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Effect of Long-Term Voluntary Exercise Wheel Running on Susceptibility to Bacterial Pulmonary Infections in a Mouse Model

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Abstract

Regular moderate exercise has been suggested to exert anti-inflammatory effects and improve immune effector functions, resulting in reduced disease incidence and viral infection susceptibility. Whether regular exercise also affects bacterial infection susceptibility is unknown. The aim of this study was to investigate whether regular voluntary exercise wheel running prior to a pulmonary infection with bacteria (*P. aeruginosa*) affects lung bacteriology, sickness severity and phagocyte immune function in mice. Balb/c mice were randomly placed in a cage with or without a running wheel. After 28 days, mice were intranasally infected with *P. aeruginosa*. Our study showed that regular exercise resulted in a higher sickness severity score and bacterial (*P. aeruginosa*) loads in the lungs. The phagocytic capacity of monocytes and neutrophils from spleen and lungs was not affected. Although regular moderate exercise has many health benefits, healthy mice showed increased bacterial (*P. aeruginosa*) load and symptoms, after regular voluntary exercise, with perseverance of the phagocytic capacity of monocytes and neutrophils. Whether patients, suffering from bacterial infectious diseases, should be encouraged to engage in exercise and physical activities with caution requires further research.

Introduction

It has been shown that regular exercise is positively associated with health. It improves muscle strength and function, cardiorespiratory fitness, quality of life and has been suggested to affect immune function as well. However, immune modulatory effects induced by regular exercise remain poorly studied [1–4]. Regular exercise of moderate intensity has been shown to exert anti-inflammatory effects (e.g. in obesity, atherosclerosis, diabetes) and may also improve immune effector functions, resulting in reduced disease incidence and viral infection susceptibility. The opposite has been observed for prolonged or very intense exercise [1;2;4–8]. In animal models it is shown that a period of moderate regular exercise reduced microbial load, inflammation, morbidity and mortality upon a viral infection [9–12]. Recently, a longitudinal cohort study in 1002 healthy adults showed that the number of days with upper respiratory tract infections (URTIs) was significantly reduced in physically fit and active adults, with higher numbers in people that hardly, or intensively exercised [13]. These studies suggest that specific exercise programs may be used to modify the course of inflammatory and/or infectious diseases.

The effects of regular exercise to microbial loads, morbidity and mortality upon a bacterial infection are unknown. In this study, we focused on *Pseudomonas aeruginosa* (*P. aeruginosa*), which is a gram-negative pathogen. *P. aeruginosa* is the most frequently isolated pathogen in patients with nosocomial acquired pneumonia, nosocomial acquired burn-wound infections [14] and pulmonary infections in patients with cystic fibrosis (CF) [15–17]. The aim of this study was to investigate whether regular voluntary exercise wheel running prior to a pulmonary infection with *P. aeruginosa* affects lung bacteriology, sickness severity and phagocyte immune function in mice.

Materials and Methods

Animals and ethics

Female Balb/c mice (n = 40, 12–15 weeks old) were obtained from Taconic (Tornbjerg, Denmark). The study procedure was

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approved by the local animal care committee (Panum Institute, Copenhagen, Denmark) and The Animal Experiments Inspectorate (2008/561–754). Mice were housed in a pathogen-free experimental unit with barrier provisions and received commercial food and water ad libitum.

Study procedure
Following 1 week recovery upon arrival, mice were randomly placed in individual cages, which were supplied with (N = 20) or without a running wheel (N = 20) (Techniplast activity cage, wheel placed in individual cages, which were supplied with (N = 20) or without a running wheel (N = 20) (Techniplast activity cage, wheel placed in individual cages, which were supplied with (N = 20) or without a running wheel (N = 20)). Mice were housed in a pathogen-free experimental unit with barrier provisions and received commercial food and water ad libitum.

Table 1. Symptom severity scoring system.

<table>
<thead>
<tr>
<th>Eyes</th>
<th>0– no signs, normal</th>
<th>1– sore red eyes</th>
</tr>
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<tbody>
<tr>
<td>Lesions</td>
<td>0– none</td>
<td>1– lesion on head</td>
</tr>
<tr>
<td>Fur</td>
<td>0– well groomed</td>
<td>1– ruffled fur</td>
</tr>
<tr>
<td>Neurological/neuromuscular</td>
<td>0– normal movement</td>
<td>2– hunched back</td>
</tr>
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Symptom severity scoring system was adapted from Murphy et al.11. Animals were scored twice post-infection. Cumulative score may range from 0 to 10, indicating no to severe illness.

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Distance covered weekly in the running wheel was measured online by a cycle computer (BC 1400; Sigma Sport, Neustadt, Germany). General health monitoring was performed daily and lung function was measured at day 27. At day 29 mice were inoculated intranasally with *P. aeruginosa* (Fig. 1), after anaesthetization using an intraperitoneal injection of a mixture of 65 mg/kg ketamine (Intervet, Skovlund, Denmark), 13 mg/kg Xylazine (Intervet) in sterile isotonic saline. The bacterial inoculum (50 μL sterile saline containing 5×10^6 colony forming units (CFU) of *P. aeruginosa*) was applied drop wise to the nostrils of the mice. This dose was chosen, based on previous titration studies, which showed a small possible working dose of 1×10^6 to 1×10^7 CFUs/50 μL. Lower doses were fully cleared by all mice and higher doses were lethal within a few hours. Mice were held in an upright position until the complete inoculum was inhaled. Mice had access to the running wheels until the inoculation took place, which represents the usual sequence of events best. In normal life, patients do not know in advance when *P. aeruginosa* acquisition will take place. Exercise will therefore be continued until patients get sick. Following inoculation, mice were housed in an isolated cabinet (Scanbur, Karslunde, Denmark) and had no access to a running wheel anymore. 16 hours post-infection (overnight), following symptom severity scoring, mice were sacrificed using 300 μL of an intraperitoneal injection containing 200 mg/ml pentobarbital and 20 mg/ml lidocaine, since mice were too sick to let them live. A mortality study was not allowed by the ethical committee.

Measurement of Pulmonary Function
Whole Body Plethysmography (Buxco, Troy, NY, USA) was performed as previously described (n = 40) [18]. In brief, WBP was used to measure the effect of the intervention on lung function in mice at day 27. Mice were individually placed inside the chambers. During a 5 minute measurement, breathing frequency (breaths/min) and tidal volume (ml) were measured and recorded.

Bacteria and inoculation
Mice were inoculated using the laboratory *P. aeruginosa* strain PAO1 [19]. Bacteria were grown overnight in Luria–Bertani (LB) medium at 37°C 175 rpm. The next day, 1 ml of broth was resuspended in 20 ml of fresh LB broth and allowed to grow until the mid-logarithmic phase (OD of 0.6 at 600 nm <1×10^9 cells/ml). Bacteria were washed and resuspended in 0.9% sterile saline at 1×10^6 CFUs/ml (5×10^6 CFUs/50 μL). Number of CFUs in inocula was verified by plating serial dilutions on blue agar plates (a modified Conradi Drigalski’s medium selective for Gram-negative rods; State Serum Institute, Copenhagen, Denmark) overnight at 37°C. The inoculum dose of 5×10^6 CFUs/50 μL was based on previous pilot experiments, which showed full clearance of the bacteria when ≤1×10^6 CFUs/50 μL were administered, whereas a dose ≥1×10^7/50 μL was lethal (data not shown). For the phagocytosis assay, an EGFP-labeled PAO1 strain was used, which has been described previously [20]. Bacteria were grown overnight in Luria–Bertani (LB) medium containing 100 μg/ml ampicillin and 10 μg/ml kanamycin, at 37°C 175 rpm. The next day, 1 ml broth was resuspended in 20 ml of fresh LB broth and allowed to grow until the mid-logarithmic phase (OD of 0.6 at 600 nm <1×10^9 cells/ml). Bacteria were washed and diluted in PBS until a final concentration of 2×10^7 CFUs/ml was reached.

Symptom severity score
Mice (n = 40) were scored for symptom severity twice 16 hours following inoculation with *P. aeruginosa* by an investigator, who was blinded for the experimental conditions. Symptom severity score
contained typical symptoms of illness, which was adapted from Murphy et al. (Table 1) [11]. Mice that displayed any of these symptoms were considered as morbid. Cumulative scores ranged from 0 to 10, based on the varying degree of symptoms of sickness.

Isolation of immune cells from spleen and lung

Immune cells were harvested from sacrificed mice, 16 hours following inoculation with \textit{P. aeruginosa}. Spleens (\(n = 20\) of \(n = 40\) mice) and lungs (\(n = 24\) of \(n = 40\) mice) were incubated in 0.9% NaCl and placed on ice. Explants were homogenized using a cell-

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**Figure 2. Effectiveness of voluntary exercise wheel running.** Each dot represents one mouse. 

\textbf{A}. Mean \(\pm\) SEM running distance per day per study week (\(n = 20\)). 

\textbf{B}. Effect of exercise wheel running on HK II and COX I protein levels in the white part of the m. quadriiceps and m. gastrocnemius (\(n = 20\) per group). Protein contents were expressed relative to the “no running wheel group” (Mean \(\pm\) SEM). 

\textbf{C}. Effect of exercise wheel running on lung function (Mean \(\pm\) SEM): tidal volume (ml), breathing frequency (breaths/min) and minute volume (ml/min) (\(n = 20\) per group).

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**Figure 3. Effect of exercise on symptom severity score and bacterial load in the lung following intranasal inoculation with \textit{P. aeruginosa}.** Each dot represents one mouse. 

\textbf{A}. Symptom severity score (Mean \(\pm\) SEM) 16 hours following intranasal inoculation with \textit{P. aeruginosa} (\(n = 20\) per group). 

\textbf{B}. Amount of colony forming units per lung (Median \(\pm\) IR) following intranasal inoculation with \textit{P. aeruginosa} (\(n = 14\) per group). Inoculation doses was \(5 \times 10^6\) CFUs/50 \(\mu\)L.

doi:10.1371/journal.pone.0082869.g003
strainer (100 µM, BD Biosciences, NJ, USA) in RPMI 1640 wash medium supplied with 2% FCS, 1% L-glutamin and Penicillin (100 U/ml) and Streptomycin (100 µg/ml). Before further handling, erythrocytes were removed by an erythrocyte lysis buffer Hybri-Max R7757, according to the manufacturer’s protocol. Next, immune cells (splenocytes and immune cells from the lung) were washed in RPMI 1640 wash medium and frozen in freeze medium, which contained 90% FCS and 10% DMSO. Media and supplements were obtained from Invitrogen (Invitrogen, CA, USA).

Lung bacteriology

Lungs were removed from sacrificed mice, 16 hours following inoculation with P. aeruginosa. Lungs (n = 28 of n = 40 mice) were incubated in 0.9% NaCl and placed on ice. Both lungs of individual mice were pooled and homogenized on ice in 3 ml sterile saline using a homogenizer (Heidolph diax 600, Struers, Ballerup, Denmark) at 13500 rpm. To determine the amount of CFUs, serial dilutions were plated on blue agar plates and incubated overnight at 37°C. Colonies were tested for oxidase activity with oxidase reagents (State Serum Institute). Colonies attained a deep blue colour within 10 sec when they were of P. aeruginosa origin (presence of the enzyme complex cytchrome c).

Determination of skeletal muscle mitochondrial enzymes

Muscle lysate preparations. The white part of the musculus (m.) gastrocnemius and m. quadriceps femoris were removed from sacrificed mice and immediately frozen in liquid nitrogen and stored at ~80°C. Whole cell lysates were prepared by homogenization in 2 ml Eppendorf tubes using a Polytron (PT 1200, Kinematica) and were incubated in ice-cold lysis buffer A [50 mM HEPES (pH 7.4) 10% glycerol, 20 mM Na Pyrophosphate, 150 mM NaCl, 1% NP-40, 20 mM β-glycerophosphate, 10 mM NaF, 1mM EDTA, 1 mM

Figure 4. Effect of exercise on capacity of phagocytes to take up P. aeruginosa. A. Monocytes and neutrophils were gated by forward and side scatter (left panel). Representative dotplots of monocytes (left panel) and neutrophils (right panel) incubated with (lower panel) or without (upper panel) EGFP-labeled P. aeruginosa and selection of EGFP-positive cells. Bacteria were opsonized with 4% mouse serum. B. Phagocytic capacity of neutrophils and monocytes (Mean ± SEM) isolated from the spleen (n = 6 per group) and lungs (n = 10 per group). Each dot represents one mouse. doi:10.1371/journal.pone.0082869.g004
EGTA, 2 mM PMSF, 10 μg/ml aprotinin, 10 μg/ml leupeptin, 2 mM Na3VO4, 5 mM benazamidine) for 20 sec (PT 3100, Kinematica). Homogenates were rotated end-over-end at 4°C for 1 h. Soluble debris was collected by centrifugation at 17,500 g (30 min, 4°C) and supernatants were snapfrozen in liquid nitrogen and stored at −80°C.

**SDS-PAGE and Western Blotting.** Total protein content in lysates were determined by the bicinchoninic acid method (Pierce Chemical, Rockford, IL). Muscle whole cell lysates were subjected to SDS-page (7.5–15% Tris-HCl gels; Criterion, Bio-Rad, Denmark), and were transferred (semidy) to PVDF membranes (Immobilon Transfer Membrane, Millipore), blocked with Tris-buffered saline-Tween 20 (10 mM tris-Base (pH 7.4), 0.9% NaCl, 1% Tween 20 (TBST) +2% skimmed milk), and incubated with primary antibodies (TBST +2% skimmed milk) followed by incubation with horseradish peroxidase-conjugated secondary antibody (TBST +2% skimmed milk) (Dako, Glostrup, Denmark). Primary antibodies used were: anti-hexokinase II (anti-HK II) and anti cytochrome C Oxidase I (Molecular Probes, Eugene, OR).

**Results**

**Effectiveness of voluntary exercise wheel running**

To assess whether voluntary exercise wheel running was adequate to achieve training-induced adaptations, daily running distance and HK II and COX I skeletal muscle protein levels were determined in the white part of the m. quadriceps femoris and m. gastrocnemius. On average mice ran 8.7 ±0.1 km per day (mean ± SEM) (Figure 2a). Except for the HK II protein content in the m. quadriceps femoris, COX I and HK II protein contents were significantly increased in the exercise wheel group (Figure 2b). Exercise wheel running resulted in a significant decrease in breathing frequency, but tidal volume and minute volume were equal between both experimental groups (Figure 2c).

**Effect of exercise on symptom severity score and lung bacteriology**

To determine that the lungs were selectively targeted by nasal inoculation, intranasal administration of radio-labelled peptide solution (50 μl) was performed as has been described, in a separate group of mice (data not shown) [18]. The mean percentage of radioactive particles detected in the lungs (relative to the control fluid) was 71% (range 61–76%). No radio-active particles were detected in the stomachs of the mice, indicating that the inocula were specifically delivered to the lungs without being swallowed.

To investigate whether regular exercise affects *P. aeruginosa* pulmonary infection susceptibility, post-infection symptom severity score and lung bacteriology were determined. Mice in the running wheel group had a significantly higher symptom severity score, suggesting more severe illness, 16 hours after intranasal inoculation with *P. aeruginosa* (Figure 3a). Furthermore, mice in the exercise wheel running group had a significantly higher amount of *P. aeruginosa* CFU in their lungs (Figure 3b).

**Effect of exercise on the phagocytic capacity of phagocytes**

The phagocytic capacity of monocytes and polymorphonuclear leukocytes (neutrophils) was determined to investigate whether regular exercise affects the phagocytic capacity of phagocytes and whether a change in these innate immune functions could be associated with the changes in lung bacteriology. The phagocytic capacity was determined using flow cytometry by analyzing uptake of EGFP-labelled *P. aeruginosa* by monocytes and neutrophils after 30 minutes of co-culture (Figure 4a shows representative examples). The capacity of monocytes and neutrophils to phagocytose *P. aeruginosa*, 16 hours post-infection, was not affected by regular exercise (Figure 4b).

**Discussion**

The aim of this study was to investigate whether regular voluntary exercise prior to a pulmonary infection with *P. aeruginosa* in mice affects lung bacteriology, sickness severity and phagocyte immune function. We observed that exercised mice had more severe illness and a higher *P. aeruginosa* infection loads in the lungs. The phagocytic capacity of monocytes and neutrophils from spleen and lungs was not affected 16 hours post-infection. Collectively, these data indicate that regular voluntary exercise can enhance susceptibility to a bacterial pulmonary infection.

We are the first investigating the effect of regular exercise on bacterial infection load. Limited data are available showing that regular exercise leads to a reduced viral infection load and associated morbidity and mortality in animals [10–12] and a reduced upper respiratory tract infection frequency in humans.
infection may lead to different results. Different
mice strains may lead to complete different results. Additionally,
future research should focus on longer follow-up times post-
mice strains (e.g. NH57388) [23], which allows longer
follow-up times due to their lower lethality. Furthermore, the
exercise modality used in our study had a voluntary character,
which may induce completely different effects on infection
susceptibility compared to involuntary treadmill running used in
the previous studies [10–12].

Voluntary exercise wheel running was chosen as an exercise
model, since a standardized treadmill exercise protocol leads to
stress responses due to its involuntary character, which may
therefore be a potential study confounder [24]. It has been
demonstrated that voluntary exercise wheel running leads to
similar skeletal muscle adaptations as standardized involuntary
moderate treadmill running [25], supporting its use as effective
exercise modality to induce training effects in mice. Average
running distance covered by the mice in our study was comparable
to what was found in other studies [26;27]. Furthermore, we
showed that 4 weeks of voluntary exercise wheel running induced
an aerobic training effect on skeletal muscle enzyme content,
which was comparable to what was shown for HKII [28;29] and
COXI [30] by previous studies. Taken together, these data suggest
that voluntary exercise wheel running in our study was effective to
induce skeletal muscle adaptations and is representative for
moderate exercise. Furthermore, this is the first study that defines
mouse phagocyte function at the level of individual cells in
response to exercise and infection using a novel assay. The data
show that exercise and infection does not modulate intrinsic
phagocyte function, which we believe is relevant and novel to the
field.

A change in the phagocytic capacity of monocytes and
neutrophils might be an explanation for the increased exercise-
induced bacterial infection susceptibility. However, although a
higher sickness severity and lung bacteriology were measured after
regular voluntary exercise, we showed that the capacity of
neutrophils and monocytes to phagocytose P. aeruginosa was
unaffected 16 hours post-infection. Whether innate immune
function is directly affected by regular exercise has been poorly
investigated by others and contrary results have been published.
Regular intense exercise leads to a reduced capacity of neutrophils
to phagocytose opsonized latex beads and produce superoxide
anions [31], whereas this was not affected [31] or improved [32]
by regular moderate exercise. In our phagocytosis assay opsonized
live bacteria and whole blood cells in co-culture were used, which
allows bacteria-cell and cell-cell interactions that may modulate
bacterial defense mechanisms and represents the in vivo situation
better. This novel assay allows to define mouse phagocyte function
at the level of individual cells in response to exercise and infection
and is therefore of additional value to the field. Altogether, the role
of exercise-induced changes in innate immune function remains
unclear. Effects are probably dependent on the exercise modality
and animal model used. Furthermore, more studies are needed
addressing the role of exercise in differential innate immune
defense mechanisms. For future research, a separate group of
mice, not infected by P. aeruginosa, should be included. This will
help unravel exercise-induced changes in immune defense
mechanisms that may not be visible anymore 16 hours post-
infection.

We observed no effect of regular voluntary exercise on the
phagocytic capacity of neutrophils and monocytes, however other
innate immune functions, such as the killing capacity of
phagocytes or defensin levels in the lung, might be affected.
Furthermore, it has been reported that moderate regular exercise
leads to reduced circulating levels of cells with an activated
phenotype, indicated by increased anti-inflammatory regulatory T
Treg [33] and reduced inflammatory (CD16+ high)
monocytes levels [8;34–37]. These preferential changes in
circulating subsets towards cells with a reduced activated
phenotype might lead to reduced antigen responsiveness, which
may lead to a reduced antigen clearance and increased disease
frequency. Unfortunately, changes in cell population numbers
have not been estimated in our study.

It may be possible to extrapolate data to other bacteria that
more commonly lead to pulmonary infections, such as Staphylococ-
cus aureus, Streptococcus pneumoniae or Hemophilus influenzae. However,
this requires more research, since differences in immunological
responses to different bacteria and dissimilarities in virulence
factors may lead to different results.

Collectively, our data showed that voluntary moderate exercise
can enhance bacterial (P. aeruginosa) infection susceptibility with
perseverance of the phagocytic capacity of monocytes and
neutrophils 16 hours post-infection. However, it requires further
research to explore innate immune defense mechanisms at other
time-points than 16-hours post-infection and measurement of
other determinants that may be involved. Whether cell numbers or
other innate immune functions, such as the killing capacity, were
affected, has to be studied.

Conclusion

Although regular moderate exercise has many health benefits,
healthy mice show increased bacterial (P. aeruginosa) infection load
and symptoms, after regular voluntary exercise, with perseverance
of the phagocytic capacity of monocytes and neutrophils. Whether
patients, suffering from bacterial infectious diseases, should be
encouraged to engage in exercise and physical activities with
cautions, requires further research.

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Author Contributions

Conceived and designed the experiments: PvdW HKJ AdV OC JW JF HH
CvdE, JB HA. Performed the experiments: PvdW AdV JF. Analyzed the
data: PvdW JF. Contributed reagents/materials/analysis tools: PvdW AdV
JF OC HKJ JB JW. Wrote the paper: PvdW HKJ AdV OC JW JF HH
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