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1 **A review of physical activity and circulating-miRNA expression: Implications in cancer risk**
2 **and progression**

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14
15 **Running title:** Physical activity, MiRNA expression and cancer

16 **Key words:** microRNAs; c-miRNA; physical activity; exercise; cancer

17 **Abbreviations list:**

18 AGO2: Argonaute2

19 CCL2: Chemokine ligand 2

20 c-miRNA: circulating miRNA

21 CPK: Phosphocreatine Kinase

22 DNA: DeoxyriboNucleic Acid

23 EGFR: Epidermal Growth Factor Receptor

24 ERK: Extracellular signal-Regulated Kinases

- 1 FIIT: Frequency, Intensity, Timing and Type
- 2 HDL: High Density Lipoprotein
- 3 IGF1R: Insulin-like Growth Factor 1 Receptor
- 4 LDL: Low Density Lipoprotein
- 5 MAPK: Mitogen-Activated Protein Kinases
- 6 miRNA: microRNA
- 7 mRNA: messenger RNA
- 8 MVB: Multi-Vesicular Bodies
- 9 PA: Physical Activity
- 10 PBMC: Peripheral Blood Mononuclear Cell
- 11 PDCD4: Programmed cell death 4
- 12 PI3K: PhosphoInositide 3-Kinase
- 13 PLC: PhosphoLipase C
- 14 PTEN: Phosphatase and tensin homolog
- 15 RT-qPCR: real-time quantitative reverse transcription polymerase chain reaction
- 16 RNA: RiboNucleic Acid
- 17 RNase: ribonuclease
- 18 RTK: Receptor Tyrosine-Kinase
- 19 STAT3: Signal Transducer and Activator of Transcription 3
- 20 TIMP3: Tissue Inhibitor of MetalloProteinases-3
- 21 VO_{2max} : maximal oxygen consumption
- 22

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1 **ABSTRACT**

2 The role of circulating microRNAs (c-miRNAs) in carcinogenesis has garnered
3 considerable scientific interest. MiRNAs may contribute actively to cancer development and
4 progression, making them potential targets for cancer prevention and therapy. Lifestyle factors
5 such as physical activity (PA) have been shown to alter c-miRNA expression but the subsequent
6 impact on cancer risk and prognosis is unknown. To provide a better understanding of how PA
7 reduces the risk of cancer incidence and improves patient outcomes, we conducted a review of
8 the impact of PA on c-miRNA expression, which includes a comprehensive synthesis of studies
9 examining the impacts of acute and chronic exercise on expression of c-miRNAs. While the
10 variability in methods used to assess miRNA expression creates challenges in comparing and/or
11 synthesizing the literature, results to date suggest that the circulating form of several miRNAs
12 known for playing a role in cancer (c-miR-133, c-miR-221/22, c-miR126 and c-let-7) are altered
13 by both acute and chronic PA. Additional research should develop standardized procedures for
14 assessing both c-miRNA and PA measurement to improve the comparability of research results
15 regarding the direction and amplitude of changes in c-miRNAs in response to PA.

16

17

1 INTRODUCTION

2 MicroRNAs (miRNAs) are implicated in the etiology of various diseases, including
3 cancer (1), and understanding their biologic characteristics has led to novel insights for cancer
4 diagnosis, treatment and prognosis (2). MiRNAs are considered to be stable in healthy
5 individuals, but external factors including lifestyle can impact their expression. Several studies
6 have reported that physical activity (PA) can modulate miRNAs' expression (3–5). The impact of
7 PA on reducing cancer risk and improving cancer progression has been well documented, but the
8 exact mechanisms underlying these relations are not yet completely understood (6,7). A better
9 understanding of altered expression and function of miRNAs in response to various forms of PA
10 could assist in clarifying the role of PA in cancer prevention and prognosis.

11

12 MiRNAs and cancer

13 MiRNAs are a class of small noncoding RNAs that regulate gene expression post-
14 transcriptionally, either by mRNA cleavage, mRNA destabilization, or inhibition of translation
15 (8). Since the first miRNA was discovered by Lee *et. al.* in 1993, more than 2500 human miRNA
16 sequences have been identified (miRBase) (9). This rapid expansion of discovery can be partially
17 explained by the broad importance of miRNAs in regular bodily functions. MiRNAs are
18 predicted to modulate more than 60% of protein-coding genes (10) and are involved in numerous
19 integral cellular processes, including development, proliferation, metabolism, and signal
20 transduction (11,12). Given their regulatory importance, it is not surprising that miRNAs are
21 widely implicated in carcinogenesis and progression. The mechanistic role of miRNAs in cancer
22 was first discussed by Johnson *et. al.* in 2005 (13) and the number of studies has been rapidly
23 expanding ever since. In both solid and hematological tumors, numerous miRNAs have been
24 found to be altered, and their expression are associated with the severity and stage at diagnosis

1 (14). In breast cancer, for example, several miRNAs have been observed as very early biomarkers
2 of this disease (15).

3 The role of miRNAs in carcinogenesis and cancer progression is twofold. Both *in vivo*
4 and *in vitro* studies have demonstrated they target either tumor suppressors or oncogenes (16).
5 Expression of particular miRNAs can downregulate various oncogenes or re-express tumor
6 suppressor genes, leading to tumor suppression, whereas upregulation of other miRNAs, also
7 referred to as oncomiRs, inhibits tumor suppressor genes or over-express oncogenes, thereby
8 promoting tumor cell proliferation and metastasis (16).

9 MiRNAs are found in tissues and organs and are also released into the circulation in a
10 remarkably stable form (17). The expression of those c-miRNAs has been found to be modified
11 in numerous cancers including, but not limited to: colorectal, prostate, breast, hepatocellular,
12 gastric and head and neck cancers (1,18–24). Altered c-miRNA expression was first observed in
13 B-cell lymphoma patients by Lawrie *et. al.* in 2008 (25) and it is now established that, on
14 average, the expression of 100 c-miRNAs are altered in each cancer type. More importantly, the
15 discovery of c-miRNAs in body fluids resulted in the implication of new possible pathways
16 through which miRNAs may impact tumor development and progression, and led to novel
17 insights for their use as therapeutic tools for cancer (27).

18

19 **MiRNAs as potential mediators of the association between physical activity and cancer**

20 PA has been shown to reduce cancer risk and progression (6,28–31). Multiple
21 hypothesized biologic mechanisms have been proposed to explain these benefits (6,29,32)
22 including reductions in chronic inflammation, regulation of metabolic factors, changes in insulin
23 resistance, enhanced immune system function, and levels of circulating sex hormones, myokines
24 or adipokines (6,29,32,33). The exact mechanisms, however, whereby PA alters cancer risk and

1 progression at various cancer sites are not fully understood and additional pathways are likely.
2 Since miRNAs are now well recognized for playing important roles in carcinogenesis and cancer
3 outcomes, they could be involved in the PA-related benefits towards cancer.

4 The impact of PA on miRNAs has been investigated by several research groups, but
5 mainly in the context of physical performance, muscle pathogenesis and muscular dysfunction
6 related to aging, as well as in muscle disorders associated with diabetes, cancer and inflammation
7 (3). The majority of the miRNAs shown to be altered by either acute or chronic exercise in these
8 studies are muscle-specific miRNAs, also called myomiRs. MiRNAs are differentially expressed
9 within various organs, and if a miRNA is expressed more than 20-fold in a specific tissue
10 compared with the mean of its expression in other tissues, it is thus considered as a tissue-specific
11 miRNA (34). The expression of a variety of miRNAs, and particularly myomiRs, is modulated by
12 PA within muscle tissues (4,35) as well as in plasma (5). Zacharewicz *et. al.* (4) have published a
13 detailed review on miRNA expression within muscles in response to PA. Here we restrict our
14 review to miRNA expression in blood following acute or chronic PA.

15 C-miRNAs are currently being extensively studied due to several advantages from a
16 clinical and etiological perspective including a remarkable stability in the circulation, resistance
17 to RNase activity (36), and preservation through multiple freeze-thaw cycles (37). Consequently,
18 c-miRNAs can be easily evaluated by standard and relatively inexpensive qRT-PCR techniques,
19 even in low concentrations (38), and their measurement is a non-invasive procedure (39). This is
20 in stark contrast to the analysis of miRNA expression within specific tissues, which require
21 biopsies. Based on these differences, c-miRNAs measured from stored blood samples will prove
22 advantageous in the conduct of large epidemiological studies of PA-related cancer etiology. For
23 these reasons, in this review we focused on the role of c-miRNAs as an underlying mechanism

1 mediating PA's benefits against cancer through the exploration of potential links between PA-
2 induced c-miRNA modulation and cancer-related c-miRNA expression.

3
4 The majority of c-miRNAs are derived from leukocytes and endothelial cells (40) but they
5 can also originate from organs exposed to high blood flow (3). When exercising, the blood flow
6 is significantly elevated, with up to a 80-fold blood flow increase in times of high physical output
7 (41,42), leading to expression changes in miRNAs originating from various organs (43–45), and
8 in particular from skeletal muscles. The release of miRNAs in the blood circulation can originate
9 from destroyed tissues (46,47), especially if the exercise load is great (48). However, increases in
10 the expression of c-miRNAs have also been reported in the absence of cell damage markers in
11 plasma (49). MiRNAs can, in fact, be exported by active transport systems, either encapsulated in
12 extracellular vesicles (such as exosomes) (46,50,51), or associated with protein or lipid-based
13 complexes (e.g., Argonaute2 (*AGO2*), high density lipoproteins (*HDL*) and low density
14 lipoproteins (*LDL*)) (36,52–54). Importantly, increasing evidence shows that miRNAs, through
15 their circulating form, can be transported from donor cells to recipient cells, where they exert
16 their functions (18,54). C-miRNAs are thus being recognized as important components in
17 intercellular communication (53,55,56), and have notably been demonstrated to play key roles in
18 crucial cellular processes, such as apoptosis, proliferation, metastasis, and immunity (57,56). For
19 example, exosomal-miR-105 secreted by breast cancer cells and transferred to endothelial cells
20 have been shown to promote metastasis (58).

21

22

23

1 MATERIALS AND METHODS

2 We conducted a literature search up to March of 2016 in PubMed using the following
3 search strategy: « miRNAs AND exercise » or « miRNAs AND physical activity » or
4 « microRNAs AND exercise » or « microRNAs AND physical activity ». Only studies conducted
5 in humans containing data measuring circulating miRNAs were included. We did not employ a
6 minimum sample size threshold and studies with small numbers of participants were also
7 included, as the total number of studies meeting our inclusion criteria was relatively small.
8 Studies examining populations with disease were excluded, and all studies included in the review
9 presented measurements among healthy subjects as underlying diseases may impact c-miRNAs.
10 To our knowledge, there are no data on the effect of PA on c-miRNA expression in cancer
11 patients. One study has investigated the impact of PA on miRNA expression within tumor tissue
12 based on an animal model, and is included in the discussion section. We also analyzed reference
13 lists of the identified studies for additional relevant articles. The title and abstract were examined,
14 and full text was obtained if the paper seemed eligible. No period or language restrictions were
15 applied. We compiled the results from studies investigating c-miRNA expression in response to a
16 single bout of PA (acute PA) in either normally active individuals (Table 1) or trained subjects
17 (Table 2) as well as the impact of a training period and/or regular PA (chronic PA) on basal c-
18 miRNA expression (Table 3).

19 Tables 1 and 2 include details on study (design, sample size, timing of blood draws),
20 participant (age, gender, PA level) and protocol characteristics (training program if any, type of
21 exercise (resistance or endurance exercise). Included in these tables are descriptions of the
22 number of miRNAs screened, number of miRNAs altered by PA, miRNAs measured but not
23 altered, and undetectable or unreliable miRNAs.

1 With regards to the type of exercise, we considered predominantly endurance exercises as
2 exercises involving the whole body and increasing oxidative capacity and aerobic endurance (e.g.
3 a marathon run), while resistance exercises were defined as exercises using machines, weights, or
4 even individuals' body weight to stimulate muscle hypertrophy and increase muscular strength or
5 power (e.g. leg press, squats, pull-ups). We highlight the distinctions between normally active
6 and "trained" participants, based on information provided by the studies. We considered the
7 subjects trained if: 1) the subjects underwent a specific training program described in the study;
8 2) a large bout of exercise such as a marathon run was included in the protocol as undergoing
9 such an effort implies previous training (even though not always specified in the reviewed
10 studies); 3) the authors stated that the participants were "trained individuals" and/or part of a
11 competitive program. We considered the subjects "untrained" or "normally active" if the
12 participants engaged in recreational activity ≤ 4 hours per week and/or if specified in the study.
13 In total, we included 5 studies examining normally active individuals and 10 studies investigating
14 trained individuals, according to our criteria.

15 To facilitate comparisons across studies, we present the data for c-miRNAs that were
16 examined in multiple studies. We first synthesize and discuss the results obtained for c-miRNA
17 expression following acute PA, followed by a discussion and synthesis of results examining basal
18 miRNA expression in response to chronic PA.

19 PA has also been shown to modulate miRNA expression within peripheral blood
20 mononuclear cells (PBMCs). PBMCs are leukocytes with a round nucleus, and comprise
21 lymphocytes (T cells, B cells, and natural killer cells), monocytes, and dendritic cells (59).
22 Similar to c-miRNAs, PBMC miRNAs can easily be detected by standard RT-qPCR techniques,
23 but it remains controversial whether their expression is similar or not to whole blood miRNAs
24 (60,61). Thus, even though two different research groups found an impact of acute PA in

1 circulating leukocytes (62–65), those results are not discussed in this review.

2

3

1 **RESULTS**

2 We have identified a total number of 16 studies in our review, which are displayed in
3 tables 1, 2 and 3. Among these studies, 14 investigated c-miRNA expression in response to a
4 single bout of exercise (66–68,48,69,49,65,70–76), and six (49,66,71,75,77,78) evaluated the
5 impact of chronic exercise on c-miRNA expression.

6

7 **Impact of acute physical activity on c-miRNA expression**

8 Acute PA refers to a single isolated PA session. It is clear that a single bout of PA alters
9 expression of several c-miRNAs shortly after its completion (Table 1 and 2). However, the
10 modalities of PA (frequency, intensity, timing and type (FITT)) and the individual's physical
11 fitness levels (trained or untrained) may impact those changes. Modifications in several c-
12 miRNAs are not always observed immediately after PA, but are seen only after 2-3 hours of rest.
13 For example, Banzet *et. al.* reported no changes in miRNA expression immediately after the
14 completion of a single bout of eccentric exercise (30 minutes downhill walking) but observed an
15 increase in miR-1, miR-133a, miR-133b, miR-499-5p and miR-208b six hours post bouts of PA
16 (68). These c-miRNAs then returned to baseline expression after periods of inactivity, which has
17 been reported to be relatively slow in some studies (66–68,70,72). For example, decreased
18 expression of c-miR-221 was still observed by Sawada *et. al.* three days post-completion of a
19 resistance exercise session (67).

20 ***Muscle- or cardiac-specific miRNAs***

21 In healthy individuals, muscle- or cardiac specific miR-1, miR-133, miR-206, miR-499,
22 miR-208 are expressed at low levels in the circulation, whereas miR-486 is generally found in
23 higher concentrations (79,74). In response to PA, several studies have shown an increase in the
24 circulating forms of miR-1, miR-133, miR-206, miR-208 and miR-499 immediately after the

1 completion of various PA modalities (FITT) (48,68,70,72,73,75,76), and a decrease in miR-486
2 (66). It can be noted that specific exercise modalities appear to impact changes in miRNA levels.
3 Banzet *et. al.* found different c-miRNA expression patterns in normally active participants who
4 underwent a downhill walk versus others who completed an uphill walk (68). Downhill walking
5 is considered an eccentric exercise as the muscles actively lengthen during this effort, whereas
6 uphill walking induces active shortening of the muscles and is thus considered a concentric
7 exercise. Interestingly, Banzet *et. al.* found significantly higher muscle/cardiac specific c-miRNA
8 expression for participants who walked downhill compared to subjects walking uphill (68). Thus,
9 these data suggest that the type of muscle contraction involved in the exercises impacts c-miRNA
10 expression. Furthermore, data from various studies also suggests that muscle/cardiac c-miRNAs
11 can be differentially expressed depending on PA's intensity. For example, when looking at c-
12 miR-133, Uhlemann *et. al.* showed that modifications in c-miR-133 expression in response to PA
13 were correlated with phosphocreatine kinase (*CPK*) activity, a marker for muscle damages: the
14 more damaging the exercise was, the most altered c-miR-133 expression was (48).

15 Modulations in muscle/cardiac c-miRNA expression post-exercise appear to be
16 temporary, yet the exact delay before a return to baseline values is unclear. When examining
17 measures taken one day post-exercise, most studies showed that muscle and cardiac specific c-
18 miRNAs had returned to their basal value. Others, however, reported a decrease in expression of
19 those c-miRNAs compared to immediately after exercise, but still significantly elevated
20 compared to baseline values. Focusing on c-miR-1 for example, four studies found similar
21 expression of this c-miRNA between pre-exercise and 24 hours post exercise (49,68,75,76),
22 while one other observed significantly higher expression compared to baseline value (but
23 attenuated from expression measured immediately after exercise) (70).

24 Interestingly, high inter-individual variation in c-miR-499 expression has been reported in

1 response to an acute bout of endurance exercise in two different studies (68,72) which suggests
2 that c-miR-499 is highly dependent on participants' characteristics, notably their training status.
3 MiR-499 is a cardiac-specific miRNA and studies have shown its circulating form may represent
4 a marker of myocardial injury (80–84). Strenuous exercises such as marathon running can induce
5 transient myocardial injuries (85–88), this risk being higher in less trained individuals (87,89).
6 Therefore, the inter-individual variation observed in c-miR-499 expression following a marathon
7 run may reflect variation in training among participants, and/or cardiac muscle exhaustion.

8

9 ***Other circulating miRNAs***

10 Non muscle- or cardiac-specific c-miRNAs have also been reported to be impacted by
11 acute PA, but the exact direction and magnitude of those changes remain unclear. Two different
12 research groups observed an up-regulation of c-miR-126, an endothelial-specific miRNA
13 involved in angiogenesis (90), immediately after a single bout of PA (48,72), while no statistical
14 differences in c-miR-126 expression pre- and post-PA have also been reported (48,69).
15 Interestingly, Uhlemann *et. al.* measured c-miR-126 expression before and after an acute bout of
16 PA: subjects were either trained or untrained and the exercises which had to be completed varied
17 among protocols in type, duration and intensity (48). They observed an upregulation in c-miR-
18 126 in response to a single maximal symptom-limited test performed by healthy individuals, as
19 well as in trained men who underwent four hours of bicycling at 70% of their anaerobic
20 threshold, and in trained runners who completed a marathon. However, Uhlemann *et. al.* also
21 reported no significant difference in c-miR-126 expression in trained subjects who performed a
22 resistance training session compared to basal values (48). Since miR-126 is an endothelial-
23 specific miRNA, the authors explained the increase in c-miR-126 expression following acute
24 exercise observed in three of their protocols by exercise-induced endothelial damages, while they

1 suggested that the resistance exercise session, which resulted in unaltered c-miR-126 expression,
2 did not cause such damages (48).

3 C-miR-146a, a miRNA known for playing a role in inflammation and immunity (91,92)
4 has also been found to be altered by acute PA, however, the effects appear to be highly dependent
5 on the type of activity intervention. Two studies have reported an up-regulation of this c-miRNA
6 in response to a single bout of endurance exercise in trained individuals (49,72), but Nielsen *et.*
7 *al.* observed opposite results with a decrease in c-miR-146a in response to a similar type of PA in
8 normally active subjects (71). In contrast, Van Craenenbroeck *et. al.* reported no change in c-
9 miR-146a expression in response to a single maximal symptom-limited test, while Sawada *et. al.*
10 measured no alteration in c-miR-146a expression in healthy men immediately after they
11 performed resistance exercise session but found a decrease in its expression three days post-
12 exercise (67). Interestingly, in trained athletes, Baggish *et. al.* found an upregulation miR-146a in
13 response to an acute bout of PA both before and after a training program, the magnitude of the
14 elevation being higher after completion of the training program (93).

15 Similarly, changes in the circulating expression of miR-221 and miR-222, important
16 players in vascular biology (94), have been reported, but high variations can be found between
17 the studies (49,67,71). In response to a 60 min cycle ergometer exercise bout below anaerobic
18 threshold, c-miR-221 has been found to be down-regulated in normally active participants by
19 Nielsen *et. al.* (71), as opposed to Baggish *et. al.* who showed an up-regulation of c-miR-221
20 expression in trained individuals following an acute exhaustive cycling exercise (49). When
21 assessing the impact of a short exhaustive bout of PA on those c-miRNA expression, Sawada *et.*
22 *al.* did not report any changes immediately after PA completion, but found a decrease three days
23 later (67). C-miR-222 expression in response to an acute bout of PA has only been investigated
24 by two different studies: one of them showed an upregulation of this c-miRNA in trained men

1 undergoing an exhaustive bout of exercise (49), while the other one reported no change in its
2 expression between before and after a resistance exercise session (67). The differences observed
3 between studies are likely attributable to differences in protocols, suggesting that alterations of c-
4 miRNAs in response to acute PA are dependent on the dose and type of exercise (FIIT) as well as
5 participants' characteristics (e.g. age, gender, fitness level, health status, personal history, diet,
6 smoking habits, etc).

7

8 **Impact of chronic physical activity on c-miRNA expression**

9 Chronic PA is defined as regular PA done over an extended time period (a minimum of
10 several weeks). Interestingly, contrary to what is observed for c-miRNA expression following an
11 acute bout of PA (Table 1 and 2), there is a general trend for a down-regulation of c-miRNAs
12 expression in response to chronic PA (Table 3). Among the six different studies investigating the
13 impact of chronic PA on resting expression of c-miRNAs we included in our review, four were
14 intervention trials (49,66,71,75) and two were observational studies (77,78). The blood samples
15 analyzed in those research projects were taken at rest, at least 12 hours after the last training
16 session.

17 ***Muscle- or cardiac-specific miRNAs***

18 Cardiac- or muscle specific c-miRNA expression changes in response to chronic PA are
19 hard to measure because of their low concentrations in humans at rest, consequently, there are
20 limited results thus far. For c-miR-1, one study reported no change between its resting expression
21 before and after a 10-week marathon training period in either trained or untrained individuals
22 (75), whereas two other research groups found its expression too low to interpret its measurement
23 (66,78). A trend towards a decrease in c-miR-133 expression in response to a supervised training
24 on a cycle ergometer was found by Nielsen *et. al.* (71), while other studies reported no changes

1 (49,75) or non-detectable amounts for the quantification of c-miR-133 (66,78). Several studies
2 measured the resting expression of c-miR-206 (66,78), c-miR-208 (66) and c-miR-499 (66,78)
3 before and after a training period, but their expressions were too low to be interpreted. Finally,
4 Aoi *et. al.* found that a four week cycling program down-regulates c-miR-486 basal expression
5 (66).

6 ***Other circulating miRNAs***

7 When evaluating c-let-7d expression, a miRNA that has a crucial role in cell
8 division and differentiation (95,96), Nielsen *et. al.* showed a down-regulation of its baseline
9 expression after a 12 week training period (71) while Bye *et. al.*'s observational study (77)
10 showed that subjects with high maximal oxygen uptake (VO_{2max}) (145.2 ± 20.7 mL/kg^{0.75}/min) had
11 a lower c-let-7d expression compared to individuals engaging in similar activity levels but with
12 lower VO_{2max} (101.1 ± 18.0 mL/kg^{0.75}/min).

13 For c-miR-21, Nielsen *et. al.* reported that baseline expression was decreased after chronic
14 PA (71), while the results obtained from Bye *et. al.*'s observational study shows that
15 independently of activity levels, individuals with high VO_{2max} have decreased c-miR-21 basal
16 expression compared to subjects with lower VO_{2max} (77). However, Baggish *et. al.* found an up-
17 regulation of c-miR-21 after 13 weeks of rowing training, while Wardle *et. al.* reported no
18 alteration in expression between athletes (endurance or resistance trained) and controls, but
19 showed a significant increase in resistance trained individuals when compared to endurance
20 athletes (72,78).

21 C-miR-221 and c-miR-222 expression in response to chronic PA remains unclear.
22 Baggish *et. al.* reported increased expression of c-miR-222 after a 13-week training program
23 (72), in line with Wardle *et. al.*'s findings when comparing endurance trained athletes with
24 control individuals (78). However, Wardle *et. al.* found a down-regulation of c-miR-222 in

1 resistance trained athletes, and Bye *et. al.*'s reported a decrease in c-miR-222 expression in
2 individuals with high VO_{2max} when compared to subjects with a lower VO_{2max} (77,78). Similarly,
3 various results have been found for the changes of c-miR-221 expression in response to chronic
4 PA: Baggish *et. al.* reported an increase in its baseline expression after a training period (72),
5 whereas Wardle *et. al.* found no statistical differences between trained athletes (endurance or
6 resistance) and controls, but a down-regulation in resistance trained athletes when compared with
7 endurance trained athletes (78).

8

9

1 **DISCUSSION**

2 **Potential impact of PA-induced c-miRNA changes on cancer risk, progression, and** 3 **treatment**

4 Overall, the current results available from the scientific literature suggest that several c-
5 miRNAs are impacted by acute PA (miR-1, miR-133, miR-206, miR-208, miR-499, miR-486,
6 miR-126, miR-146, miR-221 and miR-222) and/or by chronic PA (miR-133, miR-486, let-7d,
7 miR-21, miR-222, and miR-221). Importantly both acute PA and chronic PA appear to induce
8 changes in c-miRNA expression depending on exercise modalities and individuals' fitness status.
9 While results to date are promising and suggest a clear impact of PA on miRNA expression,
10 comparisons between studies are challenging and efforts should be devoted towards standardized
11 protocols and procedures for miRNA collection, analysis and reporting.

12 The studies included in this review suggest that PA modulates c-miRNA expression in
13 healthy individuals. Several studies have also observed that PA can alter c-miRNA expression
14 within disease populations such as patients with chronic kidney diseases (69) and pre-diabetic
15 individuals (97). To our knowledge, however, no data exists regarding the impact of PA on
16 miRNA in cancer patients. PA also appears to be able to influence miRNA expression within
17 organs other than skeletal muscles (98,99). Taken together, these elements suggest that PA may
18 influence c-miRNA expression in cancer patients, perhaps via c-miRNA intercellular
19 communication. This hypothesized mechanism is illustrated in Figure 1.

20 Throughout this section, we discuss how modulation of specific c-miRNA expression by
21 PA might impact cancer risk, progression and treatments, and provide some examples of
22 promising early findings. Figure 2 presents hypothesized examples of how PA could impact
23 cancer via c-miRNA modulation using c-miR-133, c-miR-221/222, c-miR-126 and c-let-7.

24 ***Impact of miRNAs on cancer risk and development***

1 Multiple miRNAs are involved in DNA repair, checkpoint functions, tumor suppression,
2 etc. (100), and their modulation by PA might play an important role in cancer risk and
3 progression. For example, PA can alter c-miR-133 expression (48,68,70–73,75,76,101), a well
4 known myoMiR participating in myoblast differentiation which has also been identified as a
5 tumor suppressor (102) in several cancers, including ovarian, colorectal, bladder, breast, prostate,
6 and gastric cancers (101,103–108). MiR-133 has also been shown to be modified within muscle
7 tissues in response to acute and chronic PA. More specifically, acute bouts of exercise seem to
8 increase muscular miR-133 expression (109,110), while training tends to decrease expression
9 (109,26). These data suggest that miR-133 can translocate from muscle tissue to blood vessels,
10 and that this miRNA can impact cancer progression as depicted in Figure 1. Several studies
11 suggest that miR-133 targets several oncogenes, such as the epidermal growth factor receptor
12 (*EGFR*) (101) and the insulin-like growth factor 1 receptor (*IGF1R*) (108,111). When activated,
13 those oncogenes stimulate various pathways causing deregulation in several cell processes,
14 eventually leading to carcinogenesis. For example, activation of *EGFR* pathway leads to the
15 stimulation of intracellular signaling cascades such as the mitogen-activated protein
16 kinases/extracellular signal-regulated kinases (*MAPK/ERK*) pathway, which plays a role in cell
17 cycle progression, differentiation, proliferation, and apoptosis (112,113). When activated, the
18 *EGFR* pathways also stimulate the phosphoinositide 3-kinase - protein kinase B (*PI3K/AKT*)
19 cascade, known for its crucial role in regulation of apoptosis and protein synthesis (114,115). An
20 increase in c-miR-133 by PA originating from muscle tissue, may therefore impact tumor cells
21 and regulate target oncogenes and associated pathways.

22 Similarly, let-7 is a tumor suppressor and pro-apoptotic miRNA (116) whose expression
23 is decreased in numerous cancers (117), and reported to be modulated in plasma by exercise
24 (71,77). While no direct evidence was identified in humans, in an animal model, breast tumor-

1 bearing mice who underwent five weeks of interval exercise training (treadmill running) had
2 increased let-7 expression within the tumor itself when compared to breast-tumor sedentary mice
3 (118). Let-7 is known for inhibiting mRNA translation of well-known oncogenes, including the
4 *RAS* family (*HRAS*, *KRAS*, and *NRAS*) (13) and *c-MYC* (119) (120). When activated, *Ras*
5 stimulates several signaling pathways, including *MAPK* cascade and *PI3K/AKT* (121), thereby
6 influencing many cellular functions.

7 We must note the complex and often paradoxical role of miRNAs, with several miRNAs
8 exerting stimulatory as well as inhibitory effects depending on cancer type or stage of the disease
9 (122–124). MiR-221 and miR-222 for example have a dual role: they can either act as tumor
10 suppressors as oncogenes. On one hand, miR-221 and miR-222 have been found to retard cancer
11 progression in several cancer types, and their expression in the circulation have been found to be
12 altered by PA in several studies (49,71,72,77,78). In gastrointestinal stromal tumors for example,
13 miR-221 and miR-222 are thought to have prophylactic effects by negatively regulating the stem
14 cell factor receptor *KIT*, and are found under-expressed in tumors when compared to healthy
15 tissues (125–127). *KIT* is a receptor tyrosine-kinase (*RTK*), and its activation leads to the
16 stimulation of several intracellular signaling pathways, including the signal transducer and
17 activator of transcription 3 (*STAT3*), *PI3K*, phospholipase C (*PLC*), and the *MAPK* cascade (128–
18 130). *KIT* promotes cell survival, proliferation and motility (131), and its inhibition by miR-221
19 and miR-222 therefore contributes to carcinogenesis suppression. Modulation of those miRNAs
20 by PA could thereby inhibit *KIT* activation, consequently lowering the risk of developing cancer.

21 On the other hand, miR-222 and miR-221 have been shown to act as oncomiRs in other
22 cancer types. In lung and liver cancer for example, these miRNAs have been shown to inhibit the
23 action of the phosphatase and tensin homolog (*PTEN*), known to inhibit *MAPK/ERK* pathway,
24 and the tissue inhibitor of metalloproteinases-3 (*TIMP3*), thereby enhancing cell proliferation and

1 migration through *PI3K/AKT* pathway (132). The dual role played by miR-222 and miR-221
2 suggest that clarifying the influence of exercise modalities (endurance vs resistance, short vs long
3 duration, regular vs irregular training, etc.), tissue and/or cancer site of interest will be extremely
4 important in subsequent research.

5 ***Impact of miRNAs on cancer invasion and metastasis***

6 PA also modulates c-miRNAs involved in cell proliferation, invasion and metastasis
7 (Figure 2). For example miR-21 is altered by resistance and endurance training (71,72,78) and is
8 also known for participating in tumor invasion. In fact, *in vitro* studies have shown that in several
9 cancer types, miR-21 knock-down mice displayed suppression of cell proliferation and tumor
10 growth (133), as well as reduced invasion and metastasis (133–135). Furthermore miR-21
11 negatively regulates tumor suppressor programmed cell death 4 (*PDCD4*) (136) and downstream
12 signaling targets (137,138) in colorectal cell lines. The results in this review (Tables 1, 2 and 3)
13 suggest that acute exercise can transiently upregulate c-miR-21 expression (65,93), while chronic
14 exercise (which reflects physiological adaptations) can also lead to alterations in miR-21
15 expression within circulation (71,77), however, the influence of chronic PA is less clear. By
16 lowering miR-21 expression within cancer cells, PA may restore *PDCD4* and *PTEN* activation
17 and limit cancer proliferation. This is supported by literature that suggests PA is able to modulate
18 miR-21 within multiple tissues/fluids, for example muscle tissue in mice (139) as well as in
19 plasma in healthy human subjects (93,65,71,77,78), as well as in tumors of breast tumor-bearing
20 mice (118) (Figure 1).

21 The up-regulation of c-miR-126 by acute PA (48,72) might also represent a pathway
22 through which PA impacts cancer progression. In breast cancer, miR-126 regulates the tumor
23 microenvironment composition by directly inhibiting stromal cell-derived factor-1 alpha
24 (*CXCL12*) expression and indirectly suppressing chemokine ligand 2 (*CCL2*) expression in

1 cancer cells (140). These two chemokines play a role in recruiting stromal cells to the primary
2 tumor microenvironment (141,142), thereby leading to cancer cell invasion and metastasis.
3 Therefore, the increase in c-miR-126 expression in response to acute PA followed by active
4 transport into tumor cells could lead to inhibition of *CXCL12* and *CCL2*, consequently
5 suppressing cancer expansion by modifying the tumor microenvironment composition (48).

6 Overall, PA-induced c-miRNA expression changes could have the potential to impact
7 tumorigenesis and cancer development. Importantly, several studies suggest that re-expression of
8 tumor-suppressor miRNAs within tumor tissues can inhibit tumor growth, thereby representing a
9 promising therapeutic tool against cancer (18,143–145). For example, re-expression of let-7
10 within various tumor types have been proven to slow cancer growth (95,146–148) and is thus
11 considered a promising tool against cancers under-expressing let-7 family members (146,149).
12 Additional research, particularly large intervention studies in populations of cancer patients are
13 needed to determine the exact impact of PA on miRNA expression and potential roles in cancer
14 therapy.

15

16 **Limitations of the research to date**

17 Investigating c-miRNAs in response to PA presents several challenges. First, to date,
18 there are few studies that have compared similar c-miRNAs using comparable methods to enable
19 direct comparisons across studies. Although some consistency has been observed for several c-
20 miRNAs such as miR-133 (48,70,72,73,75,76), contradictory results have often been observed.
21 This inconsistency can largely be attributed to discrepancy in methods across studies, including:
22 1) differences in sample collection; 2) post-processing of samples and; 3) the use of serum or
23 plasma for miRNAs' extraction.

24 Different normalization strategies have been used between the reviewed studies. The

1 current results available on c-miRNA expression changes in response to PA should therefore be
2 carefully interpreted. For example, Nielsen *et. al.* used a stable expressed c-miRNA to account
3 for the biological variation between samples, whereas Baggish *et. al.* used a synthetic spike in
4 approach (71,72). Some studies also included a hemolysis control phase in the study design, since
5 it has been shown that hemolysis occurring during blood collection has substantial impact on the
6 miRNA content in plasma/serum (150). This issue occurs because erythrocytes contain numerous
7 miRNAs that unavoidably will contaminate a plasma sample if the erythrocyte bursts during
8 sampling (151).

9 Another methodologic factor likely to impact the reliability of the results obtained from the
10 various studies reviewed here is the fact that miRNA concentrations vary between serum and
11 corresponding plasma samples (152). Analyzing and comparing miRNA expression from serum
12 and plasma within or between studies should be done carefully.

13 To date, miRNA expression in response to PA has mainly been measured in the
14 circulation and in muscles, but it would also be interesting to study the changes in miRNA
15 expression in other tissues. More specifically, investigating miRNA expression after PA in target
16 tissues, and more specifically tumor tissues, would provide novel data of how PA can impact
17 cancer through miRNA modulation. Tissue-specific approaches would also aid in a better
18 understanding of the role of c-miRNAs in specific cancer sites that may result in the development
19 of targeted novel therapies.

20

21

1 **CONCLUSIONS AND FUTURE DIRECTIONS**

2 PA represents a lifestyle behaviour that influences the expression of several c-miRNAs,
3 some of which have been associated with carcinogenesis and cancer progression. Our results
4 suggest that alteration of miRNAs within the circulation is dependent on the
5 type/modality/frequency of exercise as well as on the participants characteristics. Furthermore,
6 the evidence to date on c-miRNA expression in response to PA is limited by small sample sizes
7 without standardized measures of miRNA or physical activity. miRNAs appear to have a
8 meaningful impact on cancer risk and progression, however, the effect vary between cancer
9 types. Therefore, it appears essential to provide a better understanding of how various types of
10 PA in a specific population could impact c-miRNA expression: it could represent a useful tool for
11 healthcare practionners in establishing and monitoring PA programs for cancer patients.

12
13 Future research should focus on large epidemiologic studies with standardized blood
14 storage and collection as well as standardized measures of c-miRNA expression and objective
15 measures of PA. Additional consistency is needed to provide more meaningful conclusions as
16 well as standarization of PA measurement. Further investigation into the effects of PA on
17 miRNAs is necessary and could have implication both for cancer prevention, treatment and
18 survival outcomes.

19

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Table 1: Effect of acute physical activity on the expression of c-miRNAs in healthy and normal activity subjects

Reference	Subjects	Type of acute PA	Plasma/serum base	No of miRNAs screened	MiRNAs altered by PA (compared to basal values)		Unaltered miRNAs among the measured ones	miRNAs not detectable or unreliable		
					Immediately post-ex	During recovery				
Acute endurance exercise										
Aoi <i>et. al.</i> , 2013 (66)	10 males 21.5±4.5 yrs	60min cycling exercise (70% VO ₂ max)	Serum	-	miR-486↓		Post 3h: miR-486↓	NONE	miR-1 miR-133a miR-133b	miR-206 miR-208b miR-499
Banzet <i>et. al.</i> , 2013(68)	9 males 27 to 36 yrs	30min uphill walking exercise (concentric)	Plasma	-	miR-181b↑ miR-214↑ miR-499-5p↑		Post 2h and 6h: miR-133a↑ miR-133b↑	miR-181a		miR-206 miR-208a
Banzet <i>et. al.</i> , 2013 (68)	9 males 27 to 36 yrs	30min downhill walking exercise (eccentric)	Plasma	-	NONE		Post 2h and 6h: miR-133a↑ miR-133b↑	miR-181a miR-181b		miR-206 miR-208a
Uhlemann <i>et. al.</i> , 2014 (48)	7 males and 6 females 30.4±2.0 yrs	Maximal cycle ergometry test	Plasma	-	miRNA-126↑		No recovery blood draw time points	miR-133		
Van Craenenbroeck <i>et. al.</i> , 2015 (69)	7 males and 5 females 43.4±4.7 yrs	Maximal cycle ergometry test	Plasma	-	miR-150↑		No recovery blood draw time points	miR-146a miR-21	miR-126 miR-210	
Acute resistance exercise										
Sawada <i>et. al.</i> , 2013 (67)	3 males 29.9±1.2 yrs	Bench press and leg press (5 sets of 10 reps with 1min rest between sets)	Serum	1458	NONE		Post 1 day: miR-149*↑ Post 3 days: miR-146a↓ miR-221↓	miR-20a miR-21 miR-133a miR-210	miR-222 miR-328 miR-1908	miR-299-5p

*Results of a systematic review of studies investigating the impact of acute PA on c-miRNA expression in healthy and “normal” activity levels humans subjects either immediately after acute exercise completion and/or several hours up to a couple days after.

Abbreviations: ex: exercise; wk: week; yrs: years.

Table 2: Effect of acute physical activity on the expression of c-miRNAs at various time points in healthy trained subjects

Reference	Subjects	Training program	Type of acute PA	Plasma/ Serum base	No of miRNAs screened	MiRNAs altered by PA (compared to basal values)		Unaltered miRNAs among the measured ones	miRNAs not detectable or unreliable	
						Immediately post-ex	During recovery			
Acute endurance exercise										
Baggish <i>et. al.</i> , 2011 (49)	10 males 19.1±0.6 yrs	13 weeks rowing training	Maximal cycle ergometry test	Plasma	-	miR-146a↑ miR-222↑	miR-21↑ miR-221↑	No recovery blood draw time points	miR-20a miR-328	miR-210 miR-133a
Tonevitsky <i>et. al.</i> , 2013 (65)	8 males 21.7±2.6 yrs	Regular ski training	30min run on a treadmill (80% VO ₂ max)	Serum	200	miR-24-2-5p↑ miR-27a-5p↑ miR-181a-5p↑		<u>Post 1/2h and post 1h:</u> miR-24-2p↓ miR-27a-5p↓ miR-181-5p↓ <u>Post 1h:</u> miR-21-5p↑		
Mooren <i>et. al.</i> , 2014 (70)	14 males 42.8±6.0 yrs	Regular endurance training	Marathon run	Plasma	-	miR-1↑ miR-133a↑ miR-206↑	miR-208b↑ miR-499↑	<u>Post 1 day:</u> miR-1↑ miR-133a↑	miR-206↑	miR-21 miR-155
Nielsen <i>et. al.</i> , 2014 (71)	13 males 28±8 yrs	12 weeks endurance training (cycle ergometry)	60min cycle ergometry exercise (65% Pmax)	Plasma	188	miR-221↓ miR-30b↓ let7i↓ miR-652↓	miR-106a↓ miR-146a↓ miR-151-3p↓ miR-151-5p↓	<u>Post 1h:</u> miR-338-3p↑ miR-330-3p↑ miR-223↑ miR-139-5p↑ <u>Post 3h:</u> miR-1↑ miR-133a↑‡	miR-143↑ miR-145↑‡ miR-424↑‡	miR-133b↑‡
Baggish <i>et. al.</i> , 2014 (72)	21 males 51.8±1.4 yrs	Regular endurance training	Marathon run	Plasma	-	miR-126↑ miR-1↑ miR-133a↑ miR-208a↑	miR-499-5p↑ miR-208a↑ miR-134↑ miR-146a↑	<u>Post 1 day:</u> miR-499-5p↑		
Uhlemann <i>et. al.</i> , 2014 (48)	13 males 32.4±2.3 yrs	Regular endurance training	4h cycle ergometry exercise (70% anaerobic threshold)	Plasma	-	miR-126↑		<u>Post 1h:</u> NONE <u>Post 1 day:</u> NONE		miR-133
Uhlemann <i>et. al.</i> , 2014	22 males 56.8±5.2 yrs	Regular endurance	Marathon run	Plasma	-	miR-126↑ miR-133↑		No recovery blood draw time points		

(48)	yrs	training							
Gomes <i>et al.</i> , 2014 (73)	5 males 31.6±4.39 yrs	Regular endurance training	Half-marathon run	Plasma	-	miR-1↑ miR-133a↑ miR-206↑		No recovery blood draw time points	
Cui <i>et al.</i> , 2015 (74)	18 males 20.23±0.9 7 yrs	Regular exercise training (activity type not specified)	Cycle ergometry sprint intervals (2 sets of 30s all out sprints with 4min rest between sets)	Plasma	-	miR-1↓ miR-133a↓ miR-133b↓	miR-122↓ miR-16↓	No recovery blood draw time points	miR-206 miR-499
Clauss <i>et al.</i> , 2016 (75)	15 males 40.1±1.4 yrs	Marathon training ≤40km/wk for 10 wk	Marathon run	Plasma	-	miR-1↑ miR-133a↑		<u>Post 1 day:</u> miR-133a↑	miR-30a miR-26a miR-29b
Clauss <i>et al.</i> , 2016 (75)	15 males 40.0±1.7 yrs	Marathon training ≥55km/wk for 10 wk	Marathon run	Plasma	-	miR-1↑ miR-133a↑ miR-30a↑		<u>Post 1 day:</u> NONE	miR-26a miR-29b
Min <i>et al.</i> , 2016 (76)	20 males and 8 females 53.0±6.5 yrs	Regular endurance training	Marathon run	Plasma	-	miR-1↑ miR-133a↑ miR-206↑		<u>Post 1 day:</u> miR-499-5p↑	
Acute resistance exercise									
Uhlemann <i>et al.</i> , 2014 (48)	4 males and 7 females 37±2 yrs	Non-supervised regular training (activity type not specified)	Lat pulldown, leg press and butterfly (3 sets of 15 reps with 1min rest between sets)	Plasma	-	miR-133↑		<u>Post 1h:</u> NONE	miR-126

Legend: ‡ is placed after borderline significant miRNAs

*Results of a systematic review of studies investigating the impact of acute PA on c-miRNA expression in healthy trained human subjects either immediately after acute exercise completion and/or several hours up to a couple days after.

Abbreviations: No: number; ex: exercise; reps: repetitions; wk: week; yrs: years.

Table 3: Effect of chronic/regular/long-term physical activity on c-miRNA levels in healthy subjects

Reference	Type of study	Participants characteristics	Training program	Blood draw timing & plasma /serum base	No of miRNAs screened	MiRNAs altered by chronic PA	miRNAs measured but not altered by chronic PA	miRNAs not detectable/ unreliable
Chronic endurance exercise								
Baggish <i>et. al.</i> , 2011 (49)	Intervention	10 males 19.1±0.6 yrs Very trained	13 weeks rowing training	At least 12h post exercise -plasma	-	miR-146a↑ miR-222↑ miR-21↑	miR-221↑ miR-20a↑ miR-328 miR-210	miR-133a
Aoi <i>et. al.</i> , 2013 (66)	Intervention	10 males 21.5±4.5 yrs Normally active	4 weeks cycling training	2 days post training period -serum	-	miR-486↓		miR-1 miR-133a miR-133b miR-206 miR-208b miR-486 miR-499
Nielsen <i>et. al.</i> , 2014 (71)	Intervention	7 males 28±5 yrs Normally active	12 weeks of supervised training on cycle ergometer	3 days and 5 days post training period -plasma	188	miR-342-3p↓ let-7d↓ miR-103↑ miR-107↑ miR-766↓ miR-25↓ miR-148a↓	miR-185↓ miR-21↓ miR-148b↓ ‡ miR-133a↓ ‡ miR-92a↓ ‡ miR-29b↓ ‡	
Wardle <i>et. al.</i> , 2015 (78)	Observational	20 males 22.6±3.7 yrs Trained (endurance athletes) vs Control (not active)	Trained: 13h of training per week	At least 12h post PA -plasma	-	miR-222↑	miR-16-2 miR-20a-1 miR-103a miR-192	miR-451 miR-21 miR-146a miR-221 miR-1 miR-133a miR-206 miR-499
Clauss <i>et. al.</i> , 2016 (75)	Intervention	15 males 40.1±1.4 yrs Normally active	Marathon training: Running of ≤ 40km/week for 10 weeks	After the training period -plasma	-	NONE	miR-1 miR-133a miR-30a	miR-26a miR-29b
Clauss <i>et. al.</i> , 2016 (75)	Intervention	15 males 40.0±1.7 yrs Trained	Marathon training: Running of ≥ 55km/week for 10 weeks	After the training period -plasma	-	NONE	miR-1 miR-133a miR-30a	miR-26a miR-29b
Chronic resistance exercise								

Wardle <i>et al.</i> , 2015 (78)	Observational	20 males 22.2±2.1 yrs Trained (resistance athletes) vs Control (not active)	Trained: 13h of training per week	At least 12h post PA -plasma	-	miR-222↓	miR-16-2 miR-20a-1 miR-103a miR-192	miR-451 miR-21 miR-146a miR-221	miR-1 miR-133a miR-206 miR-499
Unspecified chronic exercise (endurance and/or resistance exercise)									
Bye <i>et al.</i> , 2013 (77)	Observational	<u>MiRNA screening:</u> 12 males 12 and females 40-45 yrs	Training included in lifestyle	Before the start of the exercise test measuring the subjects' VO ₂ max -serum	720		<u>Screening:</u> Males and females: miR-210↓ miR-125a ↓ miR-652 ↑		miR-125 in the validation cohort
		<u>MiRNA validation:</u> 38 males 38 and females 40-45 yrs Active vs non-active based on VO ₂ max					Males only: miR-151↑ miR-29a↓ let-7d↓	Women only: miR-210↓ miR-125a↓ miR-21↓	
							<u>Validation cohort:</u> Males and females: miR-222↓ miR-210↓ Males only: miR-21↓		

Legend: ‡ is placed after borderline significant miRNAs

*Results of a literature review of intervention and observational studies investigating the impact of chronic PA on c-miRNA expression in humans.

Abbreviations: No: number; yrs: years.

Figure Legend

Figure 1: Hypothesized pathways of miRNA transport from muscles to tumor cells via the circulation. MiRNAs can be exported from one cell to another via plasma through various active transport systems including: exosomes developed within multivesicular bodies (MVBs); released into the blood circulation after fusion of the MVBs with the plasma membrane; transport through protein or lipid-based complexes, such as *HDL*, and delivered to recipient cells.

Abbreviations: MVB: Multi-Vesicular Body.

Figure 2: Hypothesized mechanisms of action of physical activity on cancer risk and progression through c-miRNA modulation. Multiple c-miRNAs (MiR-126, MiR-221/222, Mir-133 and Let-7) which impact pathways involved in cancer risk and progression have been shown to be altered by physical activity.

Muscle

Plasma

Tumor



