



# Refractory neutrophils and monocytes in patients with inflammatory bowel disease after repeated bouts of prolonged exercise

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## Abstract

**Background:** Neutrophils and monocytes are key immune effector cells in inflammatory bowel disease (IBD) that is associated with chronic inflammation in the gut. Patients with stable IBD who perform exercise have significantly fewer flare-ups of the disease, but no underlying mechanism has been identified. Therefore, the aim of this study was to compare the responsiveness/refractoriness of these innate immune cells after repeated bouts of prolonged exercise in IBD patients and controls.

**Methods:** Patients with IBD and age- and gender-matched healthy controls were recruited from a cohort of walkers participating in a 4-day walking event. Blood analysis was performed at baseline and after 3 days of walking. Responsiveness to the bacterial/mitochondrial-stimulus N-Formylmethionine-leucyl-phenylalanine (fMLF) was tested in granulocytes and monocytes by measuring the expression of activation markers after adding this stimulus to whole blood.

**Results:** In total 38 participants ( $54 \pm 12$  years) were included in this study: 19 walkers with and 19 walkers without IBD. After 3 days of prolonged exercise, a significant increase in responsiveness to fMLF was observed in all participants irrespective of disease. However, IBD patients showed significantly less responsiveness in neutrophils and monocytes, compared with non-IBD walkers.

**Conclusions:** Increased responsiveness of neutrophils and monocyte to fMLF was demonstrated after repetitive bouts of prolonged exercise. Interestingly, this exercise was associated with relative refractoriness of both neutrophils and monocytes in IBD patients. These refractory cells might create a lower inflammatory state in the intestine providing a putative mechanism for the decrease in flare-ups in IBD patients after repeated exercise.

## KEYWORDS

exercise, flare-ups, inflammatory bowel disease, monocyte, neutrophil

## 1 | INTRODUCTION

Inflammatory bowel disease (IBD) is a chronic active inflammatory condition of the digestive tract. It includes both Crohn's disease, which can affect all parts of the digestive system, and ulcerative colitis, which mainly affects the colon and rectum (Baumgart & Sandborn, 2007). IBD is caused by an imbalance in the three major components that contribute to gut homeostasis: the tissue, intestinal microbes, and immune cells (Fournier & Parkos, 2012; Maloy & Powrie, 2011). During intestinal inflammation, intestinal cells, monocyte-derived macrophages, and T helper 17 cells stimulate the recruitment of polymorphonuclear leukocytes (PMN) and monocytes through the production of chemokines and cytokines (Ajuebor et al., 1999; Fournier & Parkos, 2012; Witowski et al., 2000). The resulting gradients of these mediators stimulate massive amounts of blood PMNs and monocytes to transverse the endothelium and reach the lamina propria of the intestinal tract, where PMNs and monocytes contribute to the inflammation (Fournier & Parkos, 2012; Kucharzik et al., 2005; MacDermott, 1999).

Exercise has a beneficial effect on IBD, likely by changing the three major components that contribute to gut homeostasis (epithelium, intestinal microbes, and immune cells) (Bilski et al., 2016; Codella et al., 2018; Monda et al., 2017). A large observational study showed that patients with stable IBD were significantly less likely to develop active disease in 6 months when undertaking activities (Jones et al., 2015). However, the underlying pathophysiologic mechanisms have not been elucidated.

Several studies have shown an altered cellular adaptive immune response (T-cell changes, Natural killer cell activity, salivary IgA production), cytokine production (IL6, IL8, IL10), and innate immune responses (granulocyte cell count, granulocyte respiratory burst, neutrophil/lymphocyte ratio, and macrophage activity) for several hours to days, during recovery from prolonged exercise (Brown et al., 2018; Peake et al., 2015; Simpson et al., 2015; Terink et al., 2018). However, repeated bouts of prolonged moderate exercise result in acute inflammation the first day, followed by a normalization/adaptation of the immune response every consecutive day (Terink et al., 2018).

PMNs and monocytes play a critical role in the pathophysiology of IBD (Fournier & Parkos, 2012; Kühl et al., 2007; Zhou & Liu, 2017). Responsiveness/refractoriness of PMNs and monocytes can be tested *in vitro*, adding the bacterial/mitochondrial stimulus N-Formylmethionine-leucyl-phenylalanine (fMLF) (Hesselink et al., 2019; Marasco et al., 1984; Spijkerman et al., 2020). Testing the responsiveness of innate immune cells to fMLF is valuable to the understanding of functional cellular activity in several diseases (Groeneveld et al., 2017; Hietbrink et al., 2013; Pillay et al., 2010). It is known that cellular responsiveness to fMLF is significantly increased in patients with IBD flare-ups (Anton et al., 1989). Testing PMN and monocyte responsiveness to fMLF might help in understanding the role of PMNs and monocytes in exercise immunology. Therefore, this study aimed to compare the responsiveness of these innate immune cells after repeated bouts of prolonged exercise in IBD patients and controls.

## 2 | METHODS

### 2.1 | Study population

A total of 19 patients with IBD were included in the study. Inclusion criteria for all IBD patients were age  $\geq 18$  years and diagnosis of Crohn's disease or ulcerative colitis made by a gastroenterologist. IBD patients were not included when they used specific biologicals (infliximab, adalimumab, golimumab, ustekinumab) as these might change the immune response. All patients completed a distance of 30, 40, or 50 km per day on 3 consecutive days at a self-selected pace. As a control group, a total of 19 age- and gender-matched healthy controls were recruited who also underwent the same repeated exercise bouts. This study was approved by the Medical Ethical Committee region Arnhem-Nijmegen (CMO registration number: 2019-5375) and was registered at trialregister.nl as NL7872. All participants provided written informed consent before participation. This study was conducted in accordance with the Declaration of Helsinki.

### 2.2 | Baseline measurements

Baseline data were collected 1 or 2 days before the start of the event, after a minimum resting period of 24 h. At baseline, body height and weight (Seca 888 scale) were measured to calculate body mass index (BMI). All participants completed a general questionnaire on demographics, smoking, and medication use, and the validated Short Questionnaire to Assess Health enhancing physical activity (SQUASH) (Wendel-Vos et al., 2003). IBD walkers completed an extended general questionnaire with additional questions on type and extent of IBD, age of disease onset, number of flare-ups, and previous IBD-related surgeries. Participants' heart rate was measured every 5 km during the first exercise day using a two-channel ECG chest band 130 system. Heart rate (HR) was used to estimate exercise intensity as a percentage of the maximum HR (exercise intensity = measured HR/expected maximal HR  $\times$  100%), where expected max HR =  $208 - 132 (0.7 \times \text{age})$  (Tanaka et al., 2001).

### 2.3 | Blood sampling

Venous blood was drawn at baseline and after 3 days of repeated bouts of exercise. A 4 ml Vacutainer® sodium heparin blood tube (Becton Dickinson) was drawn, which was directly inserted in the automated AQUIOS CL® "Load & Go" flow cytometer (Beckman Coulter).

### 2.4 | Flow cytometry analysis

The AQUIOS CL combines robotic automated sample preparation with an analysis of cells using flow cytometry (Spijkerman et al., 2019). The AQUIOS CL has one 488 nm diode laser, two light

scatter channels (forward scatter and side scatter), five fluorescence channels, and an electronic volume measure. Absolute leukocyte count was based on an electronic-volume measurement. A cassette filled with blood tubes was placed in the machine and the barcodes of the samples were saved. After automatic blood mixing, the samples were cap-pierced, and 43  $\mu$ l was pipetted into a 96-deep wells plate, that is used for antibody staining. The wells plate contained the bacterial/mitochondrial-derived stimulus formyl-methionyl-leucyl-phenylalanine (fMLF) (Sigma Aldrich) with an end concentration of  $10^{-6}$  M. Consecutively, 18  $\mu$ l of a monoclonal antibody mix bound to different fluorescent labels was added to the 96-wells plate. After 15 min of incubation, the blood was lysed using 335  $\mu$ l of lysing reagents A and 100  $\mu$ l of lysing reagent B. Lysing reagent A is a cyanide-free lytic reagent that lyses red blood cells. Lysing reagent B slows the reaction caused by reagent A and preserved the white blood cells for measurement in the flow cell. Finally, 100  $\mu$ l of the prepared sample was aspirated for analysis.

A customized antibody mix was made specifically for this research purpose. This panel consisted of CD35-FITC (clone J3.D3, Beckman Coulter), CD16-PE (clone 3G8, Beckman Coulter), CD62L-ECD (clone DREG56, Beckman Coulter), CD11b-PC5 (clone Bear1, Beckman Coulter), and CD10-PC7 (clone ALB1, Beckman Coulter).

The .lmd data files were exported from the AQUIOS CL<sup>®</sup> and imported into FlowJo<sup>®</sup> analysis software (Tree Star Inc.). The gating strategy is shown in Figure S1. Granulocytes and monocytes were gated based on forward scatter and side scatter. Neutrophils and eosinophils in the granulocyte gate were identified based on the positivity or negativity of CD16 expression. The median fluorescent intensity (MFI) of CD35, CD11b, CD62L, and CD10 on gated neutrophils was used to describe the measure of neutrophil and monocyte responsiveness to fMLF.

## 2.5 | Statistical analysis

The statistical analyses were conducted in SPSS 26 (SPSS Inc.). Graphs were created with GraphPad Prism version 7 (GraphPad software Inc.). Data were checked for normality with the use of the D'Agostina & Pearson test and visual inspection of Q-Q plots. Statistical significance was defined as a *p*-value <0.05. Normally distributed data were presented as mean with SD and significance was tested by a *t* test. Non-normally distributed data were presented as median with interquartile range (IQR) and significance was tested by a Mann-Whitney U test. Dichotomous data were shown as an absolute count with the percentage of the total, in which differences were tested with the Pearson Chi-square test.

## 3 | RESULTS

In total 38 participants were included in this study, of whom 19 IBD walkers, 19 non-IBD walkers. One IBD walker fell during exercise on day 1 and dropped out, he was excluded from all statistical analysis.

Clinical disease characteristics of IBD patients are shown in Table 1. The IBD study groups consisted of 8 patients with Crohn's disease and 10 patients with ulcerative colitis. The mean age of diagnosis was  $33 \pm 13$  years. One year before the walking event, a total of 8 (44%) IBD patients had no flare-ups, 6 patients had one to two flare-ups and four patients had three or more flare-ups. Baseline characteristics of both between the IBD walkers and the age/gender-matched control group are shown in Table 2. The mean age of the study population was  $54 \pm 12$  years and the average BMI of all participants was  $26.0 \pm 3.8$  kg/m<sup>2</sup>. In each group, 11 participants were female. No significant differences were found between IBD walkers and non-IBD walkers regarding participant characteristics, except for training distance during the last 2 weeks before the walking event (IBD walkers vs. non-IBD walkers, *p* = 0.03).

Responsiveness to fMLF, determined by flow cytometric determination of innate immune markers, is shown in Figure 1. The cellular responsiveness to fMLF is shown as the Median Fluorescent

**TABLE 1** Disease characteristics of patients with inflammatory bowel disease

	IBD (n = 18)
Age of diagnosis (years)	33 $\pm$ 13
Crohn's disease/Ulcerative colitis	8 (44%)/10 (66%)
<b>Disease location Crohn's disease (n [%])</b>	
Small bowel	2 (25%)
Colon	2 (25%)
Small bowel and colon	2 (25%)
Unknown	2 (25%)
<b>Disease location ulcerative colitis (n [%])</b>	
Pancolon	2 (20%)
Hemicolon	3 (30%)
Rectum	5 (50%)
<b>Flare-ups last 12 months (n [%])</b>	
None	8 (44%)
1–2 flare-ups	6 (33%)
3–4 flare-ups	2 (11%)
More than 4 flare-ups	2 (11%)
<b>Treatment of IBD (n [%])</b>	
Receiving IBD medication	11 (61%)
5-ASA oral	9 (50%)
5-ASA rectal	4 (22%)
Corticosteroids oral	4 (22%)
Corticosteroids rectal	2 (11%)
Other immunosuppressants	1 (6%)
No use of IBD medication	7 (39%)
Received surgery for IBD	1 (6%)

Note: Continuous data are shown as median (IQR) and dichotomous data are shown as an absolute amount (percentage).

Abbreviations: ASA, 5-aminosalicylic acid; IBD, inflammatory bowel disease.

**TABLE 2** Baseline characteristics of patients with IBD and control group with no IBD

	IBD (n = 18)	Non-IBD (n = 19)
Age (years)	54 ± 11	54 ± 14
Male n (%) / female n (%)	7 (39%) / 11 (61%)	8 (42%) / 11 (58%)
Body mass index (kg/m <sup>2</sup> )	25.7 ± 3.8	26.0 ± 4.5
<b>Smoking (n (%))</b>		
Never	9 (50%)	13 (68%)
Current	1 (6%)	0 (0%)
Former	8 (44%)	6 (32%)
<b>Walking distance per day (n (%))</b>		
30 km	5 (28%)	2 (11%)
40 km	11 (61%)	13 (68%)
50 km	2 (11%)	4 (21%)
<b>Average walking speed per day (km/h)</b>		
Day 1 (km/h)	4.5 ± 0.8	4.4 ± 0.7
Day 2 (km/h)	4.4 ± 1.0	4.4 ± 0.8
Day 3 (km/h)	4.5 ± 0.8	4.4 ± 0.7
<b>Physical activity</b>		
Total activity score <sup>a</sup>	10,147 ± 5030	9919 ± 4291
Average heart rate at day 1 (bpm)	114 ± 14	113 ± 11
Exercise intensity at day 1 (%)	67 ± 8	66 ± 7

Note: Continuous data are shown as mean ± SD, significance is tested with the t test. Categorical data are shown as an absolute amount (percentage), the significance is tested with the Pearson chi-square test. \* $p < .05$ . Abbreviations: bpm, beats per minute; IBD, inflammatory bowel disease; SQUASH, short questionnaire to assess health enhancing physical activity. <sup>a</sup>Total activity score represents intensity factors per activity multiplied by the minutes per week spent on each activity as derived from the SQUASH.

Intensity(MFI) of innate immune markers: Nephilysine (CD10) (Figure 1a), Complement receptor 3 (CD11b) (Figure 1b–d), Complement receptor 1 (CD35) (Figure 1e–g) and L-selectin (CD62L) (Figure 1h–j).

Smaller increased responsiveness to fMLF was shown after 3 days of prolonged exercise in the expression of the activation markers CD11b and CD35 in IBD walkers compared with non-IBD walkers in neutrophils ( $p = .01$ ;  $p = .03$ ) and monocytes ( $p = .001$ ;  $p = .008$ ). No difference in CD11b and CD35 expression was demonstrated between the study groups at baseline measurements. No difference in responsiveness was seen in the cell adhesion receptor CD62L in neutrophils, monocytes, and eosinophils between the study groups. The maturation/activation marker CD10 showed a similar smaller increased responsiveness to fMLF after 3 days of repeated prolonged exercise in IBD walkers compared with non-IBD walkers in neutrophils ( $p = 0.005$ ). However, already at day 0, a lower expression of CD10 was demonstrated in the neutrophil

compartment of IBD walkers compared with non-IBD walkers ( $p = 0.01$ ).

The data obtained after 1 and 2 days of walking can be found in the online supplement (Figures S2 and S3).

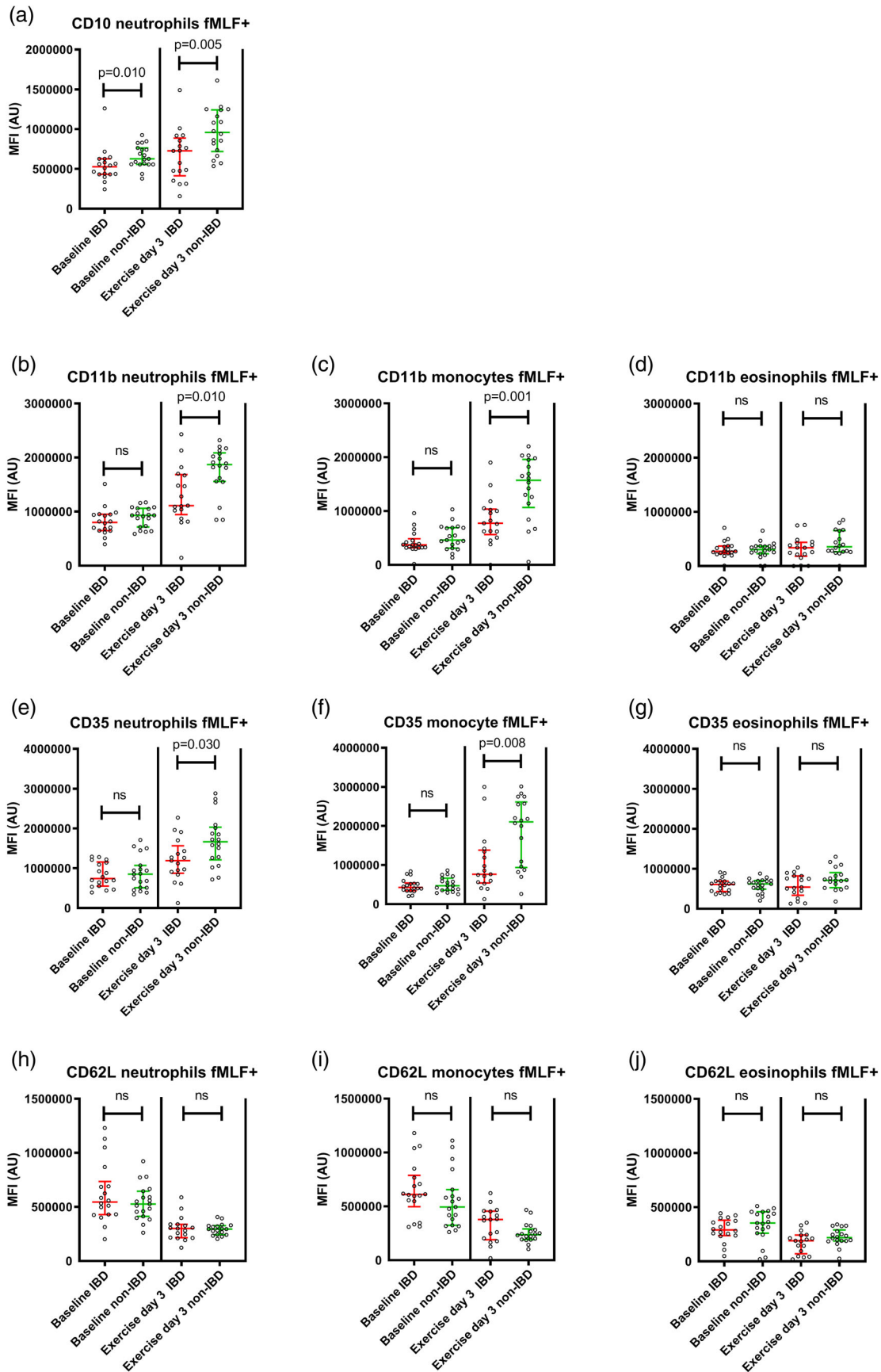
## 4 | DISCUSSION

This study investigated the effect of three repeated bouts of prolonged exercise on neutrophils, eosinophils, and monocytes in patients with IBD. We used automated point-of-care flow cytometry in a field laboratory with an integrated system to test the fMLF responsiveness of eosinophils, neutrophils, and monocytes. We found that IBD patients demonstrated a smaller increase in neutrophil and monocyte responsiveness in activation markers CD35 and CD11b towards an inflammatory stimulus after repeated walking, compared with non-IBD walkers. A decreased neutrophil responsiveness was also observed in the activation/maturation marker CD10.

In previous studies on repeated prolonged exercise, conducted during the same walking event, a general increase in cytokines and direct innate immune activation was found after the first day in all tested participants (15). After the second and third day, a normalization/adaptation of the innate immune system was demonstrated. The present study showed no difference between controls and IBD patients in the responsiveness of neutrophils, eosinophils, and monocytes to fMLF during the first 2 days of exercise (Figure S2). Only at day 3 increased responsiveness of neutrophil and monocytes was found in all walkers (IBD and non-IBD), but was significantly less increased in IBD patients. The underlying mechanism remains to be established, but it is tempting to speculate that increased responsiveness is the result of a priming effect in response to damage-associated molecular patterns (DAMPs) originating from mild-exercise-induced tissue damage during the first 2 days. Apparently, this situation leads to a suppression of the proinflammatory response in IBD patients.

The neutrophil activation markers CD35, CD11b, and CD10 showed the same significant differences between the study groups after 3 days of repeated bouts of prolonged exercise. The complement receptors CD11b and CD35 showed no difference in expression between participants with IBD and without IBD at day 0. However, CD10 was also significantly different at day 0, which might be an indirect effect of the additional role as a maturation marker (Marini et al., 2017). Patients with IBD are characterized by chronic inflammation, which might associate with an overall younger neutrophil compartment (left shift) in the bloodstream, resulting in a lower CD10 (Fournier & Parkos, 2012).

In diseases with hypo inflammation of the innate immune system, a decreased neutrophil responsiveness in the peripheral blood is associated with worse clinical outcomes (infectious complications and sepsis) (Edelman et al., 2013; Groeneveld et al., 2017; Hietbrink et al., 2013). In diseases associated with hyper inflammation, decreased neutrophil responsiveness is associated with better clinical outcomes (allergic/auto-immune diseases) (Kanters et al., 2007). Three days of exercise in IBD patients is associated with the occurrence of



**FIGURE 1** Responsiveness of innate immune cells to the bacterial/mitochondrial stimulus fMLF in IBD ( $N = 18$ ) versus non-IBD patients ( $n = 19$ ). Responsiveness is determined by flowcytometric analysis of the cellular activation markers CD10 (a), CD11b (b–d), CD35 (e–g) and the adhesion marker CD62L (h–j). MFI is compared between study groups at day 0 and after 3 consecutive days of prolonged moderate exercise with the Mann–Whitney U test. Data are presented as scatter plot with median and interquartile range. IBD, inflammatory bowel disease; MFI, Median fluorescent intensity; AU, arbitrary units [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

less responsive neutrophils and monocytes in the peripheral blood. This possibly explains the better clinical outcomes in IBD patients.

The current study focused on exercise-induced changes in the activation phenotypes of innate immune cells in the context of expression of activation-associated epitopes. This is a rather narrow part of the immune response initiated by exercise. Surely, many other processes that are induced under these conditions can modulate this immune response. These are mediated by an array of soluble mediators including growth factors, cytokines, and myokines (Bay & Pedersen, 2020; Campderrós et al., 2020). Apart from these mediators, the immune response to exercise is also affected by changes in the microbiota (Adams et al., 2020). A last relevant hypothesis is the modulation of netosis in the response of innate immune cells to exercise (Shi et al., 2020). Direct evidence of netosis of innate immune cells in vivo during exercise is, however, lacking. Recently, a comprehensive review describes the future directions in the field of exercise immunology (Nieman & Pence, 2020).

In conclusion, increased responsiveness of neutrophils and monocyte to fMLF was demonstrated after repetitive bouts of prolonged exercise. Interestingly, this exercise was associated with relative refractoriness of both neutrophils and monocytes in IBD patients. These refractory cells might create a lower inflammatory state in the intestine, providing a putative mechanism for the decrease in flare-ups in IBD patients after repeated exercise.

## CONFLICT OF INTEREST

All authors declare that they do not have potential conflicts of interest.

## AUTHOR CONTRIBUTION

All authors made substantial contributions to the conception of the work. Roy Spijkerman, Lillian Hesselink, and Coen CWG Bongers worked on data acquisition. Roy Spijkerman, Lillian Hesselink, and Carlo Bertinetto performed the data analysis. All authors worked on the interpretation of data. Roy Spijkerman made a substantial contribution to the drafting of the work. All authors made a substantial contribution to revising the work critically for relevant intellectual content. All authors approved the final version to be published. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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## REFERENCES

- Adams, K., Weber, K. S., & Johnson, S. M. (2020). Exosome and immunity training: How pathogen exposure order influences innate immune cell lineage commitment and function. *International Journal of Molecular Sciences*, 21(22), 8462. <https://doi.org/10.3390/ijms21228462>
- Ajuebor, M. N., Das, A. M., Virág, L., Flower, R. J., Szabó, C., & Perretti, M. (1999). Role of resident peritoneal macrophages and mast cells in chemokine production and neutrophil migration in acute inflammation: Evidence for an inhibitory loop involving endogenous IL-10. *Journal of Immunology*, 162(3), 1685–1691.
- Anton, P. A., Targan, S. R., & Shanahan, F. (1989). Increased neutrophil receptors for and response to the proinflammatory bacterial peptide formyl-methionyl-leucyl-phenylalanine in Crohn's disease. *Gastroenterology*, 97(1), 20–28.
- Baumgart, D. C., & Sandborn, W. J. (2007). Inflammatory bowel disease: Clinical aspects and established and evolving therapies. *Lancet*, 369(9573), 1641–1657.
- Bay, M. L., & Pedersen, B. K. (2020). Muscle-organ crosstalk: Focus on Immunometabolism. *Frontiers in Physiology*, 11, 567881. <https://doi.org/10.3389/fphys.2020.567881>
- Bilski, J., Mazur-Bialy, A., Brzozowski, B., Magierowski, M., Zahradnik-Bilska, J., Wójcik, D., Magierowska, K., Kwiecien, S., Mach, T., & Brzozowski, T. (2016). Can exercise affect the course of inflammatory bowel disease? Experimental and clinical evidence. *Pharmacological Reports*, 68(4), 827–836.
- Brown, M., McClean, C. M., Davison, G. W., Brown, J. C. W., & Murphy, M. H. (2018). The acute effects of walking exercise intensity on systemic cytokines and oxidative stress. *European Journal of Applied Physiology*, 118(10), 2111–2120.
- Campderrós, L., Sánchez-Infantes, D., Villarroja, J., Nescolarde, L., Bayès-Genis, A., Cereijo, R., Roca, E., & Villarroja, F. (2020). Altered GDF15 and FGF21 levels in response to strenuous exercise: A study in Marathon runners. *Frontiers in Physiology*, 11, 550102. <https://doi.org/10.3389/fphys.2020.550102>
- Codella, R., Luzi, L., & Terruzzi, I. (2018). Exercise has the guts: How physical activity may positively modulate gut microbiota in chronic and immune-based diseases. *Digestive and Liver Disease*, 50(4), 331–341.
- Edelman, J. J. B., Fung, Y. L., Pennings, G. J., Reddel, C. J., Bannon, P. G., Bayfield, M. S., Kritharides, L., Fraser, J. F., & Vallety, M. P. (2013). Off-pump coronary artery bypass surgery induces prolonged alterations to host neutrophil physiology. *Shock*, 39(2), 149–154.
- Fournier, B. M., & Parkos, C. A. (2012). The role of neutrophils during intestinal inflammation. *Mucosal Immunology*, 5, 354–366.
- Groeneveld, K. M., Koenderman, L., Warren, B. L., Jol, S., Leenen, L. P. H., & Hietbrink, F. (2017). Early decreased neutrophil responsiveness is related to late onset sepsis in multitrauma patients: An international cohort study. *PLoS One*, 12(6), e0180145.
- Hesselink, L., Spijkerman, R., Van Wessel, K. J. P., Koenderman, L., Leenen, L. P. H., Huber-Lang, M., & Hietbrink, F. (2019). Neutrophil heterogeneity and its role in infectious complications after severe trauma. *World Journal of Emergency Surgery: WJES*, 29, 14–24.
- Hietbrink, F., Koenderman, L., Althuisen, M., Pillay, J., Kamp, V., & Leenen, L. P. H. (2013). Kinetics of the innate immune response after trauma. *Shock*, 40(1), 21–27.

- Jones, P. D., Kappelman, M. D., Martin, C. F., Chen, W., Sandler, R. S., & Long, M. D. (2015). Exercise decreases risk of future active disease in patients with inflammatory bowel disease in remission. *Inflammatory Bowel Diseases*, 21(5), 1063–1071.
- Kanters, D., ten Hove, W., Luijk, B., van Aalst, C., Schweizer, R. C., Lammers, J. W. J., Leufkens, H. G. M., Raaijmakers, J. A. M., Bracke, M., & Koenderman, L. (2007). Expression of activated Fc $\gamma$ RII discriminates between multiple granulocyte-priming phenotypes in peripheral blood of allergic asthmatic subjects. *The Journal of Allergy and Clinical Immunology*, 120(5), 1073–1081.
- Kucharzik, T., Hudson, J. T., Lügering, A., Abbas, J. A., Bettini, M., Lake, J. G., Evans, M. E., Ziegler, T. R., Merlin, D., Madara, J. L., & Williams, I. R. (2005). Acute induction of human IL-8 production by intestinal epithelium triggers neutrophil infiltration without mucosal injury. *Gut*, 54(11), 1565–1572.
- Kühl, A. A., Kakirman, H., Janotta, M., Dreher, S., Cremer, P., Pawlowski, N. N., Loddenkemper, C., Heimesaat, M. M., Grollich, K., Zeitz, M., Farkas, S., & Hoffmann, J. C. (2007). Aggravation of different types of experimental colitis by depletion or adhesion blockade of neutrophils. *Gastroenterology*, 133(6), 1882–1892.
- MacDermott, R. P. (1999). Chemokines in the inflammatory bowel diseases. *Journal of Clinical Immunology*, 77, 44–49.
- Maloy, K. J., & Powrie, F. (2011). Intestinal homeostasis and its breakdown in inflammatory bowel disease. *Nature*, 474, 298–306.
- Marasco, W. A., Phan, S. H., Krutzsch, H., Showell, H. J., Feltner, D. E., Nairn, R., Becker, E. L., & Ward, P. A. (1984). Purification and identification of formyl-methionyl-leucyl-phenylalanine as the major peptide neutrophil chemotactic factor produced by *Escherichia coli*. *The Journal of Biological Chemistry*, 259(9), 5430–5439.
- Marini, O., Costa, S., Bevilacqua, D., Calzetti, F., Tamassia, N., Spina, C., De Sabata, D., Tinazzi, E., Lunardi, C., Scupoli, M. T., Cavallini, C., Zoratti, E., Tinazzi, I., Marchetta, A., Vassanelli, A., Cantini, M., Gandini, G., Ruzzenente, A., Guglielmi, A., ... Scapini, P. (2017). Mature CD10+ and immature CD10- neutrophils present in G-CSF-treated donors display opposite effects on T cells. *Blood*, 129, 1343–1356.
- Monda, V., Villano, I., Messina, A., Valenzano, A., Esposito, T., Moscatelli, F., Viggiano, A., Cibelli, G., Chieffi, S., Monda, M., & Messina, G. (2017). Exercise modifies the gut microbiota with positive health effects. *Oxidative Medicine and Cellular Longevity*, 2017, 3831972.
- Nieman, D. C., & Pence, B. D. (2020). Exercise immunology: Future directions. *Journal of Sport and Health Science*, 9(5), 432–445.
- Peake, J. M., Della, G. P., Suzuki, K., & Nieman, D. C. (2015). Cytokine expression and secretion by skeletal muscle cells: Regulatory mechanisms and exercise effects. *Exercise Immunology Review*, 21, 8–25.
- Pillay, J., Ramakers, B. P., Kamp, V. M., Loi, A. L. T., Lam, S. W., Hietbrink, F., Leenen, L. P., Tool, A. T., Pickkers, P., & Koenderman, L. (2010). Functional heterogeneity and differential priming of circulating neutrophils in human experimental endotoxemia. *Journal of Leukocyte Biology*, 88, 211–220.
- Shi, Y., Liu, T., Nieman, D. C., Cui, Y., Li, F., Yang, L., Shi, H., & Chen, P. (2020). Aerobic exercise attenuates acute lung injury through NET inhibition. *Frontiers in Immunology*, 11, 409. <https://doi.org/10.3389/fimmu.2020.00409>
- Simpson, R. J., Kunz, H., Agha, N., & Graff, R. (2015). Exercise and the regulation of immune functions. *Progress in Molecular Biology and Translational Science*, 135, 355–380.
- Spijkerman R, Hesselink L, Bongers S, van Wessem KJP, Vrisekoop N, Hietbrink F, Koenderman L, Leenen LPH. Point-of-care analysis of neutrophil phenotypes: A first step toward Immuno-based precision medicine in the trauma ICU. *Critical Care Explorations* 2020;2:e0158.
- Spijkerman, R., Hesselink, L., Hellebrekers, P., Vrisekoop, N., Hietbrink, F., Leenen, L. P. H., & Koenderman, L. (2019). Automated flow cytometry enables high performance point-of-care analysis of leukocyte phenotypes. *Journal of Immunological Methods*, 474, 112646.
- Tanaka, H., Monahan, K. D., & Seals, D. R. (2001). Age-predicted maximal heart rate revisited. *Journal of the American College of Cardiology*, 37(1), 153–156.
- Terink, R., Bongers, C. C. W. G., Witkamp, R. F., Mensink, M., Eijsvogels, T. M., Klein Gunnewiek, J. M. T., & Hopman, M. T. E. (2018). Changes in cytokine levels after prolonged and repeated moderate intensity exercise in middle-aged men and women. *Translational Sports Medicine*, 1(3), 110–119.
- Wendel-Vos, G. C. W., Schuit, A. J., Saris, W. H. M., & Kromhout, D. (2003). Reproducibility and relative validity of the short questionnaire to assess health-enhancing physical activity. *Journal of Clinical Epidemiology*, 56(12), 1163–1169.
- Witowski, J., Pawlaczyk, K., Breborowicz, A., Scheuren, A., Kuzlan-Pawlaczyk, M., Wisniewska, J., Polubinska, A., Friess, H., Gahl, G. M., Frei, U., & Jörres, A. (2000). IL-17 stimulates intraperitoneal neutrophil infiltration through the release of GRO $\alpha$  chemokine from mesothelial cells. *Journal of Immunology*, 165(10), 5814–5821.
- Zhou, G. X., & Liu, Z. J. (2017). Potential roles of neutrophils in regulating intestinal mucosal inflammation of inflammatory bowel disease. *Journal of Digestive Diseases*, 18(9), 495–503.

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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