What is the physiological time to recovery after concussion? Systematic review

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ABSTRACT

Aim or objective The aim of this study is to consolidate studies of physiological measures following sport-related concussion (SRC) to determine if a time course of postinjury altered neurobiology can be outlined. This biological time course was considered with respect to clinically relevant outcomes such as vulnerability to repeat injury and safe timing of return to physical contact risk.

Design Systematic review.

Data sources PubMed, CINAHL, Cochrane Central, PsychINFO.

Eligibility criteria for selecting studies Studies were included if they reported original research on physiological or neurobiological changes after SRC. Excluded were cases series ≤5 subjects, reviews, meta-analyses, editorials, animal research and research not pertaining to SRC.

Results A total of 5834 articles were identified, of which 80 were included for full-text data extraction and review. Relatively few longitudinal studies exist that follow both physiological dysfunction and clinical measures to recovery.

Summary/conclusions Modalities of measuring physiological change after SRC were categorised into the following: functional MRI, diffusion tensor imaging, magnetic resonance spectroscopy, cerebral blood flow, electrophysiology, heart rate, exercise, fluid biomarkers and transcranial magnetic stimulation. Due to differences in modalities, time course, study design and outcomes, it is not possible to define a single ‘physiological time window’ for SRC recovery. Multiple studies suggest physiological dysfunction may outlast current clinical measures of recovery, supporting a buffer zone of gradually increasing activity before full contact risk. Future studies need to use generalisable populations, longitudinal designs following to physiological and clinical recovery and careful correlation of neurobiological modalities with clinical measures.

INTRODUCTION

Establishing the time of recovery after a concussion is a difficult task for healthcare providers. These determinations have been limited by subjective symptom scores and imperfect clinical and neuropsychological testing. In addition, patients frequently experience more persistent symptoms including, but not limited to, chronic migraines, anxiety, post-traumatic stress disorder, attention problems and sleep dysfunction. Clinicians must determine whether these are premorbid maladies, downstream effects of concussion, unrelated phenomena or a true representation of ongoing concussion pathophysiology. Because of these assessment challenges and the potential for repeat injuries when returning patients to sports too early, clinicians are frequently left in a quandary with limited data to guide decision-making. Some recent studies suggest the physiological time of recovery may outlast the time for clinical recovery.1–3 The consequences of this are uncertain, but one possibility is that athletes may be exposed to additional risk by returning to play while there is ongoing brain dysfunction. Possible hazards may include repeat injury, prolonged symptoms, increased risk of musculoskeletal injury, more severe physiological dysfunction or increased risk for neurodegenerative disease.4–7 Therefore, this systematic review addressed three main clinical questions:

1. How does the time course of physiological recovery compare with the time line of clinical recovery after sport-related concussion (SRC)?
2. Should there be a minimum stand-down period following SRC?
3. Is the duration or content of graded return to play progressions appropriate?

METHODS

To identify relevant articles, we searched PubMed, CINAHL, Cochrane Central and PsychINFO. In order not to miss potentially relevant studies and because of the broad range of physiological markers, our search strategy included five search categories (exercise tolerance, brain physiology, advanced brain imaging, blood/serum biomarkers and functional assessment of physiology) (table 1). The initial search, designed in collaboration with the lead authors and two biomedical librarians, resulted in 7175 records (figure 1). Authors of this systematic review were asked to contribute any papers missed by the initial search, resulting in one addition. After removing duplicates, there were 5834 unique records. Two reviewers independently screened the titles of each record and excluded irrelevant studies or non-primary literature. 2293 records remained after this step. After applying exclusion criteria between two independent reviewers, 106 articles remained. The exclusion criteria were as follows: case reports, case series with ≤5 subjects, review articles, meta-analyses, editorials, animal research and research not pertaining to SRC. There were 46 articles.
The authorship group determined that dividing the studies into categories of physiological markers for each modality was as follows: (1) functional MRI (fMRI), (2) diffusion tensor imaging (DTI)/diffusion MRI, (3) magnetic resonance spectroscopy (MRS), (4) cerebral blood flow (CBF), (5) electrophysiology, (6) heart rate, (7) response to exercise, (8) fluid biomarkers and (9) transcranial magnetic stimulation. Although the number of studies varied between physiological categories, the overall level of evidence between categories was similar with almost all studies rated level 3. Thus, no single physiological marker category was clearly superior to the others. Each category will be summarised below, with a more detailed evidence table provided in the online supplementary materials. While most of the articles reviewed did not specify exact criteria for concussion diagnosis, in general, they did require clinical diagnosis by an experienced healthcare provider.

FUNCTIONAL MRI

There were 18 studies investigating fMRI after concussion. Signal changes in fMRI are postulated to represent altered brain activation but there is no clear consensus on the time frame for fMRI recovery after SRC. There were changes in cerebral activation ranging from 3 days to 23 months after clinical recovery and/or return-to-play (RTP).2,23 However, some fMRI changes only appear after symptoms are improving or even after resolution, suggesting more persistent network modifications may be separate phenomena from acute concussion physiology.24 25

Summary: Changes in fMRI activation vary based on brain trauma, time points and brain region of interest analysed. Among the categories of physiological markers for each modality, they did require clinical diagnosis by an experienced healthcare provider.
longitudinal studies, four used DTI\textsuperscript{26–29} and one used myelin water fraction (MWF).\textsuperscript{30} One article found imaging consistent with clinical data, with radial diffusivity increased and fractional anisotropy (FA) decreased at post injury day 2 (PID) with normalisation by 14 days after injury.\textsuperscript{26} One article examined both voxel and region of interest-based DTI analyses and reported increased FA at 1, 8 and 32 days after injury.\textsuperscript{27} In this study, symptoms recovered between PID1-8 and behavioural surveys for anxiety and depression recovered between 8–32 days after injury. In one article, there was increased FA and axial diffusivity (AD) and decreased mean diffusivity (MD) that persisted from 5 to 180 days post injury.\textsuperscript{28} However, others found changes in FA varied depending on region of interest and showed increased MD at chronic time points.\textsuperscript{31} MWF was reduced at 3 days after injury, tended to be decreased at day 14 and normalised by day 60.\textsuperscript{30} Diffusion kurtosis imaging showed changes from controls at 1 day after injury and persisting at day 8, but recovery of symptoms and cognition occurred between 1 and 8 days after injury.\textsuperscript{39}

Summary: Following SRC, changes in white matter orientation as measured by DTI are detectable with different methods. Multiple, but not all, studies show persistence of these changes even as clinical symptoms and other measures (behavioural surveys, cognitive testing) tend to resolve over time. Thus, measures of white matter orientation are altered after SRC and may persist beyond clinical recovery. However, it is unclear what biological mechanisms underlie the DTI changes or whether similar changes in diffusivity represent different mechanisms at different time points.

MAGNETIC RESONANCE SPECTROSCOPY
There were a total of 10 studies that used magnetic resonance spectroscopy (MRS) to measure physiological change after sports concussion. Five studies demonstrated acute reductions in N-acetylaspartate/creatine (NAA/Cr) ratios after SRC. Metabolic disturbance lasted until 7,\textsuperscript{32} 15\textsuperscript{33} and up to 30\textsuperscript{31} 34 35 days after injury, despite recovery of clinical parameters by 15 days.\textsuperscript{3 36 37} Another study showed more persistent alterations to the NAA/Cr ratio.\textsuperscript{34} Three athletes who had a second concussion during the metabolic disturbance had prolonged NAA recovery.\textsuperscript{35} Abnormal ratios of myo-inositol or glutamate to creatine may be late but not acute markers of prior mild traumatic brain injury.\textsuperscript{31} 35 38 One level 3 article showed abnormal gamma-NTP, a phosphorous metabolite, months after SRC.\textsuperscript{39}

Summary: MRS can detect metabolic derangements following SRC. This evidence indicates that metabolic abnormalities may be detected beyond the window of clinical recovery. Preliminary evidence indicates that a repeat injury when the brain is metabolically vulnerable prolongs recovery. Additional work demonstrating the effect of repeat injury after clinical recovery, but before metabolic normalisation, will be required to determine whether metabolic recovery should be used to guide RTP recommendations.

CEREBRAL BLOOD FLOW
Phase contrast angiography, arterial spin labelling and transcerebral Doppler have been assessed in eight articles. There was
reduced cerebral blood flow (CBF) at rest that persisted beyond the time of clinical recovery. Arterial spin labelling is an increasingly used, non-invasive technology that shows changes in CBF after concussion. 40 CBF abnormalities were resolved by 30 days post injury in most patients. 41 42 Although a single level 2 study demonstrated that global CBF was increased 40 days post injury in symptomatic athletes relative to controls, it decreased in asymptomatic athletes. 43 Athletes may need to be challenged with exercise or hypercapnia to find this change in blood flow. 44 45 There may be chronic effects on cerebrovascular reactivity that need to be further elucidated. 46

Summary: Mounting evidence suggests an alteration of CBF following SRC, but the time course is not certain. Further longitudinal studies are needed to elucidate the acute versus chronic effects. The single study showing converse changes in blood flow depending on symptom level suggests that altered CBF may not definitively signify ongoing dysfunction.

ELECTROPHYSIOLOGY
Fifteen total studies used electrophysiological measures to assess concussion and recovery. The majority of electroencephalogram (EEG) and event-related potential (ERP) studies looked for chronic effects of concussion. Two studies, with unique EEG algorithms, demonstrated a significant injury effect at 8 days after concussion, with recovery by day 45. 47 48 although the athlete’s symptoms recovered between days 5 and 8. Eight studies showed persistent effects from 7 to 45 days after injury regardless of the symptom burden of the athletes. 49–55 Chronically, EEG and ERP demonstrate changes up to 4 years from injury that appear to outlast the clinical effects of concussion, with multiple studies showing decreased P300 amplitude on ERP. 56–60

Summary: Various methods using ERP and several novel EEG algorithms have shown an electrophysiological effect of SRC. More longitudinal studies are needed to distinguish acute concussion physiology from remote effects of prior trauma. Two studies finding significant effects on EEG at 8 days post injury and recovery at 45 days after injury indicate possible physiologic perturbations detectable after clinical recovery. However, given the proprietary algorithms that were used in these studies, replication will be needed before any definite conclusions can be made.

HEART RATE
Four articles (one level 2, three level 3) examined cardiac parameters after concussion. In one article, there was no significant change in resting heart rate or intervals, but a significant change in exercise-induced variability, a measure of sympathovagal balance. 61 In another article, there was shorter interbeat interval after concussion but a time course was not profiled. 62 One study showed decreased complexity of heart rate during isometric hand grip testing on the second day after injury. 63 In one article, there was decreased stroke volume (as estimated by SysSlope) on days 2 and 7 after injury. 64

Summary: There is currently no specific modality or time course of cardiac function that delineates concussion recovery or correlates well with existing measures of clinical recovery.

EXERCISE
The role of controlled aerobic exercise to facilitate concussion recovery has provoked considerable interest, but the postinjury time course of impaired exercise tolerance has not been defined. Two studies demonstrated reduced exercise tolerance in subjects with chronic postconcussion syndrome. 65 66

Summary: There is insufficient evidence to delineate an accurate window of postinjury physiological dysfunction as related to exercise tolerance in the acute and subacute periods.

FLUID (BLOOD AND URINE) BIOMARKERS
Ten articles looked at potential fluid biomarkers for cerebral injury. 67–76 Some examined correlates with clinical measures and others monitored trajectories of change after a diagnosed concussion. Cytoskeletal protein spectrin-N-terminal-fragment was elevated at 12, 36 and 144 hours after concussion (n=18–25) and had returned to baseline in (n=10) athletes who were clinically cleared for return to play. 77 Total tau (another cytoskeletal molecule) was elevated after concussion, 78 and if elevated at 144 hours after injury, was associated with persistent symptoms. Other markers (s100b, neuron-specific enolase) were not changed. 79 Tau-C, but not Tau-A, was elevated after concussion; increased Tau-A at 144 hours was associated with persistent symptoms. 80 S100b was increased 3 hours after concussion but not at days 2, 3, 7 or after exertion. 81 Elevated glial fibrillary acidic protein was seen <24 hours postconcussion but not between 24 and 72 hours after injury; the change at <24 hours was associated with symptoms. 82 One study examined biomarkers after impact exposure but not clinically diagnosed concussion, 83 whereas others examined biomarkers after concussion but either did not project a time course of molecular change 74 75 or looked at a broad set of markers. 76

Summary: There are no reliable markers to monitor recovery from SRC. Fluid biomarkers have the potential to help inform either diagnosis or monitor for recovery after concussion. Before they may be recommended for clinical use, however, their utility must be demonstrated in longitudinal studies with limited attrition and clinical recovery as the primary outcome.

TRANSCRANIAL MAGNETIC STIMULATION
There were four level 3 studies that used transcranial magnetic stimulation. Three of these examined cortical excitability after concussion and found increased inhibition. One reported increased inhibition in the corticospinal tract at 2–4 days after concussion with normalisation by 10 days after injury, 84 another found cortical hypo-excitability persisting beyond the time of clinical recovery, up to 28 days after injury, 85 and the third article showed increased inhibition in the motor system that persisted beyond 9 months post injury. 79 The last article took a different approach and reported prolonged motor latencies that persisted through PID10. 86

Summary: In two articles, there were persistent abnormalities in cortical excitation beyond the window of clinical recovery. Another study found electrophysiological dysfunction acutely after SRC that did not correlate with symptoms. Further experiments are needed to define the time window of altered cortical excitability after SRC.

DISCUSSION
This article presents a wide range of data relating to physiological recovery after SRC. Much of the data suggest that the window for physiological recovery extends beyond that for recovery of clinical signs and symptoms. However, multiple considerations preclude making strong clinically actionable recommendations given the current evidence. These considerations fall into three main categories:

1. There is a broad range of different physiological measures studied after SRC, each of which almost certainly has a different time course, severity, method of measurement and...
common theme of finding significant results using very sensi-

populations and inappropriate or absent controls. There is a

sizes is limited, given frequent selection biases, unique study

animal models.

is possible to examine pathophysiological risk using preclinical

pathophysiology and clinical dysfunction. Such studies may be

occurring before normalisation of physiological changes may be

Where possible, analysis of the consequences of repeat injury

or cohort studies that did not follow subjects to full recovery.

The review aimed to address the following three questions:

1. How does the time course of physiological recovery compare
   with the time line of clinical recovery after SRC?
2. Should there be a minimum stand-down period following
   SRC?
3. Is the duration or content of graded return to play
   progressions appropriate?

Recommendation 1
How does the time course of physiological recovery compare
with the time line of clinical recovery after SRC?

The time course of recovery for multiple physiologically
measurable parameters appears to exceed clinical recovery. A
definitive time point for physiological recovery after SRC is yet
to be determined. Reliable studies of MRS and CBF appear to
demonstrate a physiological disturbance for greater than 15 days
but less than 30 days after injury. This is not only longer than
the average clinical time to recovery in adults, but in individual
papers there was evidence of clinical recovery prior to physio-
logical recovery.\textsuperscript{36} \textsuperscript{37} \textsuperscript{40} The time course of biological disturbance
is less clear with other modalities like DTI, electrophysiology
and fluid biomarkers. Longitudinal studies are necessary to char-
acterise the progression of physiological recovery. It is unclear
whether changes in neurobiology represent dysfunction, vulner-
ability or recovery.

It is prudent to incorporate a ‘buffer zone’ of gradually
increasing cognitive and physical activity between the time of
neurological (symptomatic) recovery and return to full contact
risk.

Recommendation 2
Should there be a minimum stand-down period following SRC?

There is limited clinical evidence that repeat concussion during
the window of neurometabolic disturbance leads to prolonged
recovery. Therefore, from a physiological standpoint, we are
unable to determine whether there needs to be a minimum stand-
down period after injury. The most rigorous evidence regarding
this still comes from animal data where intersubject variability
is low, injury severity consistent and time points are precise.
These studies show vulnerability\textsuperscript{31} \textsuperscript{82} if a repeat injury occurs
before complete metabolic recovery. The duration of this time
window in humans with concussion is unclear. The significance
of ‘subconcussive impacts’ and biological changes reported after
playing contact sports for a set time are also unclear. Animal and
human studies indicate that repeat concussion prior to recovery
result in more severe and prolonged physiological and clinical
disturbances. This supports immediate removal from contact
risk after an identified injury.

As there is (are) currently no standard biomarker(s) for physio-
logical dysfunction underlying vulnerability to repeat concussion
in humans, the stand-down time should be determined by thor-
ough clinical assessment.

Recommendation 3
Is the duration or content of graded return to play progressions
appropriate?

There is insufficient evidence to recommend a change to the
current graded return to play progression. To answer this ques-
tion, there is need for data on the effect of repeat brain injury
and the effect of exercise on ongoing concussion physiology.
These studies need to be adequately powered, have a longitudi-

nal component, use one or more potential clinical correlates
and have appropriate controls. Such studies are necessary to
determine the time course of both physiological and clinically

SUMMARY AND RECOMMENDATIONS

The review aimed to address the following three questions:
measurable dysfunction. Longitudinal analyses are important in determining whether subclinical changes become clinically relevant with ageing or later developing disease processes. Outcomes from such studies need to be carefully defined with respect to risk of repeat injury, risk of new musculoskeletal injury, risk of worsened symptoms, prolongation of recovery, neurocognitive impairment or chronic neurodegeneration.

Further studies investigating physiological biomarkers of concussion should be undertaken. These studies should select generalisable populations, implementing longitudinal cohorts that follow patients to physiological and clinical recovery and examine the relationship between physiological disturbance and clinical outcomes. While not specific to this question, our understanding of concussion physiology would certainly benefit from more objective diagnostic and recovery criteria, and research to better define ‘concussion’ and ‘recovery’ is a high priority.

**CONCLUSION**

Given the limitations of the available data, we recommend that medical providers continue to use clinical data to manage return to play while preserving physiological metrics for research until more conclusive data are obtained. This review shows that the window of physiological dysfunction can outlast that of clinical recovery. These data support using a ‘buffer zone’ of a graduated window of physiological dysfunction can outlast that of clinical recovery. These data support using a ‘buffer zone’ of a graduated return to activity/return to play progression before full return to contact risk.

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**Competing interests**

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