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ORIGINAL ARTICLE

Daniel Courteix · Philippe Obert · Anne-Marie Lecoq
Patrick Guenon · Günter Koch

Effect of intensive swimming training on lung volumes, airway resistances and on the maximal expiratory flow-volume relationship in prepubertal girls

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Abstract The aim of the present study was to analyse the effect of 1 year of intensive swimming training on lung volumes, airway resistance and on the flow-volume relationship in prepubertal girls. Five girls [9.3 (0.5) years old] performing vigorous swimming training for 12 h a week were compared with a control group of 11 girls [9.3 (0.5) years old] who participated in various sport activities for 2 h per week. Static lung volumes, maximal expiratory flows (MEF) at 75, 50 and 25% of vital capacity, 1-s forced expiratory volume ($FEV_{1.0}$) and airway resistance (R_{aw}) were measured by means of conventional body plethysmograph techniques. Prior to the training period there were no significant differences between the two groups for any of the parameters studied. Moreover, for both groups, all parameters were within the normal range for children of the corresponding age. After 1 year of training, vital capacity (VC), total lung capacity (TLC) and functional residual capacity (FRC) were larger ($P < 0.05$) in the girl swimmers than in the control group, while physical development in terms of height and weight was similar. $FEV_{1.0}$ ($P < 0.01$), MEF_{25}, MEF_{50} ($P < 0.05$) and MEF_{75} as well as the ratio MEF_{50} / TLC ($P < 0.05$) had increased in the girl swimmers but were unchanged in the control group. R_{aw} tended to be lower in the girl swimmers and higher in the control group. The results indicate that intensive swimming training prepuberty enhances static and dynamic lung volumes and improves the conductive properties of both the large and the small airways. As to the causative mechanism, it can be speculated that at prepuberty intensive swimming training promotes isotropic lung growth by harmonizing the development of the airways and of alveolar lung spaces.

Key words Lung volumes · Maximal expiratory flow rates · Airway resistance · Maturation · Exercise

Introduction

Young swimmers have been shown to have larger lung volumes and a greater cardiorespiratory functional capacity than other children (Mead 1960; Engström et al. 1971; Andrew et al. 1972; Vaccaro et al. 1980). The impact of swimming training on the development of lung volumes has, however, yet to be clearly established. Swimming training may increase respiratory muscle strength, and thereby enhance the ability to inflate the lungs, or directly accelerate lung growth as an adaptive response to exercise (Zinmam and Gaultier 1986). It can also be presumed that only children endowed with large lung volumes pursue competitive swimming training. Most studies concerning pulmonary adaptation in swimmers have been confined to the measurements of static and dynamic lung volumes. However, dynamic lung volumes and in particular the 1-s forced expiratory volume ($FEV_{1.0}$) reflect the conductive properties of the large airways only. Conversely, the analysis of the flow-volume relationship during forced expiratory manoeuvres by means of maximal expiratory flow/volume (MEF/volume) curves allows assessment of the status of the small airways and thus yields additional information about the ventilatory capacity (Hyatt and Black 1973; Zapletal et al. 1976; Farrel 1981; Beardsmore et al. 1989). While the technique has been used in adults, both in healthy subjects and particularly in those with pulmonary disease, it is rarely applied to children (Beardsmore et al. 1989). There is no information about

D. Courteix (✉) · P. Obert
Laboratoire de la Performance Motrice,
Faculté du Sport et de l'Education Physique,
Université d'Orléans, rue de Vendôme,
BP 6749, F-45067 ORLEANS Cedex2, France

A.-M. Lecoq · P. Guenon
Laboratoire d'Explorations Fonctionnelles Respiratoires,
Centre Hospitalier Régional, 1 rue Porte-Madeleine,
F-45000 Orléans, France

G. Koch
Department of Physiology, Free University,
Arnimallee 22, D-14195 Berlin, Germany

the effect of endurance training on the functional properties of the small airways in child swimmers.

The primary purpose of the present study was therefore to assess the effect of intensive swimming training on the conductive properties of the small airways in terms of flow–volume characteristics in prepubertal girls. Furthermore, it attempted to assess the usefulness of flow–volume analysis for better understanding of the pulmonary system's functional modifications in swimmers.

Methods

Subjects

A total of 16 healthy girls took part in the study after having undergone a medical examination including an electrocardiogram. The aim and the protocol of the study were described to both the children and their parents and individual written consent was obtained. The study was approved by the Regional Bioethic Committee, Orleans, France. Among the 16 girls, 5 belonged to a local youth swimming team; 11 girls of identical age were recruited from primary schools and served as a control group. Both groups were matched concerning body height, body mass and biological maturation assessed according to Tanner (1962) and Marshall and Tanner (1969) (Table 1).

Training programme

From September 1993 to August 1994, the girls had four training sessions a week each lasting 2 h. During the first 3 months, the programme consisted essentially of games and technical swimming exercise. After December 1993 a more specific swimming training (long-distance swimming) dominated, the intensity being increased gradually. The total distance covered per week increased from 10 000 m to 15 000 m. During the same period, the girls participated in competitions with, on average, two events per month. After a pause during August 1994, the training programme started again in September 1994, the duration and intensity being further increased. At the time of the re-study (December 1994) the girls were training for 12 h per week, the weekly distance covered exceeding 20 000 m. The frequency of participation in competitions was unchanged (two per month).

With regard to swimming performance, the girls were situated well above swimmers of a similar age group. In fact, at the time of the re-study, all had qualified for the regional championships and had the same performances as those of experienced girl swimmers aged 13–14 years. The control group was much less active than the girl swimmers. They were engaged in various activities for only about 2 h per week.

Experimental procedures

Two series of studies were conducted, the first one in December 1993, the second one exactly one year later in December 1994, using the same protocol and techniques.

Vital capacity (VC), functional residual capacity (FRC), residual volume (RV) and total lung capacity (TLC) as well as $FEV_{1.0}$ were measured by means of a pressure-compensated volume displacement body plethysmograph (MASTERLAB, Jaeger) with the girls seated and breathing through a mouthpiece (Mead 1960). Only the best of three measurements was taken into account.

Maximal expiratory flow curves were recorded over the whole range of VC by means of an automatic electronic measuring device during a forced expiratory VC manoeuvre and maximal expiratory flows were calculated at 75, 50 and 25% of VC (MEF_{75}, MEF_{50}, MEF_{25}). Airway resistance (R_{aw}) was derived from plethysmographic measurements of pressure and flow (DuBois et al. 1956). All measurements were repeated until three reproducible values were obtained.

Statistical analysis

A Kolmogoroff-Smirnoff test and a suitable Shapiro-Wilk test for small samples were used to verify that the values showed a satisfactory Gaussian distribution. Pre- and post-training data in each group were compared by means of Student's *t*-test for paired data. Significant differences between groups were identified by analysis of variance. All tests were done using the "Programme Conversationnel de Statistiques pour les Sciences et le Marketing" (PCSM).

Results

As shown in Table 1, there were no differences in body height and mass between the experimental and the control groups either at the pre- or the post-training examinations. Moreover, at the time of the post-training study, all the girls were still prepubescent and corresponded to the first stage of maturation according to Marshall and Tanner (1969), i.e. not exhibiting any breast development or appearance of pubic hair.

There were no significant differences between the experimental and the control group regarding static lung volumes, $FEV_{1.0}$, R_{aw} and the maximal expiratory flows at the initial pre-training study (Tables 2 and 3). In both groups, all data obtained were in accordance with predicted normal values (Zapletal et al. 1987). After 1 year of intensive swimming training, VC, FRC and TLC were significantly greater ($P < 0.05$) in the swimmers than in the control group while the ratios FRC/TLC and RV/TLC were mainly unchanged. $FEV_{1.0}$ and

Table 1 Anthropometric characteristics before (*Pre*) and after (*Post*) 1 year of training [means (SD)]

		Experimental $n = 5$	Control $n = 11$	Statistical significance of between-group differences
Age (year)	Pre	9.3 (0.5)	9.4 (0.5)	NS
	Post	10.3 (0.6)***	10.3 (0.4)***	NS
Height (cm)	Pre	135 (4)	130 (9)	NS
	Post	142 (5)***	136 (10)***	NS
Mass (kg)	Pre	30.5 (2.8)	28 (4.4)	NS
	Post	32.6 (3.2)*	29.3 (3.7)	NS

* $P < 0.05$, *** $P < 0.001$ post-versus pre-training study, NS: not statistically significant

Table 2 Lung volume characteristics in the experimental and the control groups before (*Pre*) and after (*Post*) 1 year of training [means (SD)]. (*VC* Vital capacity, *FRC* functional residual capacity, *RV* residual volume, *TLC* total lung capacity)

		Experimental $n = 5$	Control $n = 11$	Statistical significance of between-group differences
VC (l)	Pre	2.25 (0.13)	1.97 (0.32)	NS
	Post	2.56 (0.19)**	2.15 (0.39)**	$P < 0.05$
FRC (l)	Pre	1.36 (0.07)	1.31 (0.31)	NS
	Post	1.63 (0.25)	1.28 (0.30)	$P < 0.05$
RV (l)	Pre	0.63 (0.14)	0.78 (0.27)	NS
	Post	0.74 (0.21)	0.63 (0.20)	NS
TLC (l)	Pre	2.89 (0.22)	2.72 (0.47)	NS
	Post	3.31 (0.34)*	2.81 (0.42)	$P < 0.05$
RV/TLC	Pre	0.22 (0.05)	0.29 (0.08)	NS
	Post	0.22 (0.05)	0.22 (0.07)*	NS
FRC/TLC	Pre	0.47 (0.02)	0.48 (0.05)	NS
	Post	0.49 (0.04)	0.45 (0.06)	NS

* $P < 0.05$, ** $P < 0.01$ post versus pre-training study, NS: not statistically significant

Table 3 Forced expiratory flows and airway resistances in the experimental and the control groups before (*Pre*) and after (*Post*) 1 year of training [means (SD)]

		Experimental $n = 5$	Control $n = 10$	Statistical significance of between-group differences
$FEV_{1.0}$ $(\mathrm{l \cdot min^{-1}})$	Pre	1.90 (0.21)	1.75 (0.26)	NS
	Post	2.26 (0.22)	1.83 (0.34)	$P < 0.01$
	Δ%	18.9**	4.8	
R_{aw} $(\mathrm{kPa \cdot l^{-1} \cdot s^{-1}})$	Pre	0.48 (0.14)	0.43 (0.11)	NS
	Post	0.46 (0.13)	0.55 (0.11)	NS
	Δ%	−4.2	26.1*	
PEF $(\mathrm{l \cdot s^{-1}})$	Pre	4.22 (0.85)	4.19 (0.63)	NS
	Post	4.40 (0.78)	4.09 (1.16)	NS
	Δ%	4.3	−2.5	
MEF_{25} $(\mathrm{l \cdot s^{-1}})$	Pre	3.61 (0.71)	3.71 (0.65)	NS
	Post	4.13 (0.83)	3.72 (0.97)	NS
	Δ%	14.5	0.2	
MEF_{50} $(\mathrm{l \cdot s^{-1}})$	Pre	2.16 (0.54)	2.49 (0.55)	NS
	Post	2.93 (0.67)	2.38 (0.56)	$P < 0.05$
	Δ%	35.6	−4.6	
MEF_{75} $(\mathrm{l \cdot s^{-1}})$	Pre	1.10 (0.35)	1.14 (0.31)	NS
	Post	1.33 (0.37)	1.04 (0.27)	NS
	Δ%	20.9	−9	

(*$FEV_{1.0}$* One-second forced expiratory volume, *PEF* peak expiratory flow, R_{aw} total airway resistance, *MEF* maximal expiratory flow at 25%, 50% or 75% of vital capacity, Δ% percentage change of post- from pre-training values)
* $P < 0.05$, ** $P < 0.01$, NS: not statistically significant

MEF_{50} increased by roughly 18% ($P < 0.01$) and 15% ($P < 0.05$) respectively (Table 3) and MEF_{50} related to TLC (MEF_{50}/TLC) by 23% ($P < 0.05$) in the girl swimmers (Table 4); there was also a clear-cut tendency towards higher values for MEF_{25} (35%) and MEF_{75} (21%) (Table 3) and MEF_{25}/TLC (18%) and MEF_{75}/TLC (7%), while there was no change in these values for the control group. The flow-volume curve significantly shifted to the right in the girl swimmers only (Fig. 1), indicating that they had higher maximal flows at each percentage of VC.

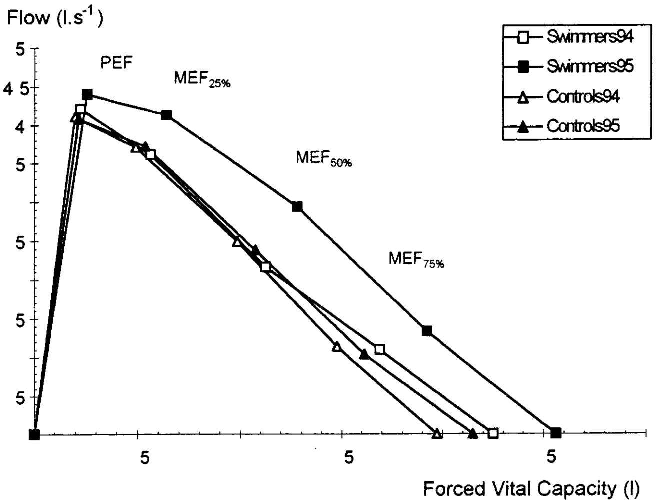

Fig. 1 Flow-volume curves in girl swimmers and controls before and after 1 year of training. Maximal expiratory flow rates are plotted at 25, 50 and 75% of vital capacity (*PEF* Peak expiratory flow)

Discussion

The results of the present study demonstrate that 1 year of intensive endurance training induces a significant increase in static and dynamic lung volumes and, in particular, an improvement of the flow-volume relationship in prepubertal girl swimmers in comparison with children who had a normal level of physical activity. They do not support the presumption that the children who choose to continue competitive swimming training are primarily endowed with large lung volumes.

Concerning the flow-volume relationship, similar observations have been reported by Farrel (1981) in adults: he found that MEF between 200 and 1200 ml of FVC increased after only 8 weeks of endurance training and attributed this finding to an improved contractility of the expiratory muscles as a result of endurance training. In fact, it has been suggested that ventilatory muscles, like other skeletal muscles, can increase their strength and endurance capacity in response to specific training (Leith and Bradley 1976). However, some observations seem to indicate that swimming training enhances inspiratory rather than expiratory muscle force. Thus, Fanta et al. (1983) showed that specific training of ventilatory muscles mainly improved the ability of the inspiratory muscles to achieve a minimal length during contraction, and Zinman and Gaultier (1986) reported that swimming training significantly augmented inspiratory, but not expiratory, muscle force. Hence, it appears unlikely that the observed higher MEF values in the girl swimmers are due to improved expiratory muscle activity.

The factors affecting maximum expiratory flow rates include elastic recoil of the lungs and the characteristics of the intrathoracic airways (Beardsmore et al. 1989). Several authors have shown that in children there is a disproportionate maturation within different compartments of the lung (De Troyer et al. 1978; Hibbert et al. 1984). From childhood to adolescence, the lung-airway system does not grow isotropically, the alveolar space developing at a faster rate than the airway system. In fact, R_{aw} has been reported to be higher in sedentary children until puberty (Hogg et al. 1970; De Troyer et al. 1978). Also, in the present study, R_{aw} had increased after 1 year in the control group but it was unchanged in the girl swimmers. It may be concluded from these observations that swimming training attenuates the dysanaptic development of the respiratory system and improves airway conductance.

The findings of a significant increase of $FEV_{1.0}$ in the girl swimmers but not in the control group and the significant difference (23%, $P < 0.01$) between the two groups after 1 year of training support this view. Similar results have been reported in relation to prepubertal and adolescent boys and girls who were compared with sedentary control groups after several years of swimming training (Andrew et al. 1972; Vaccaro et al. 1980). $FEV_{1.0}$ is dependent on R_{aw}; the close correlation ($r = 0.62$, $P < 0.01$) between the two measurements is also found in the present study (Fig. 2).

Measurement of R_{aw} and $FEV_{1.0}$ primarily reflects the conductive (or resistive) properties of the large airways. In the normal lung bronchi less 2 mm in diameter, i.e. the small airways, constitute less than 10% of the total R_{aw}. Changes that primarily affect the smaller airways can be extensive and of utmost functional importance, yet not affect R_{aw} or any test dependent on this (e.g. $FEV_{1.0}$). Conversely, the status of the small airways is reflected by the $MEF_{25–75}$ and, in particular, by the last 25–50% of forced VC. In the present study, MEF_{25}, MEF_{50} and MEF_{75} had increased by 14%, 35% ($P < 0.05$) and 21%, after 1 year of training and the flow-volume curve was significantly shifted to the right (Fig. 1) in the girl swimmers, while they were unchanged in the control group. Since the calibre of the airways (and therefore flow) is directly related to lung volume, MEF is often expressed in relation to TLC; even when doing so the increase of MEF at 25, 50 and 75% of VC in the girl swimmers remains evident, with MEF_{50}/TLC augmented by 23% ($P < 0.05$, Table 4). In agreement with our observations of the untrained children, Hibbert et al. (1984) reported the MEF_{max}/TLC ratio to be unchanged in sedentary children between 8 and 12 years of age; they also suggested that the airways might not be growing isotropically.

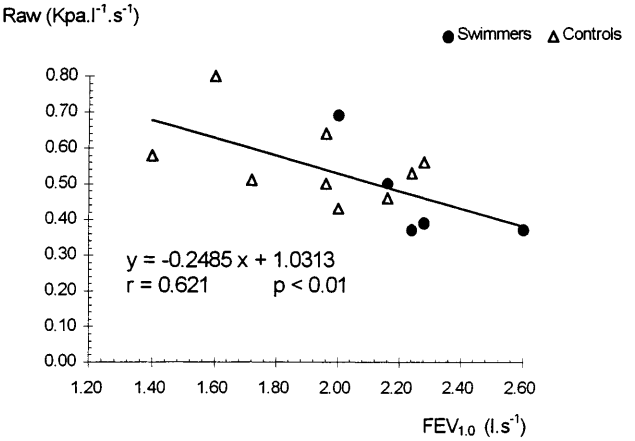

Fig. 2 Relationship between airway resistances (R_{aw}) and $FEV_{1.0}$ in the groups of girl swimmers and controls

The increase of $FEV_{1.0}$ and maximal flow, in particular at the last 50% of VC, strongly suggests that intensive swimming training improves not only the conductive properties of the large airways but also those of the small airways.

Not only did dynamic volumes and flow rates prove to be significantly increased in the girl swimmers, but the static lung volumes were also larger in comparison with those of the controls. TLC, VC and FRC exceeded by 27%, 15% and 18% respectively the corresponding values in the controls ($P < 0.05$). These observations are in full agreement with those of other groups who also demonstrated that, in young subjects participating in regular prolonged swimming training, lung volumes exceed predicted values or values found in age-matched control subjects (Newman et al. 1961; Åstrand et al. 1963; Engström et al. 1971; Andrew et al. 1972; Vaccaro et al. 1980). The reason for these changes are not obvious. Repeated heavy exercise has been suggested

Table 4 Maximal expiratory flows (*MEF*) related to total lung capacity (*TLC*) in the experimental and control group before (*Pre*) and after (*Post*) 1 year of training [means (SD)]

		Experimental $n = 5$	Control $n = 9$	Statistical significance of between-group differences
MEF_{25}/TLC (s)	Pre	1.24 (0.17)	1.41 (0.25)	NS
	Post	1.43 (0.28)	1.39 (0.25)	
	Δ%	18	−0.5	
MEF_{50}/TLC (s)	Pre	0.74 (0.15)	0.95 (0.23)	$P < 0.05$
	Post	0.89 (0.18)	0.85 (0.16)	
	Δ%	22.7	−8	
MEV_{75}/TLC (s)	Pre	0.38 (0.10)	0.44 (0.14)	NS
	Post	0.40 (0.11)	0.37 (0.07)	
	Δ%	7	−9.8	

(Stuart and Collings 1959; Maksud et al. 1971) to result in respiratory muscle hypertrophy, which would account for the larger static lung volumes; quite evidently lung volumes depend partly on the muscle power available. Hamilton and Andrew (1976), however, pointed out that it is the ventilatory stress specifically present in swimming, due to breath-holding manoeuvres associated with increased hydrostatic pressure, which improves respiratory muscle strength. As a matter of fact it appears that the phenomenon of a training-induced increase of static and dynamic lung volumes is limited to swimmers, at least at prepuberty. Careful analyses of the effects of intensive track-and-field endurance training resulting in a 20% increase of maximal oxygen uptake ($\dot{V}O_{2\,max}$) on lung volumes, pulmonary ventilation and gas exchange in prepubertal boys showed that the enlargement of lung volumes observed during the training period was entirely due to physical maturation (Koch and Eriksson 1973a, b). The same results were obtained in a longitudinal study of the development of static and dynamic lung volumes and of some essential cardiovascular parameters in boys aged 12–17 years with a high level of physical activity and who had $\dot{V}O_{2\,max}$ values of between 58 and 65 $ml \cdot kg^{-1}$ body mass (Koch and Fransson 1986). In all these studies, including the present one, the ratio of residual volumes to TLC (FRC/TLC, RV/TLC) did not alter, either in the intensively trained or in the poorly trained children.

The finding that intensive swimming training by prepubertal girls results in larger lung volumes and improves the maximal flow-volume relationship, together with the interpretation that it may favour isotropic growth of the alveolar space airway system, is most interesting. However, it must be regarded with some caution because of the relatively small number of girls in the group involved in intensive swimming training. Certainly a confirmation of the results in larger groups is desirable.

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