, the literature describes single cases, often associated with the eating of a specific type of food such as wheat.²¹⁹⁻²²² In severe cases, upper airway obstruction and vascular collapse can develop. Sometimes, problems appear to have been exacerbated by heavy doses of aspirin.²²¹

Orhan and Karakas²²³ noted that a boy with allergies to lentils and chickpeas developed an allergic reaction when he exercised 1 hour after ingesting a bowl of lentil soup. Pruritus and urticaria were associated with angioedema of the lips, hoarseness, and cough. Barg and associates²²⁴ described a case precipitated by the eating of celery. Generally, neither exercise nor food alone will trigger an attack, and problems can be avoided by avoiding the offending food for at least 4 hours prior to exercise. However, if the problem is severe, the affected individual is wise to carry an emergency kit that includes adrenaline and antihistamines.

Cold exacerbates exercise-induced bronchoconstriction, and it can occasionally trigger a severe allergic reaction.²²⁵ For instance, a 16-year-old boy gave a 4-year history of recurrent wheezing and dyspnea when he was jogging, playing handball, or cycling in cold weather, although in his case, no specific food allergies were detected. There have been reports of anaphylaxis developing in cold water, and occasionally this has been cited as a cause of drowning.^{226,227}

Air Pollutants

Vigorous exercise has the potential to increase exposure to a number of air pollutants: reducing smog, oxidant smog, fine and ultra-fine particulates, and carbon monoxide.²²⁸ Those using swimming pools may also be exposed to high concentrations of chlorine and its analogs, and scuba divers may encounter unusually high partial pressures of oxygen and free radicals.

Reducing Smog

Reducing smog comprises a mixture of carbon particles and oxides of sulfur. Ambient concentrations of these pollutants have fallen substantially in recent years, as increased restrictions have been

placed on the use of coal- and wood-burning appliances. In resting participants, the nasal turbinates precipitate much of the airborne particulate matter¹⁹⁸ and absorb as much as 90% of the oxides of sulfur^{197,199}; exposure is thus greatly increased by the oronasal breathing of vigorous exercise.

During the 20th century, severe adverse effects on health were seen in both the very young and in the elderly.²²⁹ However, at the concentrations currently encountered in the urban environment, the only likely consequence for a healthy child is some degree of bronchospasm and thus a deterioration of competitive performance; function quickly returns to normal once the episode of pollution has passed.

Concentrations of particulate matter and sulfur oxides vary widely across a city, depending on the local geography, typically rising during periods of thermal inversion.²³⁰ Except during a prolonged thermal inversion, the indoor concentration of reducing smog is substantially lower than that encountered outdoors; thus, any adverse effects on vigorous physical activity can be mitigated by exercising indoors during smog episodes.²²⁹

Oxidant Smog

The primary sources of oxidant smog are automobile and aviation exhaust. The main constituents are ozone and the oxides of nitrogen, the latter produced in the presence of bright sunshine. Concentrations of oxidant smog bear a temporal relationship to patterns of urban traffic flow, with peak levels following the morning rush hour. The ozone concentrations reached in some major cities are sufficient to cause transient deteriorations in exercise performance²³¹; more information is needed as to whether repeated exposures have adverse consequences for the development and aging of the lungs. Exposure can be minimized if training is undertaken in the early morning, before concentrations of oxidant smog have peaked.

Fine and Ultra-Fine Particulate Matter

Another possible atmospheric hazard currently attracting attention is the inhalation

of fine and ultrafine (nano)particles. Modern smoke stacks have eliminated most of the large particulate emissions, but precipitating devices have been less successful in controlling the output of fine and ultra-fine particulate matter. Nanoparticulates can penetrate deeply into the lungs, and they are sufficiently small to pass through the alveolar membrane. Molecular interactions with cellular proteins and DNA have the potential to cause immunological changes and resulting allergic reactions.²³²⁻²³⁴

Carbon Monoxide

The main source of carbon monoxide exposure for most children is automobile exhaust. Concentrations are narrowly localized to city streets where dense traffic is moving slowly and air movement is hampered by tall buildings.²³⁵ The physiological effects of carbon monoxide are similar in children and in adults: a rapid combination with hemoglobin reduces the oxygen-carrying capacity of the blood and modifies the shape of the oxygen dissociation curve. The end result is a small deterioration in an individual's maximal aerobic power.²³⁵ Effects in children are likely to be small unless they walk or cycle a substantial distance to school alongside major traffic arteries; the carbon monoxide is slowly released from the blood on returning to a region where concentrations are lower.

Chlorine

There has long been a suspicion that exposure to chlorine derivatives at indoor swimming pools could harm respiratory function. At the pH found in most pool water (7.2-7.8), the chlorine used as a pool disinfectant is hydrolyzed to hypochlorous acid (HOCl) or hypochlorite ion (OCl⁻).²³⁶ These compounds react with organic matter from sweat and/or urine to form various highly toxic compounds, particularly nitrogen trichloride, chloramide, and chlorimidine. Nitrogen trichloride is known to cause fatal pulmonary edema in rats. Concentrations vary with the quality of pool hygiene but are thought to be in the range of 0.1 to 1.0 mg/m³.

The immediate effects of a chlorinated pool seem relatively small in children.

One small-scale trial concluded that swimming sessions of sufficient duration to boost cardiorespiratory fitness did not increase symptoms in asthmatic children.²³⁷ However, a recent Belgian study of 226 ten-year-old children who were attending swimming lessons demonstrated a correlation between damage to the pulmonary epithelium (as estimated from the presence of lung proteins in the serum) and the frequency of pool attendance (0.5-6.5 h/wk).¹⁴¹ The findings were thought to be of clinical significance because the lung protein concentrations were also correlated with levels of IgE, the principal harbinger of asthma. Retrospective data on a larger sample of 1881 children further showed an association between a >10% postexercise decrease in FEV_{1.0} and the frequency of pool attendance, particularly in the younger members of the sample. The authors concluded that although the short-term risk of exercise-induced bronchospasm was reduced in the warm and humid air of an indoor pool, the long-term risks were probably increased because of chronic damage to the pulmonary epithelium.

There is certainly abundant evidence of an increased prevalence of airway hyper-responsiveness and airway inflammation in adult swimmers. Moreover, they show an increased level of eosinophil, peroxidase, and neutrophil lipocalin in the airways and sputum,^{215,236,238-241} although in at least 1 study, the increased airway responsiveness decreased or disappeared after the athletes' competitive careers had ended.²⁴⁰ A recent study of 33 elite adolescent swimmers found no evidence of pulmonary inflammation.²⁴² Another recent investigation sought evidence of lung inflammation in elite Scottish swimmers aged 11 to 16 years following 2 hours of intensive training in an indoor chlorinated pool; tidal and nasal concentration of nitric oxide (markers of such inflammation) did not increase immediately following swimming, although a surprising half of the 36 competitors complained of bronchial symptoms, and 36% had a positive bronchial response to an exercise challenge.²⁴³

Given the limited evidence of effects from exposure of children and elite

adolescent competitors to chlorine derivatives, it appears that any damage to lung structures is a relatively slow process, and is at least partially reversible once a swimmer's competitive career is completed.²⁴⁰

Scuba Diving and Oxygen Derivatives

One final respiratory hazard is presented by the sport of scuba diving. Adult scuba divers demonstrate an increased total lung capacity, a reduced pulmonary diffusing capacity, and airway obstruction, caused partly by the irritant effects of high partial pressures of oxygen and oxidants in their breathing systems.²⁴⁴ Even in teenage divers, those who explore to great depths show a faster deterioration of forced expiratory flow rates than are seen in healthy controls, suggesting a need for caution when pursuing this sport, irrespective of the individual's age.

Conclusions

As with many aspects of child health, it appears that adoption of a physically active lifestyle with an appropriate diet, as well as avoidance of obesity and cigarette smoke, is conducive to optimal development of the respiratory system; lifestyle choices can influence static and dynamic lung volumes and efficiency of the ventilatory process. There is some evidence that the risk of developing asthma is less in children who maintain a normal body mass and are physically active. A program of graded physical activity is also of therapeutic value in a number of established respiratory conditions, including asthma, cystic fibrosis, and ventilatory impairment from neuromuscular disorders. In designing an optimal physical activity program, it is important to guard against some of the hazards of deep breathing, including the precipitation of bronchospasm by the inhalation of cold, dry air and pollens; the slight risks of fatalities from asthma and anaphylactic reactions; the potential for increased exposure to atmospheric pollutants (reducing and oxidant smog, fine particulates, and carbon monoxide);

and the specific long-term hazard posed by chlorine derivatives in indoor swimming pools. **AJLM**

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