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Electrified Bar Racks for Fish Protection at Water Intakes – Risk of Fish Injuries due to Electric Fields

Final Report

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Summary

Electrified intake racks are a promising technology to prevent downstream moving fish from passing through hydropower turbines, allowing them to search for an alternative passageway. Previous large-scale laboratory flume studies have demonstrated high protection efficiencies of electrified racks for certain fish species. However, the lack of targeted studies assessing the risk of fish injuries caused by the electric field introduces uncertainty about the biological safety of these systems. This study addressed this knowledge gap by systematically evaluating the risk of internal injuries in hatchery-reared Brown Trout *Salmo trutta* exposed to electrified intake racks in the VAW laboratory.

Two rack configurations with clear bar spacings of 50 and 90 mm were tested in a large ethohydraulic flume at ETH Zurich with two electrode arrangements: (1) rod electrodes placed on the front of the bars of the rack [*Rod electrodes*], and (2) the rack used as an electrode with a second row of electrodes downstream [*Electrode DS*]. Voltages and waveforms were selected to replicate conditions previously shown to be effective in laboratory studies evaluating the species-specific fish-protection efficiency. Three waveforms were tested: (1) a pulsed direct current [pDC] waveform characterised by regular pulses with a pulse width $PW = 2$ ms and a frequency $f = 10$ Hz, (2) a gated burst pDC [gpDC] waveform consisting of bursts of five pulses with $PW = 0.3$ ms and $f = 137$ Hz, followed by a larger burst break of $BB = 196.8$ ms, and (3) a pulsed alternating current [pAC] waveform where each pulse was immediately followed by one of opposite polarity to limit corrosion. $PW = 2$ ms and $f = 5$ Hz was used to replicate the pulse width and number of pulses of the pDC waveform.

Two modes of fish interaction with electrified bar racks were considered: (1) fish interacted with the electric field upstream of the rack and were prevented from rack passage, and (2) fish passed through the rack. Experiments were conducted with hatchery Brown Trout (total length of 178 to 323 mm) to ensure that observed injuries could be related to the tested rack configurations. For each experiment, one fish was randomly caught from the holding tanks, photographed, and placed in the starting compartment for an acclimation period of ten minutes. To evaluate non-passage interaction (1), a fishing net was placed on the rack to prevent passage. After the acclimation period, the fish could move freely in the flume with constant flow depth and velocity and interact with the rack for up to 45 minutes. An experiment was terminated early if one of three criteria was met: (i) interaction with the electric field at least three times, (ii) immobilisation, or (iii) appearance of dark discolourations on the fish's skin. To evaluate rack-passage (2), the flow velocity was increased stepwise every two minutes after the acclimation period. If this did not suffice to encourage the fish to pass the rack, rack passage was further stimulated by using a handheld net. The experiment was stopped as soon as the fish passed the rack. After an experiment, fish were removed from the flume, photographed, euthanised and frozen. Skin discolourations and abnormal behaviour was assessed after exposure through visual inspection. Internal injuries were evaluated using X-ray imaging to identify spinal injuries and subsequent filleting to detect haemorrhages.

Observed internal injury rates ranged from 0% up to 65% across the tested configurations. The incidence of externally visible skin discolourations ranged from 0 to 90%. Complete absence of both internal and external injuries was observed for only one configuration: *Elektrode DS*, operated at 44 V pDC. This configuration can therefore be recommended for pilot studies. For other configurations with both *Rod electrodes* (pDC, 80 V and pAC, 40 V) and *Electrode DS* (pAC, 44 V), internal injury rates of 0 to 15% were observed. These setups are thus promising for use with a lower applied voltage. Additionally, assuming that Brown Trout are more susceptible to injuries caused by electricity than other species, it can be speculated that these configurations may be suitable for rivers where less sensitive species such as cyprinids or European eel are abundant, or at sites where turbine passage leads to high rates of fish mortality.

For the same field strength, pAC resulted in higher internal injury incidence than pDC. Consequently, results obtained for pDC cannot be directly transferred to pAC. Further research is required to quantify by how much voltage and thus field strengths need to be reduced for pAC compared to pDC. The tested gpDC waveform resulted in higher internal injury rates than the tested pDC and pAC waveforms and is thus not recommended for application at electrified bar racks.

Dark skin discolourations showed a clear association with the occurrence of internal injuries, indicating that such marks may serve as a potential indicator in monitoring campaigns involving Brown Trout. However, these discolourations frequently faded shortly after exposure and were sometimes only present on one side of the fish. These observations thus confirm that visual inspection alone is insufficient for assessing fish health post-exposure. Prior to pilot deployment, new electrified bar rack configurations should be evaluated using dedicated experimental studies to ensure that no harmful stimuli are introduced.

The main practice-relevant results are summarised as follows:

- The design of the electrification including electrode placement, waveform, and voltage, is a critical determinant of biological safety.
- Visual fish inspection alone in monitoring campaigns is insufficient for assessing fish health post-exposure to electric fields.
- The setup DS1_pDC (*Electrode DS*, pDC 44 V, $PW = 2$ ms, $f = 10$ Hz) is a promising candidate for pilot studies at hydropower plants.
- For three setups with pDC and pAC waveforms (R3_pDC, R4_pAC, DS2_pAC) a reduction of the applied voltage and thus electric field strengths may further reduce the risk of injury while still providing high fish protection efficiencies.
- The tested gpDC waveform is not recommended for use in electrified bar rack applications.

From the FOEN's point of view, this report provides first important findings regarding the influence of different electrification setups (i.e. combinations of electrode placement, waveform and voltage) on the risk of injury to fish. However, a number of questions remain unanswered for a concrete application of electrified bar racks to systems to increase fish protection and further clarifications are necessary. The FOEN plans to discuss the next steps in an expert committee in the near future.

Zusammenfassung

Elektrifizierte Einlaufrechensysteme an Wasserkraftwerken sind eine vielversprechende Technologie, um Fische vor einem Turbinendurchgang zu schützen und ihnen die Suche nach einer alternativen Abstiegsmöglichkeit zu ermöglichen. Je nach Fischart, elektrischer Feldstärke, Elektrodenplatzierung, und elektrischen Parametern wie Pulslänge und Frequenz können jedoch Fischverletzungen auftreten. Das Ziel dieser Studie war es, elektrifizierte Einlaufrechen, welche in früheren Laborversuchen eine vielversprechende Schutzwirkung gezeigt haben, systematisch in Laborversuchen auf ein mögliches Verletzungsrisiko bei Bachforellen *Salmo trutta* zu untersuchen, um die Umsetzung von Pilotprojekten zu ermöglichen.

Zwei Rechen-Konfigurationen mit lichten Stababständen von 50 und 90 mm wurden in einer ethohydraulischen Versuchsrinne an der ETH Zürich mit zwei Elektrodenanordnungen getestet: (1) Stabelektroden, die an der Vorderseite der Rechenstäbe angebracht wurden [*Rod electrodes*], und (2) Rechen als Elektrode mit einer zweiten Reihe an Elektroden stromabwärts [*Electrode DS*]. Spannungen und elektrische Wellenformen wurden ausgewählt, um Bedingungen aus früheren Studien zur artenspezifischen Fischschutzeffizienz zu replizieren. Drei Wellenformen wurden getestet: (1) gepulster Gleichstrom [pDC], charakterisiert durch reguläre Pulse mit einer Pulslänge $PW = 2$ ms und einer Frequenz $f = 10$ Hz, (2) eine *gated burst* pDC [gpDC] Wellenform, bestehend aus Gruppen von fünf Pulsen mit $PW = 0.3$ ms und $f = 137$ Hz, gefolgt von einer grösseren Pause zwischen Pulsgruppen von $BB = 196.8$ ms, und (3) gepulster Wechselstrom [pAC], charakterisiert durch ein unmittelbares Aufeinanderfolgen zweier Pulse mit entgegengesetzter Polarität. Im Gegensatz zu pDC wird durch pAC keine elektrochemische Korrosion verursacht. $PW = 2$ ms und $f = 5$ Hz wurden verwendet, um die Pulslänge und die Anzahl der Pulse der pDC-Wellenform zu replizieren.

Es wurden zwei Arten von Fischinteraktionen mit elektrifizierten Rechen betrachtet: (1) Fische interagieren mit dem elektrischen Feld im Oberwasser des Rechens und werden daran gehindert, den Rechen zu passieren, und (2) Fische passieren den Rechen. Die Experimente wurden mit Zucht-Bachforellen (Gesamtlänge 178 bis 323 mm) durchgeführt, um sicherzustellen, dass beobachtete Verletzungen mit den getesteten elektrischen Feldern in Verbindung gebracht werden konnten und nicht bereits bestanden. Für jeden Versuch wurde ein Fisch zufällig aus den Hälterungsbecken gefischt, fotografiert und für die Akklimatisierungszeit von zehn Minuten im Startbecken platziert. Um Recheninteraktion ohne Rechenpassage (1) mit den Experimenten nachzubilden, wurde ein Fischernetz am Rechen montiert, wodurch eine Rechenpassage verunmöglicht wurde. Nach der Akklimatisierungszeit konnte sich der Fisch bei konstanter Fliesstiefe und -geschwindigkeit bis zu 45 Minuten frei bewegen und mit dem Rechen interagieren. Das Experiment wurde frühzeitig abgebrochen, falls (i) der Fisch dreimal mit dem elektrischen Feld interagierte, (ii) er bewegungsunfähig wurde oder (iii) dunkle Verfärbungen auf der Haut des Fisches beobachtet wurden. Um Recheninteraktionen mit Rechenpassage (2) zu replizieren, wurde die Fliessgeschwindigkeit nach der Akklimatisierungszeit alle zwei Minuten schrittweise erhöht. Zusätzlich konnte ein handgeführtes Netz verwendet werden, um den Fisch zu motivieren sich zum Rechen hinzubewegen. Das Experiment wurde gestoppt, sobald der Fisch den Rechen passiert hatte. Nach jedem Versuch wurden die Fische aus der Versuchsrinne entfernt, fotografiert, eingeschläfert und eingefroren. Hautverfärbungen und ungewöhnliches Schwimmverhalten wurden nach dem Experiment durch visuelle Inspektionen beurteilt. Innere Verletzungen wurden mittels Röntgen, zur Diagnose von Wirbelsäulenverletzungen, und anschliessendem Filetieren, zum Befund von inneren Blutungen, untersucht.

Die beobachtete Häufigkeit der inneren Verletzungen variierte stark zwischen den getesteten Konfigurationen und reichte von 0% bis zu 65%. Die Häufigkeit von äusserlich sichtbaren Hautverfärbungen lag zwischen 0 und 90%. Nur bei einer Konfiguration, *Electrode DS* mit 44 V pDC, wurden weder innere noch äussere Verletzungen beobachtet. Diese Konfiguration kann daher für den Einsatz in Pilotstudien empfohlen werden. Bei Konfigurationen von *Rod electrodes* (pDC, 80 V und pAC, 40 V) und *Electrode DS* (pAC, 44 V) wurden tiefe Raten von 0 bis 15% (0-3 von 20 Fischen) von inneren Verletzungen beobachtet. Diese Konfigurationen sind vielversprechend, um mit einer weiteren Reduktion der Spannung bzw. Feldstärke das Verletzungsrisiko weiter zu senken, aber dennoch zuverlässige Fischschutzraten zu erzielen. Da Bachforellen im Vergleich zu anderen Fischarten tendenziell ein hohes Risiko für Fischverletzungen durch elektrische Felder aufweisen, könnten diese Konfigurationen ausserdem an Flüssen zur Anwendung kommen, in denen weniger empfindliche Arten wie Cypriniden oder der Europäische Aal häufig vorkommen, oder an Orten, an denen Turbinenpassagen zu hohen Fischsterblichkeiten führen.

Bei gleicher Feldstärke führte pAC häufiger zu inneren Verletzungen als pDC. Folglich können für pDC gut funktionierende Feldstärken/Spannungen nicht direkt auf pAC übertragen werden. Weitere Studien sind erforderlich, um zu quantifizieren, wie stark die Spannungen und damit die Feldstärken für pAC im Vergleich zu pDC reduziert werden

müssen. Die getestete gpDC-Wellenform führte zu deutlich höheren inneren Verletzungsraten als die getesteten pDC- und pAC-Wellenformen und wird daher nicht für die Anwendung an elektrifizierten Rechen empfohlen.

Es war ein klarer Zusammenhang zwischen dunklen Hautverfärbungen und inneren Verletzungen ersichtlich. Deshalb könnten Hautverfärbungen als Indikator bei Überwachungskampagnen mit Bachforellen geeignet sein. Allerdings verblassten die Verfärbungen häufig kurz nach der Exposition und waren manchmal nur auf einer Seite des Fisches vorhanden. Diese Beobachtungen bestätigen somit, dass eine visuelle Überprüfung allein nicht ausreicht, um die Unversehrtheit von Fischen nach der Interaktion mit einem elektrischen Feld zu beurteilen. Weitere spezifische Untersuchungen zum Verletzungsrisiko unter Verwendung von Röntgen und Filetieren sind daher unverzichtbar in der weiteren Entwicklung und Erforschung von elektrifizierten Fischschutz- und -leitrechen.

Die wesentlichen praxisrelevanten Ergebnisse werden wie folgt zusammengefasst:

- Das Design der Elektrifizierung, einschliesslich Elektrodenplatzierung, Wellenform und Spannung, ist ein entscheidender Faktor für die biologische Sicherheit.
- In fischbiologischen Monitoring-Kampagnen reicht die visuelle Inspektion der Fische allein nicht aus, um deren Unversehrtheit nach der Interaktion mit einem elektrischen Feld zu beurteilen.
- Das Setup DS1_pDC (*Electrode DS*, pDC 44 V, $PW = 2$ ms, $f = 10$ Hz) ist ein vielversprechender Kandidat für Pilotstudien an Wasserkraftwerken.
- Bei drei Setups mit pDC- und pAC-Wellenformen (R3_pDC, R4_pAC, DS2_pAC) könnte eine Reduktion der Spannung bzw. elektrischen Feldstärke das Verletzungsrisiko weiter senken, bei gleichzeitig hohen Fischschutzraten.
- Die getestete gpDC-Wellenform wird für die Anwendung an elektrifizierten Rechen nicht empfohlen.

Aus Sicht des BAFU liefert der vorliegende Bericht erste wichtige Erkenntnisse bezüglich des Einflusses verschiedener Elektrifizierungssetups (d.h. Kombinationen aus Elektrodenplatzierung, Wellenform und Spannung) auf das Verletzungsrisiko von Fischen. Für eine konkrete Anwendung elektrifizierter Rechen an Anlagen zur Erhöhung des Fischschutzes sind jedoch noch etliche Fragen offen und weitere Abklärungen sind notwendig. Das BAFU plant, das weitere Vorgehen zeitnah in einem Fachgremium zu besprechen.

Résumé

Les grilles d'entrée électrifiées constituent une technologie prometteuse pour empêcher les poissons en aval de passer à travers les turbines hydroélectriques, leur permettant ainsi de trouver un autre passage de dévalaison. Des études à grande échelle menées en laboratoire ont démontré la grande efficacité des grilles électrifiées pour certaines espèces de poissons. Cependant, l'absence d'études ciblées évaluant le risque de blessures causées aux poissons par le champ électrique introduit une incertitude quant à la sécurité biologique de ces systèmes. Cette étude comble cette lacune en évaluant systématiquement le risque de blessures internes chez les truites atlantiques *Salmo trutta* élevées en pisciculture et exposées à des grilles d'entrée électrifiées.

Deux configurations de grilles avec des espacements entre les barreaux de 50 et 90 mm ont été testées dans un grand chenal éthohydraulique à l'ETH Zurich avec deux dispositions d'électrodes : (1) des électrodes à tige placées à l'avant des barres de la grille [*Rod electrodes*] et (2) la grille utilisée comme électrode avec une deuxième rangée d'électrodes en aval [*Electrode DS*]. Les tensions et les formes d'onde ont été sélectionnées afin de reproduire les conditions qui s'étaient précédemment révélées efficaces dans les études en laboratoire évaluant l'efficacité de la protection des poissons de grilles électrifiées spécifique à l'espèce. Trois formes d'onde ont été testées :

(1) une forme d'onde à courant continu pulsé [pDC] caractérisée par des impulsions régulières d'une largeur $PW = 2$ ms et d'une fréquence $f = 10$ Hz, (2) une forme d'onde pDC à rafales synchronisées [gpDC] composée de rafales de cinq impulsions avec $PW = 0{,}3$ ms et $f = 137$ Hz, suivies d'une pause plus longue de $BB = 196{,}8$ ms, et (3) une forme d'onde à courant alternatif pulsé [pAC] où chaque impulsion était immédiatement suivie d'une impulsion de polarité opposée afin de limiter la corrosion. $PW = 2$ ms et $f = 5$ Hz ont été utilisés pour reproduire la largeur d'impulsion et le nombre d'impulsions de la forme d'onde pDC.

Deux modes d'interaction des poissons avec les grilles électrifiées ont été pris en compte : (1) les poissons interagissaient avec le champ électrique en amont de la grille et étaient empêchés de passer à travers celle-ci et (2) les poissons passaient à travers la grille. Les expériences ont été menées avec des truites atlantiques d'élevage (longueur totale de 178 à 323 mm) afin de s'assurer que les blessures observées pouvaient être liées aux configurations de grilles testées. Pour chaque expérience, un poisson a été capturé au hasard dans les bassins de stockage par un filet, photographié et placé dans le compartiment de départ pour une période d'acclimatation de dix minutes. Pour évaluer l'interaction sans passage (1), un filet de pêche a été placé sur la grille afin d'empêcher le passage. Après la période d'acclimatation, les poissons pouvaient se déplacer librement et interagir avec la grille pendant 45 minutes maximum, à une profondeur et une vitesse d'écoulement constantes. Une expérience était interrompue prématurément si l'un des trois critères suivants était rempli : (i) interaction avec le champ électrique au moins trois fois, (ii) immobilisation ou (iii) apparition de décolorations sombres sur la peau du poisson. Pour évaluer le passage à travers la grille (2), la vitesse d'écoulement était augmentée progressivement toutes les deux minutes après la période d'acclimatation. Si cela ne suffisait pas à encourager les poissons à passer à travers la grille, celle-ci était stimulé davantage à l'aide d'un filet à main. L'expérience était arrêtée dès que le poisson passait la grille. Après l'expérience, les poissons étaient retirés du canal, photographiés, euthanasiés et congelés. Les décolorations cutanées et les comportements anormaux étaient évalués après exposition par inspection visuelle. Les lésions internes étaient évaluées à l'aide d'une radiographie afin d'identifier les lésions spinales, puis par filetage afin de détecter les hémorragies.

Les taux de lésions internes observés variaient de 0% à 65% selon les configurations testées. L'incidence des décolorations cutanées visibles à l'extérieur variait de 0 à 90%. L'absence totale de lésions internes et externes n'a été observée que pour une seule configuration, *Electrode DS*, fonctionnant à 44 V pDC. Cette configuration peut donc être recommandée pour des études pilotes. Pour les autres configurations avec les *Rod electrodes* (pDC, 80 V et pAC, 40 V) et *Electrode DS* (pAC, 44 V), des taux de lésions internes de 0 à 15 % ont été observés. Ces configurations sont donc prometteuses pour une utilisation avec une tension appliquée plus faible. De plus, en supposant que la truite atlantique soit plus sensible aux blessures causées par l'électricité que d'autres espèces, on peut supposer que ces configurations pourraient convenir aux rivières où abondent des espèces moins sensibles, telles que les cyprinidés ou l'anguille européenne, ou aux sites où le passage dans les turbines entraîne des taux élevés de mortalité chez les poissons.

Pour une même intensité de champ, le pAC a entraîné une incidence plus élevée de blessures internes que le pDC. Par conséquent, les résultats obtenus pour le pDC ne peuvent pas être directement transposés au pAC. Des recherches supplémentaires sont nécessaires pour quantifier de combien la tension et donc les intensités de champ doivent être réduites pour le pAC par rapport au pDC. La forme d'onde gpDC testée a entraîné des taux de blessures internes plus

élevés que les formes d'onde pDC et pAC testées et n'est donc pas recommandée pour une application sur des barrières électrifiées.

Les décolorations cutanées foncées ont montré un lien évident avec la survenue de blessures internes, ce qui indique que ces marques peuvent servir d'indicateur potentiel dans les campagnes de surveillance impliquant la truite atlantique. Cependant, ces décolorations s'estompaient souvent peu après l'exposition et n'étaient parfois présentes que sur un seul côté du poisson. Ces observations confirment donc que l'inspection visuelle seule est insuffisante pour évaluer la santé des poissons après l'exposition. Avant leur déploiement pilote, les nouvelles configurations de barrières électrifiées doivent être évaluées à l'aide d'études expérimentales spécifiques afin de s'assurer qu'aucun stimulus nocif n'est introduit.

Les principaux résultats pertinents pour la pratique sont résumés comme suit :

- La conception de l'électrification, y compris le placement des électrodes, la forme d'onde et la tension, est un facteur déterminant pour la sécurité biologique.
- L’inspection visuelle des poissons seule lors des campagnes de surveillance est insuffisante pour évaluer l’état de santé des poissons après l’exposition.
- La configuration DS1_pDC (*Electrode DS*, pDC 44 V, $PW = 2$ ms, $f = 10$ Hz) est prometteuse pour des études pilotes dans des centrales hydroélectriques.
- Pour trois configurations utilisant des formes d’onde pDC et pAC (R3_pDC, R4_pAC, DS2_pAC), une réduction de la tension, et donc des intensités de champ électrique, pourrait encore diminuer le risque de blessures tout en maintenant une efficacité élevée de protection des poissons.
- La forme d’onde gpDC testée n’est pas recommandée pour une application sur des barrières électrifiées.

Du point de vue de l'OFEV, le présent rapport fournit de premières indications importantes concernant l'influence de différentes configurations d'électrification (combinaisons de placement des électrodes, de forme d'onde et de tension) sur le risque de blessure chez les poissons. Toutefois, de nombreuses questions restent en suspens quant à l’utilisation concrète de grilles électrifiées dans les installations afin d’améliorer la protection des poissons, et des investigations supplémentaires sont nécessaires. L’OFEV prévoit de discuter prochainement des prochaines étapes au sein d’un comité d’experts.

Sommario

Le griglie di presa elettrificate rappresentano una tecnologia promettente per prevenire il transito dei pesci in migrazione verso valle attraverso le turbine idroelettriche, consentendo loro di individuare percorsi alternativi. Studi sperimentali precedenti, condotti in canali di laboratorio a grande scala, hanno evidenziato elevate efficienze di protezione delle griglie elettrificate per determinate specie ittiche. Tuttavia, la mancanza di studi specificamente orientati alla valutazione del rischio di lesioni nei pesci indotte dal campo elettrico genera incertezze in merito alla sicurezza di tali sistemi. Il presente studio colma questa lacuna mediante una valutazione sistematica del rischio di lesioni interne in trote fario *Salmo trutta* allevate in incubatoio ed esposte a griglie di presa elettrificate.

Sono state testate due configurazioni di griglia, caratterizzate da un interasse tra le barre di 50 e 90 mm, all'interno di un grande canale etoidraulico presso il Politecnico Federale di Zurigo, adottando due disposizioni degli elettrodi: (1) elettrodi a barra posizionati sul lato a monte delle barre della griglia [*Rod electrodes*]; e (2) utilizzo della griglia stessa come elettrodo, associata a una seconda fila di elettrodi posta a valle [*Electrode DS*]. Le tensioni applicate e le forme d'onda sono state selezionate per riprodurre condizioni già dimostratesi efficaci in precedenti studi di laboratorio sulla protezione ittico-specifica. Sono state analizzate tre forme d'onda: (1) corrente continua pulsata [pDC], caratterizzata da impulsi regolari con durata dell'impulso $PW = 2$ ms e frequenza $f = 10$ Hz; (2) corrente continua pulsata a raffiche controllate [gpDC], costituita da raffiche di cinque impulsi con $PW = 0.3$ ms e $f = 137$ Hz, seguite da una pausa tra le raffiche pari a BB = 196.8 ms; e (3) corrente alternata pulsata [pAC], nella quale ogni impulso è immediatamente seguito da uno di polarità opposta per limitare i fenomeni di corrosione. Per la pAC sono stati adottati $PW = 2$ ms e $f = 5$ Hz, in modo da replicare la durata dell'impulso e il numero di impulsi della configurazione pDC.

Sono state considerate due modalità di interazione tra i pesci e le griglie elettrificate: (1) interazione con il campo elettrico a monte della griglia, con impedimento del passaggio attraverso la stessa; e (2) attraversamento della griglia. Gli esperimenti sono stati condotti su trote fario allevate (lunghezza totale compresa tra 178 e 323 mm), al fine di garantire che le eventuali lesioni osservate fossero riconducibili alle configurazioni di griglia testate. Per ciascun esperimento, un individuo veniva selezionato casualmente dalle vasche di stabulazione, fotografato e collocato nel comparto di partenza per un periodo di acclimatazione di dieci minuti. Nella modalità senza attraversamento (1), una rete veniva installata sulla griglia per impedire l'attraversamento. Al termine dell'acclimatazione, il pesce poteva muoversi liberamente e interagire con la griglia per un massimo di 45 minuti, a profondità e velocità di flusso costanti. L'esperimento veniva interrotto anticipatamente al verificarsi di uno dei seguenti criteri: (i) interazione con il campo elettrico per almeno tre volte, (ii) immobilizzazione del pesce, oppure (iii) comparsa di discromie cutanee scure. Nella modalità di attraversamento (2), la velocità della corrente veniva incrementata progressivamente ogni due minuti dopo l'acclimatazione; qualora ciò non risultasse sufficiente a indurre il passaggio, questo veniva ulteriormente stimolato mediante una rete manuale. L'esperimento concludeva non appena il pesce attraversava la griglia. Al termine di ciascun test, i pesci venivano rimossi dal canale, fotografati, soppressi e congelati. Le discromie cutanee e i comportamenti anomali venivano valutati mediante ispezione visiva, mentre le lesioni interne venivano analizzate tramite esami radiografici per l'individuazione di danni alla colonna vertebrale e successiva dissezione per l'identificazione di eventuali emorragie.

I tassi di lesioni interne osservati hanno mostrato un'ampia variabilità, compresa tra 0 e 65% a seconda delle configurazioni testate. L'incidenza delle discromie cutanee visibili esternamente è risultata compresa tra 0 e 90%. La completa assenza sia di lesioni interne sia di alterazioni esterne è stata riscontrata esclusivamente per la configurazione *Electrode DS* operata a 44 V in pDC, che può pertanto essere raccomandata per studi pilota. Per altre configurazioni, sia con *Rod electrodes* (pDC a 80 V e pAC a 40 V) sia con *Electrode DS* (pAC a 44 V), sono stati osservati tassi di lesioni interne compresi tra 0 e 15%. Tali configurazioni risultano quindi promettenti, a condizione di una ulteriore riduzione della tensione applicata. Inoltre, assumendo che la trota fario presenti una maggiore sensibilità alle lesioni elettricamente indotte rispetto ad altre specie, si può ipotizzare che tali configurazioni siano idonee per corsi d'acqua caratterizzati dalla presenza di specie meno sensibili, quali i Ciprinidi o l'anguilla europea, oppure in contesti in cui il passaggio attraverso le turbine comporti elevati tassi di mortalità.

A parità di intensità del campo elettrico, la forma d'onda pAC ha prodotto un'incidenza di lesioni interne superiore rispetto alla pDC. Di conseguenza, i risultati ottenuti per la pDC non possono essere direttamente trasferiti alla pAC. Risultano pertanto necessari ulteriori studi per quantificare l'entità della riduzione di tensione, e quindi dell'intensità di campo, richiesta per la pAC rispetto alla pDC. La forma d'onda gpDC ha determinato tassi di lesioni interne più elevati rispetto alle forme d'onda pDC e pAC analizzate e non è perciò raccomandata per l'applicazione su griglie di presa elettrificate.

Le discromie cutanee scure hanno mostrato una chiara correlazione con la presenza di lesioni interne, suggerendo che tali segni possano costituire un potenziale indicatore nei programmi di monitoraggio che coinvolgono la trota fario. Tuttavia, tali discromie tendevano spesso a scomparire poco dopo l'esposizione ed erano talvolta presenti su un solo lato del pesce. Queste osservazioni confermano che la sola ispezione visiva non è sufficiente per una valutazione affidabile dello stato di salute dei pesci dopo l'esposizione. Prima di una applicazione pilota, nuove configurazioni di griglie di presa elettrificate dovrebbero essere sottoposte a studi sperimentali dedicati, al fine di garantire che non vengano introdotti stimoli potenzialmente dannosi per l'ittiofauna.

I principali risultati rilevanti ai fini pratici sono riassunti di seguito:

- La concezione dell'elettrificazione, comprendente il posizionamento degli elettrodi, la forma d'onda e la tensione, è un fattore decisivo per la sicurezza biologica.
- La sola ispezione visiva dei pesci nei programmi di monitoraggio non è sufficiente per valutare il loro stato di salute dopo l'esposizione.
- La configurazione DS1_pDC (*Electrode DS*, pDC 44 V, $PW = 2$ ms, $f = 10$ Hz) è un candidato promettente per studi pilota negli impianti idroelettrici.
- Per tre configurazioni con forme d'onda pDC e pAC (R3_pDC, R4_pAC, DS2_pAC), una riduzione della tensione, e quindi dell'intensità del campo elettrico, può ridurre ulteriormente il rischio di lesioni, mantenendo al contempo un'elevata efficacia nella protezione dei pesci.
- La forma d'onda gpDC testata non è raccomandata per l'impiego in applicazioni con griglie elettrificate.

Dal punto di vista dell'UFAM, questo rapporto fornisce i primi importanti risultati riguardo all'influenza di diverse configurazioni di elettrificazione (i.e., combinazioni di posizionamento degli elettrodi, forma d'onda e voltaggio) sul rischio di lesioni per i pesci. Tuttavia, restano ancora senza risposta diverse questioni per un'applicazione concreta di griglie a barre elettrificate nei sistemi volti ad aumentare la protezione dei pesci, e sono necessari ulteriori chiarimenti. L'UFAM prevede di discutere i prossimi passi in un comitato di esperti nel prossimo futuro.

Contents

Introduction

Fish moving downstream within river systems may have to pass numerous man-made obstacles, namely hydropower plants, weirs, or spillways, which can cause severe or lethal injuries related to turbine or spillway passage (Algera et al., 2020; Tomanova et al., 2023; Cox et al., 2023). For decades, researchers, managers, and practitioners have been designing, implementing, and assessing fish protection and guidance systems to effectively divert fish away from harmful areas and provide safer downstream passage. These measures are essential to prevent both direct mortality and sublethal injuries during downstream passage.

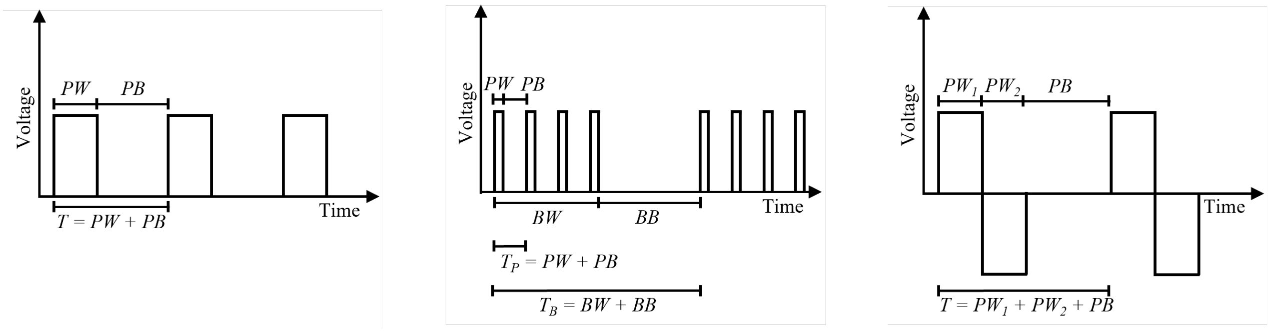
Electrifying fish guidance racks or existing intake racks has recently emerged as a promising technology to efficiently deter fish from entering harmful areas (Meister et al., 2022; Moldenhauer-Roth et al., 2025; Moldenhauer-Roth, 2025). However, electrofishing research has shown that electric fields can cause injuries in fish, including death (Snyder, 2003a). In addition, the electric fields proposed for these electrified barriers have not been used in electrofishing before, and therefore their potential to harm fish is unknown. Although from an engineering perspective these new configurations might be sound, from a biological perspective it is imperative to understand what effects they might have on fish.

A comprehensive overview of the current state of research on electrified bar racks is provided by Moldenhauer-Roth et al. (2025) and Moldenhauer-Roth (2025). Two types of electrode placement have mainly been recommended: (1) rod electrodes placed on the front of the bars of the rack [Rod electrodes], and (2) the rack used as an electrode with a second row of electrodes downstream [Electrode DS]. Moldenhauer-Roth et al. (2025) reported no fish protection efficiency [FPE] (FPE = 0%) for an intake rack with a clear bar spacing of 90 mm. Electrification of this rack with Electrode DS improved FPE up to 95% for Chub *Squalius cephalus* and up to 92% for European Eel *Anguilla anguilla* at approach flow velocities up to $U_0 = 0.6$ m/s. Rod electrodes also resulted in promising results with FPE up to 76% for chub. All experiments reported by Moldenhauer-Roth et al. (2025) were conducted with a pulsed direct current [pDC] waveform (Figure 1a) with pulse width $PW = 2$ ms and frequency $f = 10$ Hz as recommended by Moldenhauer-Roth et al. (2024). Higher protection efficiencies were reported by Haug et al. (2022a) for an intake rack with a relatively small clear bar spacing of 30 mm combined with Rod electrodes for a range of cyprinids including Chub and Bleak *Alburnus alburnus*. In their experiments, FPE increased from 62% for non-electrified trials to 96% with Rod electrodes. In contrast to the pDC settings used by Moldenhauer-Roth et al. (2025), Haug et al. (2022a) used a gated burst pDC [gpDC] waveform (Figure 1b) with $PW = 0.3$ ms and groups of five pulses with $f = 137$ Hz followed by a larger burst break of $BB = 200$ ms.

Fish response to electric fields and risk of injury

Electric fields in water elicit behavioural and physiological fish responses, which will vary considerably depending on the fish species, the electrical waveform, the orientation of the fish with respect to the electric field, the time of exposure, and the intensity of the electric field (Snyder, 2003b, p. 56; Beaumont, 2016). Electric intensity can be expressed as electric field strength E [V/m], current density $J = \sigma_w \cdot E$ [A/m^2] or power density $P_d = J \cdot E = \sigma_w \cdot E^2$ [W/m^3], where σ_w [S/m] is the ambient conductivity of the water. Fish responses to the electric field range from slight twitching, flight reactions, vibration of the fins, head, or entire body in synchrony with electric pulses, to immobilization and tetany (rigidification, respiratory arrest) (Beaumont, 2016; Moldenhauer-Roth et al., 2024). The power density thresholds at which such reactions occur depend on the characteristics of the pDC waveform, such as frequency and pulse width (Moldenhauer-Roth et al., 2024). Power Transfer Theory (Kolz and Reynolds, 1989) considers the reaction to electrostimulation to be a reflex response where both the central nervous system, the autonomic nervous system, and the direct response of the muscles of the fish play a role. An alternative explanation was proposed by Sharber and Black (1999) as cited by Beaumont (2016), the Bozeman Paradigm. This theory proposes that the fish response is caused by electrically induced epilepsy and that when the electrical stimulation overwhelms, (epileptic) seizures occur. Despite conceptual differences, both theories indicate non-voluntary reactions to electric fields if the stimulus is too intense. Exposure to electric fields therefore presents the potential to adversely affect fish.

Possible adverse effects of exposure to electric fields range from external dark discolourations (often referred to as brands), haemorrhages, and spinal injuries to death (Snyder, 2003a). Spinal injuries and haemorrhages are often not visible externally. In electrofishing research, direct current [DC] is generally considered the least harmful, followed by pDC, pulsed alternating current [pAC] (Figure 1c), and alternating current [AC], respectively (Snyder, 2003a). In addition, pulse frequency has been identified as a key determinant of injury risk, with higher frequencies associated with an increased rate of injuries (Snyder, 2003a). To minimise the risk of injury, most studies on electrified fish protection systems were conducted using pDC or gpDC (Meister et al., 2021; Haug et al., 2022a; Moldenhauer-Roth et al., 2025). However, the use of pDC or gpDC can lead to corrosion of the anodes and thus increase maintenance cost and structural risks (Unterberger et al., 2025). To prevent corrosion, the use of pAC has recently been proposed for electrified bar racks (Haug et al., 2022b; Unterberger et al., 2024).



(a) Regular pulsed DC (b) Gated burst pulsed DC (c) Regular pulsed AC

Figure 1. Pulsed direct and pulsed alternating current waveforms commonly used in laboratory experiments on electrified bar racks. Definitions according to Soetaert et al. (2019) with PW = pulse width [ms], PB = pulse break [ms], BW = burst width [ms], BB = burst break [ms] and T = period [ms]. For gated burst pDC, T_P refers to the period between individual pulses within a group and T_B to the period of the burst groups. The respective frequency is calculated as $f = 1/T$ [Hz].

Recent studies on electrified bar racks have generally assumed that fish not exhibiting externally visible injuries or abnormal swimming behaviour remained unharmed (Berger, 2018; Haug et al., 2022b; Moldenhauer-Roth et al., 2025). However, this assumption neglects potential internal injuries, which are largely undetectable by external observation. The lack of targeted studies assessing the risk of such injuries introduces uncertainty about the biological safety of these systems, particularly when used to guide fish away from hazardous routes at hydropower facilities (e.g., turbines). Insights from electrofishing research indicate that Trout, Char, and Salmon are generally more susceptible to external discolourations, spinal injuries, associated haemorrhages and probably mortality during electrofishing than other fish species (Snyder, 2003b, p. 75). Soetaert et al. (2019) found that injuries of the vertebral column result from simultaneous electrically induced muscle contractions on both sides of the fish's body, an unnatural response because mutual inhibition via interneurons in the spinal cord normally prevents simultaneous contractions of the left-and-right swimming muscles in fish. According to Soetaert et al. (2018) spinal injuries occur mainly in fusiform fish (streamlined body plan often found in fast-moving fish) with a large number of small vertebrae, such as Atlantic cod.

Since the voltage differential across a fish increases with its size, fish size is expected to have an influence on the response of fish to electric fields and their risk of injury (Snyder, 2003a). As Moldenhauer-Roth et al. (2024) showed, with increasing fish size, the power density thresholds that trigger immobilisation and twitch reactions decreased. In different studies on electrofishing of salmonids, larger fish have also been found to be more susceptible to spinal injuries and haemorrhages in tissues near the spine (Snyder, 2003b, p. 80).

Goals of this study

This study aims to systematically evaluate the risk of both external and internal injuries in fish exposed to electrified bar racks of different configurations and to determine electrode placement-waveform-voltage combinations suitable for fish protection at hydropower projects. To this end, two electrode placements and three types of waveforms (pDC, gpDC, and pAC) were systematically evaluated with hatchery Brown Trout *Salmo trutta* under controlled laboratory conditions. Brown Trout were selected as the test species because they are considered highly susceptible to electrically induced injuries. Furthermore, the findings are meant to direct future research on electrified racks toward non-harmful waveform characteristics and electric field strength/power density ranges.

Experimental setup and methodology

Ethohydraulic flume

Live-fish experiments were carried out in a large laboratory flume (length = 30 m, depth = 1.2 m, width = 1.5 m, Figure 2) located at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH Zurich. The flume and fish holding tanks were part of a closed water circuit connected to a 51 kW Climaventa (NECS-W 0182) cooling system. The approach flow velocity was adapted by varying the discharge and the position of two flap gates at the downstream end of the flume. Symmetrical and surface wave-free approach flow conditions were achieved through a honeycomb flow straightener and two hard foam floaters. The right channel wall (in flow direction) was made out of plastered bricks and the left channel wall out of glass covered by a perforated foil to avoid reflections while allowing for observations from an adjacent dark observation room (Figure 2). The right channel wall and the flume bed were covered with a waterproof paint in the same light-grey colour as the perforated foil. A 1.05 m long and 1.5 wide starting compartment was located 1.7 m upstream of the rack (Figure 2). A motorised gate was located at the downstream end of the starting compartment. Three top view submerged

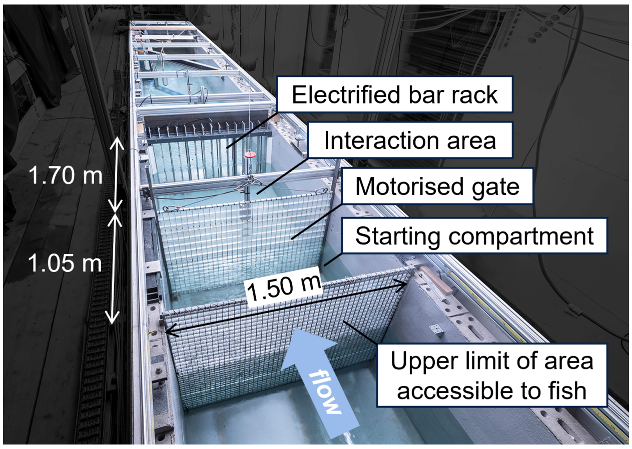


Figure 2. Top view of the experimental setup from the upstream end of the flume.

cameras (Basler acA2040-25gm-NIR) with 185° fish-eye lenses and waterproof domes were placed in the flume, one upstream and two downstream of the rack. In the observation room, an additional camera (GoPro HERO13 Black) was placed for side-view documentation of all experiments. To ensure uniform lighting conditions, white sheets were installed above the flume and illuminated by eight 1000 W halogen spotlights.

Electrified inlet racks

A pulse generator with a maximum output of 200 A, supplied by the company HyFish, was connected to the electrodes of the respective racks. Two electrified bar racks with different electrode placements were tested:

1) Rod electrodes placed on the front of the bars of the rack [Rod electrodes]

Stainless steel rod electrodes were placed on the front of the bars of a rack with a clear bar spacing of s_b = 50 mm. The bars of the rack had a with of 10 mm and the electrodes a diameter of 10 mm. To enable electrical isolation of the electrodes, the rack bars were constructed from non-conductive polyvinyl chloride [PVC] rather than metal. The rod electrodes were fixed into semi-circular grooves milled into the PVC bars and bonded using adhesive. This resulted in a total depth of bar plus electrode of 100 mm (Figure 3a). Rod electrodes were placed on every second bar, leading to a clear electrode spacing s_e of 110 mm. Groups of three adjacent rod electrodes were electrically connected and operated as anodes and cathodes (Figure 3a). For pAC, the electrode polarity was reversed at every pulse. To minimise distortion effects of the electric field near the flume walls, groups of two electrodes were used in these areas of the rack.

2) Rack as an electrode with a downstream electrode array [Electrode DS]

This rack had a clear bar spacing of s_b = 90 mm. The rack was electrified by using the rack as an electrode combined with a row of rod electrodes placed downstream of the rack (Figure 3b). The bars were constructed of aluminium. The row of stainless steel rods (diameter 15 mm) was placed at a clear distance of 141.8 mm downstream of the rack to reproduce conditions tested by Moldenhauer-Roth et al. (2025). The distance of 141.8 mm was governed by model building constraints, but the aim was to stay between 10 and 20 cm. The downstream electrodes were placed behind every second bar, resulting in a clear electrode spacing of 185 mm. This placement was chosen to minimise the risk of debris accumulation and clogging at the electrode row (Moldenhauer-Roth et al., 2025).

Electrification

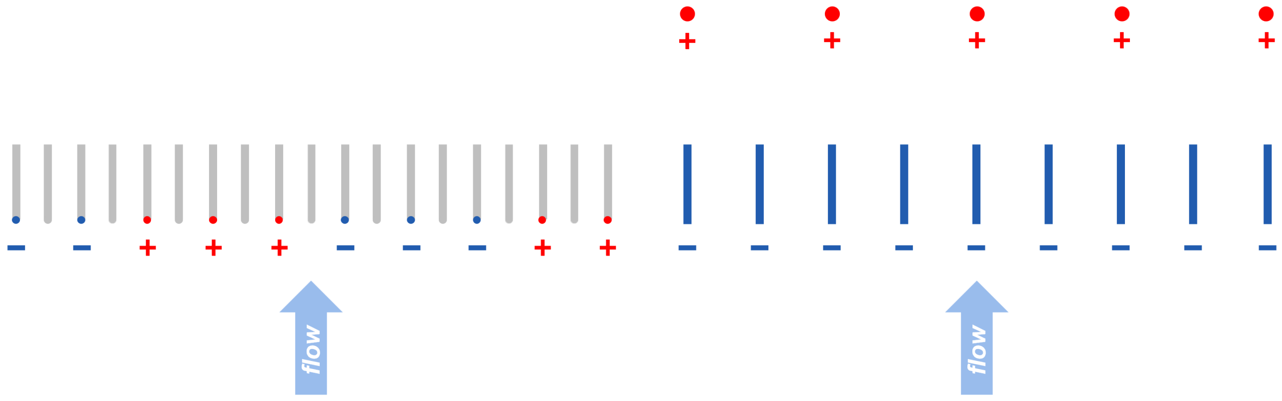
Voltages and waveforms were selected to replicate conditions previously applied in recent European studies investigating fish protection and guidance efficiencies of electrified bar racks (Haug et al., 2022a,b; Moldenhauer-Roth, 2025; Moldenhauer-Roth et al., 2025). Three waveforms were tested: 1) A pDC waveform characterised by regular pulses with a pulse width $PW = 2$ ms and a frequency $f = 10$ Hz as recommended by Moldenhauer-Roth et al. (2024), (Figure 1a), 2) a gpDC waveform consisting of bursts of five pulses with $PW = 0.3$ ms and $f = 137$ Hz, followed by a larger break of $BB = 196.8$ ms (slightly modified from Haug et al. (2022b), Figure 1b), and 3) a pAC waveform based on the pDC waveform with $PW = 2$ ms. The gpDC waveform needed to be slightly adapted, since the HyFish pulsator software was not able to produce a burst break BB of 200 ms as tested by Haug et al. (2022b). In the software, the burst break can only be defined as follows:

$$BB = n \cdot (PW + PB) + PB \qquad (1)$$

The burst break BB therefore depends on the pulse width PW and the pulse break PB and can only be modified with the factor n, which for this study was chosen as 26, resulting in a burst break of 196.8 ms. Unfortunately, HyFish was unable to easily adapt this issue and, therefore, the use of a slightly different waveform compared to Haug et al. (2022b) was necessary.

Soetaert et al. (2019) argue that the physiological effect of 20 Hz pAC would be similar to that of 40 Hz pDC since the number of pulses experienced by the neuromuscular system per second stays constant. For pAC, that would be 20 pulses in one current direction and 20 pulses with opposite current direction, whereas for pDC all 40 pulses would occur with the same current direction. The pAC waveform for this study was chosen to produce a response similar to the $PW = 2$ ms, $f = 10$ Hz pDC waveform. The pulse width was thus kept at $PW = 2$ ms and the frequency set to $f = 5$ Hz, to keep the total number of pulses equal (Figure 1c).

Table 1 summarises all tested setups. Voltages were chosen to replicate the electric field tested in previous studies on fish protection efficiencies. For Rod electrodes, 40 and 80 V were tested with the gpDC waveform to replicate conditions investigated



(a) Rod electrodes (R1_gpDC - R4_pAC)

(b) Electrode DS (DS1_pDC - DS2_pAC)

Figure 3. Illustration of the two bar racks with the polarity of the electrodes for direct current: (a) the electrified bar rack with rod electrodes mounted on the front of every second bar, with the bars made of PVC shown in grey. The rod electrodes were electrified in groups of three anodes and three cathodes (experimental groups R1_gpDC - R4_pAC). (b) The rack electrified as a cathode with a row of pole electrodes (anodes) downstream (experimental groups DS1_pDC - DS2_pAC). DS = electrode placed downstream of the rack. Illustration not to scale.

Table 1. Overview of the tested setups. Each setup was tested with a group of 20 fish for rack interaction and rack passage, except for R4_pAC and DS1_pDC which were not tested for the non-passage interaction mode. Electrode DS = electrode placed downstream of the rack, Rod electrodes = Rod electrodes placed on the front of the insulated bars of rack. Pulse parameters: PW = pulse width, PB = pulse break, f = frequency, BW = burst width, and BB = burst break (Figure 1).

Setup	Clear bar spacing s_b	Electrode placement	Type of current, Voltage	PW	PB	f	BW	BB	Interaction mode	
									Non-passage	Passage
R1_gpDC	50 mm	Rod electrodes	gpDC, 80 V	0.3 ms	7 ms	137 Hz	29.5 ms	196.8 ms	X	X
R2_gpDC	50 mm	Rod electrodes	gpDC, 40 V	0.3 ms	7 ms	137 Hz	29.5 ms	196.8 ms	X	X
R3_pDC	50 mm	Rod electrodes	pDC, 80 V	2 ms	98 ms	10 Hz	—	—	X	X
R4_pAC	50 mm	Rod electrodes	pAC, 40 V	2 & 2 ms	0 & 196 ms	5 Hz	—	—	—	X
DS1_pDC	90 mm	Electrode DS	pDC, 44 V	2 ms	98 ms	10 Hz	—	—	—	X
DS2_pAC	90 mm	Electrode DS	pAC, 44 V	2 & 2 ms	0 & 196 ms	5 Hz	—	—	X	X

by Haug et al. (2022b) (R1_gpDC, R2_gpDC). A voltage of 80 V was also tested with the pDC waveform (R3_pDC) to allow direct comparison of the gpDC and pDC waveforms. Additionally, the same setup was electrified with 40 V pAC (R4_pAC). The lower voltage was based on the hypothesis that due to the quick change in current direction, even though the absolute number of pulses stays constant, pAC may have a stronger behavioural effect and a higher risk of injury than pDC. Racks electrified with Electrode DS were tested with pDC (DS1_pDC) and pAC (DS2_pAC), respectively, at a voltage of 44 V. The pDC setup was recommended for high fish protection efficiency by Moldenhauer-Roth et al. (2025). DS1_pDC and DS2_pAC allow to directly compare pDC and pAC with identical electric field strength. All waveforms were measured with an oscilloscope (PicoScope 2206B MSO) on electrodes with opposite polarity. This allowed to verify that the waveform at the electrodes and the voltage difference between the anode and cathode corresponded to the desired setup and validate that the pulsator supplied a rectangular waveform. The measured waveforms are available in the Supplementary Material.

Numerical simulations of the electric field

The electric field generated by the tested setups was numerically simulated using Comsol Multiphysics 5.5 and the electric currents module according to the procedure outlined in Moldenhauer-Roth (2025). The following electrical conductivities σ were used in the model: Water $\sigma = 0.0312$ S/m, aluminium and stainless steel $\sigma = 35.5e6$ S/m, concrete $\sigma = 1e{-8}$ S/m, silica glass, silicone and insulating tape $\sigma = 1e{-14}$ S/m, air $\sigma = 1e{-8}$ S/m. The anode and cathodes were specified as terminals with a respective voltage of zero (cathode) and the applied voltage (anode). Current conservation was used in the entire domain. The mesh was generated according to the “normal” mesh size generator included in Comsol. All simulations were conducted in 2D as horizontal cuts through the rack. The simulated electric field strength E is reported in V/cm. According to Beaumont (2016) and Kolz and Reynolds (1989), the current density J and the power density P_d may be more representative for fish reactions. In particular, for transferring results to projects with a different water conductivity. Thus, key characteristics of the electric field are reported in terms of both E and P_d.

Live-fish experiments

Live-fish tests were carried out over nine weeks between May 5, 2025 and August 30, 2025 with Brown Trout from a Swiss hatchery. Hatchery fish were used to remove any potential confounding effect caused by electrofishing wild fish for the experiments. For each experimental week, between 20 and 35 fish were collected at the hatchery and transported to the laboratory in aerated and temperature-stable tanks. After arrival at the laboratory, fish were slowly acclimated to the water temperature in the fish holding tanks (≈ 1 °C/h). They spent at least one day in the holding tanks before being used in the experiment. Fish were kept up to seven days in the laboratory and were fed during this time with the hatchery feed. The condition of the fish (physical appearance, natural behaviour, respiratory rate) and the holding tanks, including water quality (oxygen concentration and pH), water temperature, and turbidity, were monitored daily. For the water quality monitoring, a multiparameter sensor (Hanna Instruments HI98194) was used. The water temperature ranged from 11.8 °C to 15.6 °C. The specific conductivity varied between $\sigma_{25\ ^\circ C}$ = 290-308 µS/cm and the ambient conductivity between $\sigma_{w,min,12.0\ ^\circ C} = 215$ µS/cm and $\sigma_{w,max,15.6\ ^\circ C} = 241$ µS/cm (McCleskey et al., 2012). While the specific conductivity is used to assess the water quality, the ambient conductivity determines how much current flows through the water at a given field strength, and thus the electrical stimulus experienced by the fish.

Experimental procedure

The experiments were designed by considering two primary modes of interaction with electrified bar racks that are likely to be exhibited by fish under field conditions:

1. Non-passage interaction: Fish interact with the electric field upstream or between the bars and are prevented from rack passage.
2. Passage interaction: Fish interact with the electric field upstream of the rack and subsequently pass through the rack.

In non-passage interaction, we hypothesise that the risk of injury is comparatively low as the fish is not exposed to the strongest electric field that occurs in the vicinity of the electrodes. In contrast, in passage interaction, fish have a higher probability of getting close to the electrodes, which could result in a higher likelihood of injuries.

For each experiment, one fish was randomly caught from the holding tanks, photographed, and placed in the starting compartment. Prior to each experiment, fish were visually checked for externally visible pre-existing injuries or malformations (e.g., tears in the fins, bleeding signs) and assessed for normal swimming behaviour. In case of abnormalities, the experiment was terminated and the fish was either put back in the holding tank, separated from the other fish by a net, or euthanised immediately depending on the severity of the abnormality.

1) Non-passage interaction

To evaluate non-passage interaction, a fishing net was placed on the rack (at the upstream side of the bars for R1_gpDC - R4_pAC and at the downstream side of the bars for DS1_pDC - DS2_pAC) to prevent rack passage. The flow depth was set to $h = 0.6$ m and the flow velocity to $U_0 = 0.3$ m/s. After an acclimation period of 8 minutes, the flow depth and velocity were increased to $h = 0.9$ m and $U_0 = 0.6$ m/s, respectively. After two additional minutes, the motorised gate was opened, allowing the fish to swim freely and interact with the rack for up to 45 minutes. The experiment was terminated earlier if one of three criteria was met: (i) interaction with the electric field at least three times, (ii) immobilisation, or (iii) the appearance of dark discolourations on the fish's skin. Interaction was defined as swimming closer than 10 cm to the rack for setups DS1_pDC and DS2_pAC and closer than 50 cm to the rack for setups R1_gpDC to R4_pAC. The distances were determined based on the extent of the electric field and how close to the racks avoidance reactions to the electric field were observed.

2) Passage interaction

After 10 minutes of acclimation time in the starting compartment at $U_0 = 0.3$ m/s, $h = 0.6$ m, the motorised gate was opened and the flow velocity was increased stepwise every two minutes to 0.46 m/s, 0.61 m/s, 0.73 m/s, 0.82 m/s up to the maximum discharge of the flume, resulting in $U_{0,max} = 0.88$ m/s and $h = 0.83$. If fish did not pass the rack at the highest discharge it was gently poked with a handheld net to stimulate movement and rack passage. The experiment was terminated as soon as the fish passed the rack.

During the experiments, fish movements were documented by manual observation and video recordings through the glass side wall of the flume. Video recordings of interactions are available in the Supplementary Material. Directly after the termination of an experiment, the fish was captured in the flume with a handheld net, photographed, and immediately euthanised by immersion in a concentrated solution (250 mg/l) of tricaine methanesulfonate (MS-222) until reaching stage IV anaesthetic response (Sneddon, 2012) with death confirmed by decapitation. Fish total length, body width (measured at the base of the first ray of the dorsal fin), and weight were measured using a ruler, calliper, and scale, respectively. Each fish was frozen in a labelled bag and later transported to the Institute for Fish and Wildlife Health [FIWI] of the University of Bern, to be assessed for spinal injuries and haemorrhages. The measured fish characteristics are summarised in Table 2. Overall, fish sizes were evenly distributed over the experimental groups with median total lengths ranging from TL = 251 to 277 mm. Nevertheless, some experimental groups such as R1_gpDC/passage were tested with a narrower range of fish total

Table 2. Distribution of the total length, width, and weight of the tested Brown Trout. Each experimental group (setup and interaction mode) was tested with a total of 20 fish.

Setup	Interaction mode	Total length [mm]			Body width [mm]			Weight [g]		
		Min	Max	Median	Min	Max	Median	Min	Max	Median
Control	—	178	302	253.0	20.5	35.5	30.8	66	342	195.5
R1_gpDC	Non-passage	187	323	277.5	20.3	37.7	33.5	81	412	289.0
	Passage	242	294	269.5	27.6	36.6	34.1	161	352	273.0
R2_gpDC	Non-passage	196	307	269.5	25.0	36.4	31.2	111	340	245.5
	Passage	216	303	260.0	24.8	36.2	31.1	128	365	230.0
R3_pDC	Non-passage	195	290	265.5	23.1	32.8	30.5	98	292	231.0
	Passage	227	283	267.0	25.7	33.4	31.6	146	299	238.0
R4_pAC	Passage	215	291	273.0	24.7	33.6	31.5	120	306	260.5
DS1_pDC	Passage	198	300	258.0	21.8	36.6	30.7	94	342	206.5
DS2_pAC	Non-passage	220	298	261.5	23.9	35.0	30.0	136	347	228.0
	Passage	182	305	251.5	20.6	37.9	30.4	69	352	206.5

length ranging from $TL = 242$ to 294 mm, whereas R1_gpDC/non-passage was tested with a larger range of $TL = 187$ to 323 mm. This was due to the random selection of fish from the holding tanks.

Assessment of internal injuries

Fish injuries were assessed in three categories: externally visible dark discolourations of the skin, haemorrhages, and spinal injuries. Dark skin discolourations were assessed on site immediately after each experiment and classified as D0 - no dark discolourations or D1 - observed dark discolourations. Radiological (X-ray) and pathological analyses were conducted in a blinded manner, such that the evaluating personnel at the Institute for Fish and Wildlife Health at University of Bern were unaware of the experimental treatment. The frozen fish were X-rayed (53 kV and 5 mAs) in the laterolateral and dorsoventral axis using a Toshiba X-ray machine at the Division of Clinical Radiology of the Vetsuisse Faculty Bern. The X-radiographs were captured using either a FujiFilm IP Cassettes Type D/M 24x30 cm or a FujiFilm FDR D-EVO III C35i 35x43 cm. Three fish were X-rayed simultaneously per plate. Spinal injuries were categorised based on the slightly modified classification proposed by Schram et al. (2022): S0 – no injuries visible on X-ray images, S1 – deformation and mild to moderate subluxation, S2 – compression and severe subluxation, S3 – dislocation or fracture. Examples of each classification are shown in Figure 8. Internal haemorrhages were assessed by filleting each fish parallel to the backbone on the left and right side and subsequently photographed with a Nikon D7200 digital camera. Internal haemorrhages were classified as H0 – no haemorrhage and H1 – haemorrhage present.

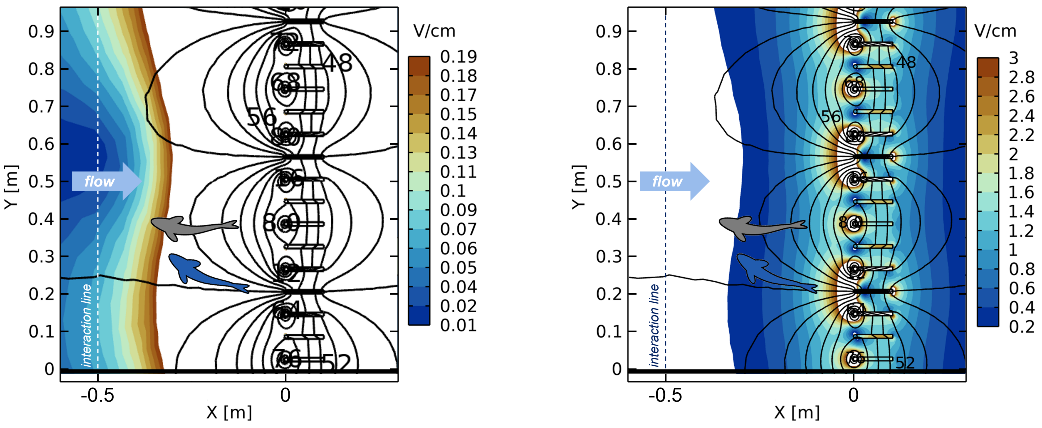
Data analysis

Data analysis was performed with R 4.5.2 (R Core Team, 2025). Data was imported from a Microsoft Excel table (Microsoft Corporation, 2023) using the R package readxl 1.4.5 (Wickham and Bryan, 2025). Data transformation was performed with the R packages tidyr 1.3.2 (Wickham et al., 2025) and dplyr 1.1.4 (Wickham et al., 2023). Visualisation was performed with the R packages ggplot2 4.0.1 (Wickham, 2016) and, for mosaic plots, with ggmosaic 0.4.0 (Jeppson and Hofmann, 2023).

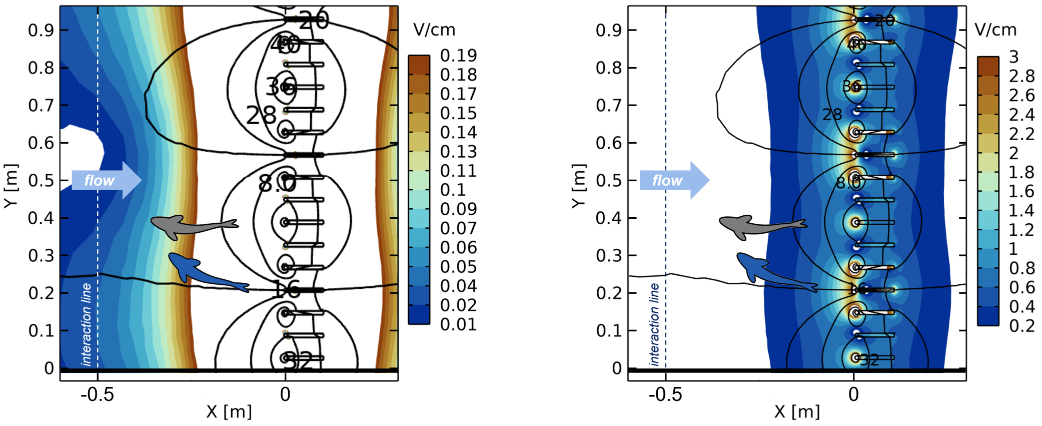
To compare non-passage and passage interaction, the prevalence of injuries between the two rack interaction scenarios were tested for difference separately for each experimental group (e.g., R1_gpDC /non-passage vs. R1_gpDC/passage), using Fisher's exact tests. This assumed that the prevalence of injury was the measure of interest and not the distribution of the injury scores (e.g., S0-S3). To compare the different experimental groups, the distribution of injury scores was of primary interest. This was tested using Wilcoxon rank sum tests with continuity correction. Comparisons between the different experimental groups were always performed using the same interaction scenario for both groups compared. To assess the relation between dark discolourations marks and the presence of injury, Fisher's exact test was used, and the phi coefficient was computed using the R package psych 2.5.6 (Revelle, 2025).

An ordinal logistic regression was modelled to assess the influence of the fish size on the presence of injury, also taking into account the influence of experimental group (setup and interaction mode). Only experimental groups in which injuries were observed were included to ensure model convergence. This ordinal regression was performed using the R package ordinal 2023.12.4-1 (Christensen, 2023). Model estimates were reported as log-odds coefficients with associated standard errors and p-values.

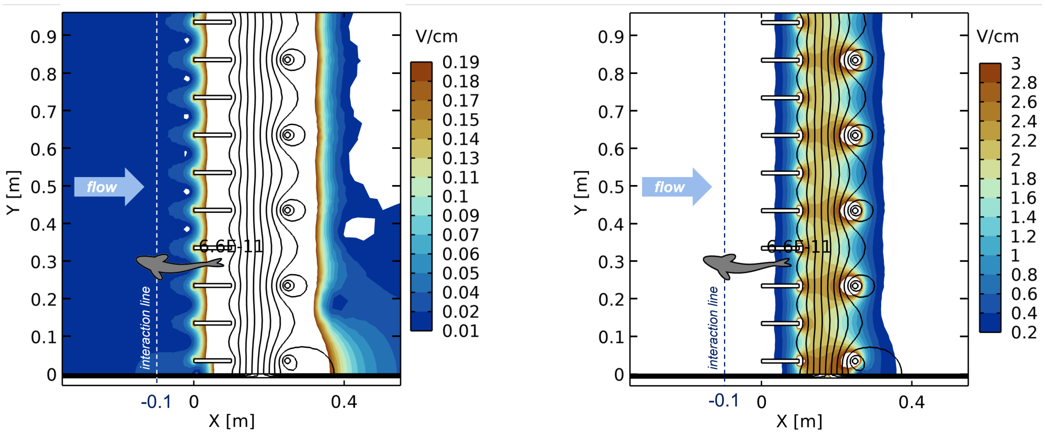
To account for multiple hypothesis testing, the Holm-Bonferroni correction was applied. The significance level was therefore adjusted by lowering it from 0.05 to 0.00625.



(a) R1_gpDC, R3_pDC: 80 V



(b) R2_gpDC, R4_pAC: 40 V



(c) DS1_pDC, DS2_pAC: 44 V

Figure 4. Numerical simulation of the electric field for the experimental groups R1_gpDC - R4_pAC and DS1_pDC - DS2_pAC. The field is simulated as a horizontal cut at the flume bottom. The left and right column show a low and high range of the voltage gradient, respectively. White areas are either below or above the respective colour scale. Black lines indicate equipotential lines (i.e., constant voltage) with a distance of 4 V.

Results

Electric field

Figure 4 shows the numerical simulation of electric field strengths in V/cm for all tested setups (Table 1). The electric field of Rod electrodes for voltages of 80 V (R1_gpDC and R3_pDC) and 40 V (R2_gpDC and R4_pAC) are shown in Figures 4a and 4b, respectively. Electrification with groups of three electrodes with similar polarity leads to a half circle pattern of equipotential lines (black lines in Figure 4). Equipotential lines indicate the orientation of the electric field and thus the direction of current. Therefore, even though the electric field strength increases continuously when approaching the rack, the fish experiences a stronger stimulus when approaching the rack in front of a group of electrodes (grey fish, high voltage potential over the length of the body) than when approaching at a change of polarization (blue fish, oriented parallel to the equipotential lines, low voltage potential over the width of the body).

Reducing the voltage from 80 to 40 V reduces both the extent of the electric field upstream of the rack and the field strength present in front of the rack and around the electrodes. The effect on the extent is relatively small. An electric field exceeding $E = 0.2$ V/cm extends 30-35 cm for 80 V and 22-25 cm for 40 V. However, the maximum electric field strength E_{max} present at a change in polarization reduces from $E_{max,80V} = 4$ V/cm to $E_{max,40V} = 2$ V/cm ($P_{d,max,80V} = 3437$-3859 µW/cm^3 to $P_{d,max,40V} = 859$-965 µW/cm^3). The reference field strength (minimum field strength present at every location in front of the tips of the bars), reduces from $E_{ref,80V} = 1.4$ V/cm to $E_{ref,40V} = 0.6$ V/cm ($P_{d,ref,80V} = 421$-473 µW/cm^3 to $P_{d,ref,40V} = 77$-87 µW/cm^3). When approaching the rack at 40 V, the fish therefore experiences both a lower absolute field strength as well as a slower increase of field strength over its body than for 80 V, which is expected to reduce the likelihood of electrically induced injuries compared to 80 V.

Figure 4c shows the electric field of the rack electrified with Electrode DS (DS1_pDC - DS2_pAC). The highest field strength develops between the rack and the downstream electrodes, and the electric field stronger than 0.2 V/cm extends to about 3 cm downstream of the tips of the bars of the rack, similar to Moldenhauer-Roth et al. (2025). The minimum field strength present everywhere between the bars and the downstream row of electrodes, and thus the minimum field strength a fish has to pass if it passes the rack is $E_{ref,DS} = 2$ V/cm ($P_{d,ref,DS} = 859$-965 µW/cm^3). The parallel arrangement of the rows of electrodes with opposite polarity leads to an orientation of the equipotential lines parallel to the rack. Since the row of downstream electrodes electrodes are placed in line with every second bar of the rack, the highest field strength is located in the wake of these bars.

Fish swimming behaviour

The hatchery Brown Trout generally approached the racks with positive rheotaxis and showed a distinct avoidance reaction upon interacting with the electric field. Quick approaches and immediate rack passage with negative rheotaxis were observed less frequently than in previous studies with wild caught Brown Trout (Moldenhauer-Roth, 2025). Fish were generally hesitant to pass the rack, resulting in multiple approaches trying to pass the rack, and thus extended time spent in the electric field for both passage and non-passage interaction. Videos of all fish-rack interactions are provided in the Supplementary Material. Due to the experimental design, no conclusions can be drawn regarding the fish protection efficiencies of the tested setups.

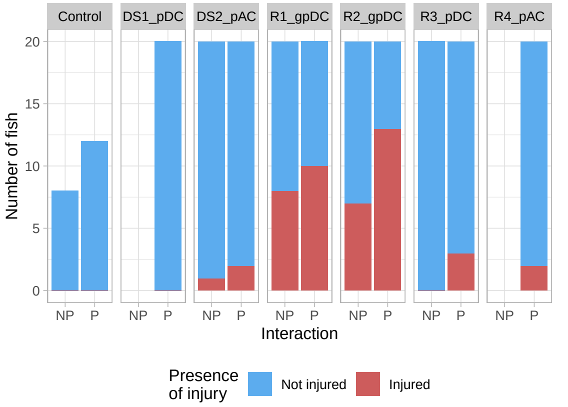


Figure 5. Number of fish with or without internal injuries in the different experimental groups when comparing non-passage (NP) and passage (P) interaction.

Observed fish injuries

The observed incidence of internal injuries and externally visible discolourations varied widely between the tested setups and interaction modes (Table 3). Examples of observed skin discolourations, haemorrhages, fractures, and subluxations are shown in Figures 6-8. Photos of the skin discolouration and haemorrhages of all tested fish are provided in the Supplementary Material.

In the control group, i.e., without electricity, no acute injuries were detected. However, some of the fish showed pre-existing spinal malformations, scoliosis, or fusions of vertebrae, which were also observed in fish from the experimental groups. Externally visible dark skin discolourations and the presence of internal injuries were significantly associated over all tested fish, with a Fisher's exact test p-value < 0.0001.

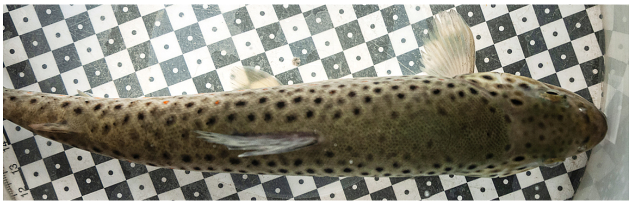
Fish size is considered a relevant factor influencing susceptibility to electricity-related injuries in electrofishing. However, for the tested size range (total length 178–323 mm) in the present study, no statistically significant influence of fish total length on the incidence of internal injuries was observed (p-value for the size effect in the ordinal regression = 0.1264).

Interaction mode

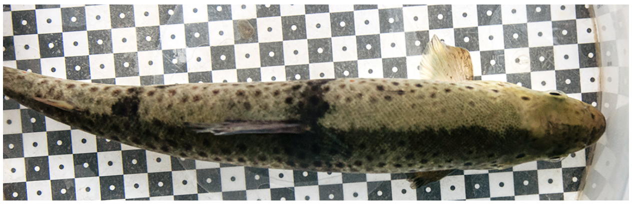
Over all setups, the incidence of internal injuries was lower or equal in non-passage than in passage interaction modes (Figure 5, Table 3). However, these differences were not statistically significant considering Fisher's exact test for each individual setup tested with both passage and non-passage interaction (R1_gpDC, R2_gpDC, R3_pDC, and DS2_pAC, p-values reported in Table 4). In both interaction modes, fish that were immobilised or pressed against the rack by the flow were likely to have internal injuries. Dark discolourations were observed less often in the non-passage than in the passage interaction for R1_gpDC and R2_gpDC (40 and 80 V). For these two setups, 90% (R1_gpDC) and 85% (R2_gpDC) of fish showed dark discolourations in the passage mode, sometimes covering up to 25% of the skin surface. In the

Table 3. Percentage of fish with dark discolourations, number of fish injuries per classification, and total percentage of fish with internal injuries for the experimental groups R1_gpDC - R4_pAC and DS1_pDC - DS2_pAC. Given the sample sizes per group, the presence or absence of a single injured fish corresponds to a change of 5% in the reported percentages. (D1) externally visible dark discolouration, (S0, H1) no injuries visible on X-ray images but haemorrhage present, (S1) deformation and mild to moderate subluxation, (S2) compression and severe subluxation, (S3) dislocation or fracture. DS = electrode placed downstream of the rack.

Setup	Electrode placement	Type of current, Applied voltage	Non-passage interaction						Passage interaction					
			D1	S0, H1	S1	S2	S3	Total (S0-S3)	D1	S0, H1	S1	S2	S3	Total (S0-S3)
R1_gpDC	Rod electrodes	gpDC, 80 V	55%	0	4	2	2	40% (8/20)	90%	0	1	8	1	50% (10/20)
R2_gpDC	Rod electrodes	gpDC, 40 V	15%	0	2	5	0	35% (7/20)	85%	0	4	7	2	65% (13/20)
R3_pDC	Rod electrodes	pDC, 80 V	15%	0	0	0	0	0% (0/20)	15%	1	2	0	0	15% (3/20)
R4_pAC	Rod electrodes	pAC, 40 V	— — — — *not tested* — — — —						10%	1	1	0	0	10% (2/20)
DS1_pDC	Electrode DS	pDC, 44 V	— — — — *not tested* — — — —						0%	0	0	0	0	0% (0/20)
DS2_pAC	Electrode DS	pAC, 44 V	15%	0	0	1	0	5% (1/20)	5%	1	1	0	0	10% (2/20)

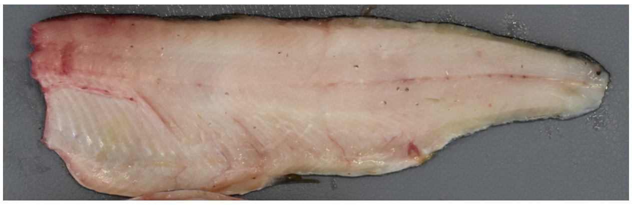


(a) D0

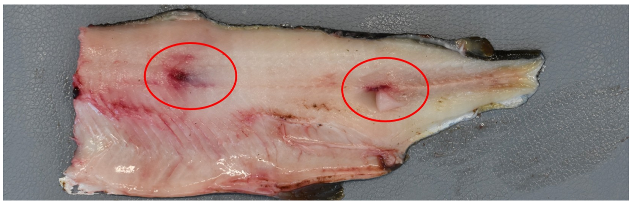


(b) D1

Figure 6. Examples for the two classifications of dark discolourations of the skin of the fish directly after the experiments: (a) D0 - no dark discolourations visible and (b) D1 - dark discolouration present, here: two stripes visible on the left side of its body and a dark discolouration covering the whole right side of its body.



(a) H0



(b) H1

Figure 7. Examples for the two classifications of haemorrhages: (a) H0 – no haemorrhage and (b) H1 – haemorrhage present: located cranial of the dorsal fin and cranial of the anal fin, marked with red circles.

Table 4. P-values for Fisher's exact test comparing non-passage and passage within a setup and p-values of the Wilcoxon rank sum test for comparison of different setups.

Experimental groups	p-value
R1_gpDC non-passage vs. passage	0.7512
R2_gpDC non-passage vs. passage	0.1128
R3_pDC non-passage vs. passage	0.2308
DS2_pAC non-passage vs. passage	1
R1_gpDC vs. R3_pDC non-passage	0.0021*
R1_gpDC vs. R3_pDC passage	0.0063
R2_gpDC vs. R4_pAC passage	0.0002*
R3_pDC vs. R4_pAC passage	0.6376
DS1_pDC vs. DS2_pAC passage	0.1626

* significant at the corrected 0.00625 level

non-passage mode, these rates were substantially lower at 55% (R1_gpDC) and 15% (R2_gpDC). For setups R3_pDC, R4_pAC, DS1_pDC, and DS2_pAC, low rates of external discolourations between 0 and 15% were observed independent of interaction mode. Discolourations for these setups were generally small, in the order of one vertical 5 mm wide streak over the height of the fish or smaller.

Rod electrodes

For the use of gpDC, a reduction of the voltage from 80 (R1_gpDC) to 40 V (R2_gpDC) did not influence the risk of injury. While the total incidence of injuries for non-passage interaction decreased from 40% to 35%, it increased from 50% to 65% for passage interaction. In contrast, both 80 V and pDC (R3_pDC) and 40 V and pAC (R4_pAC) resulted in a low incidence of internal injuries. Changing the waveform from gpDC to pDC at 80 V significantly reduced the incidence of injuries for non-passage interaction (R1_gpDC vs. R3_pDC, p = 0.0021) from 40% to 0% (Figure 9, Table 3). For the passage interaction, the incidence of injuries was reduced from 50% to 15%. However, after Holm-Bonferroni correction, the p-value of 0.0063 (R1_gpDC vs. R3_pDC) narrowly missed the threshold (adjusted $\alpha = 0.00625$), but the biological effect remained clearly evident. Similarly, changing the waveform from gpDC to pAC at 40 V (R2_gpDC vs. R4_pAC) significantly reduced the incidence of internal injuries in the passage interaction mode from 65% to 10% (p = 0.0002) (Figure 9, Table 3). While for R1_gpDC and R2_gpDC,

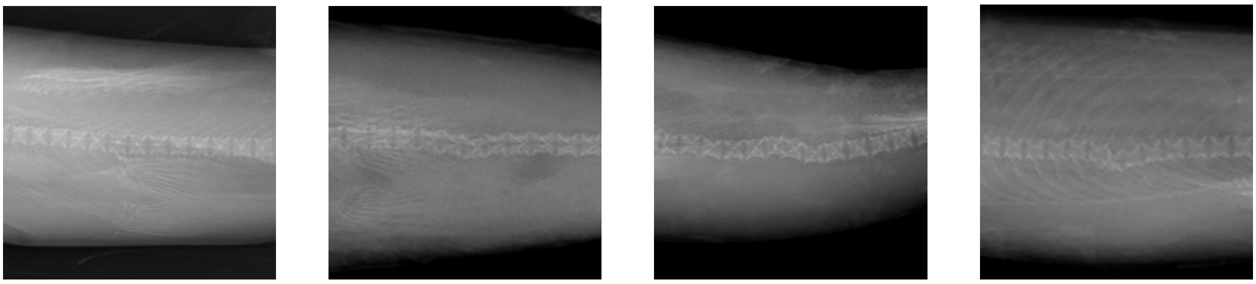

(a) S0 (b) S1 (c) S2 (d) S3

Figure 8. Examples for each classification of spinal injuries seen in X-ray images of dorsoventral view: (a) S0 - no injuries visible, (b) S1 – moderate subluxation, (c) S2 – severe compression and mild subluxation, (d) S3 – fracture.

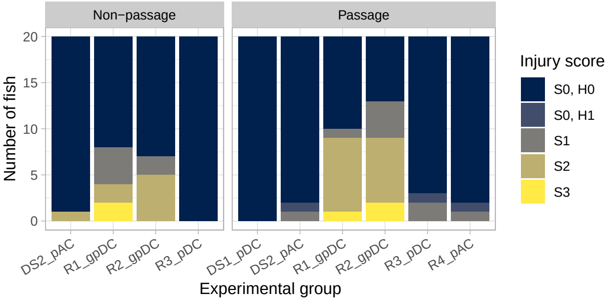


Figure 9. Distribution of internal injury scores in the different experimental groups for non-passage and passage interactions. (S0, H0) no injury, (S0, H1) no injuries visible on X-ray images but haemorrhage present, (S1) deformation and mild to moderate subluxation, (S2) compression and severe subluxation, (S3) dislocation or fracture.

several fish had spinal injuries classified as S2 and S3, no such severe spinal injuries were observed for R3_pDC and R4_pAC (Figure 9). The tested pDC and pAC waveforms thus had a significantly lower risk of fish injuries than the gpDC waveform, both in terms of the absolute number of injured fish, but also in terms of severity.

Electrodes downstream

No internal injuries or dark discolourations were observed for the experimental group DS1_pDC with 44 V for passage interaction. DS1_pDC was not tested for non-passage interaction. For DS2_pAC, one fish showed a haemorrhage and another fish had a spinal injury classified as S1, resulting in an incidence of injuries of 10% for passage interaction. For non-passage interaction, the incidence of injuries was lower (5%). However, the severity degree was higher (S2 compared to S0 and S1). For DS2_pAC, 15% (non-passage) and 5% (passage) of fish showed external discolourations.

Discussion

Waveform

The pAC waveform with $PW = 2$ ms and $f = 5$ Hz was designed to provide the same total number of pulses as the pDC waveform ($PW = 2$ mm, $f = 10$ Hz). Thus, we expected a similar incidence of injuries for both waveforms for the same electrode placement and applied voltage. However, the experimental results clearly contradict this hypothesis. DS1_pDC, DS2_pAC, R3_pDC, and R4_pAC all resulted in low numbers of injuries. Nevertheless, no injuries were observed for DS1_pDC, whereas pAC (DS2_pAC) resulted in internal injuries in 5% (interaction) and 10% (passage) of fish even though the electric field strengths were identical. Similarly, although the applied voltage and, therefore, the present field strengths were significantly reduced between R3_pDC (80V) and R4_pAC (40V), the incidence of injuries only slightly reduced from 15% to 10% for passage interaction. Applied voltages are thus not transferable between pDC and pAC, and pAC may be more harmful, even if the number of pulses is kept constant. This contradicts Soetaert et al. (2019) who state that the temporal summation of electrical stimuli determines the contractive force relevant to induce muscle cramps. This may be due to the nature of pAC, in which two pulses of opposite polarization and thus current direction follow immediately after one another as opposed to pDC and pulsed bipolar current (pulses spaced equally but with a change of polarization between each pulse). This quick change in polarization and follow up of two pulses of opposite polarization may lead to a higher number of injuries since muscles are stimulated twice without any relaxation time in between. Thus, lower voltages should be used for pAC than for pDC and further studies are necessary to determine by how far voltages and field strengths need to be reduced to achieve similar levels of fish protection and incidence of injuries for pDC and pAC.

Among the tested waveforms, the gpDC configuration resulted in the highest incidences of injuries. This is likely related to the frequency of pulses within the pulse groups. Within a group of pulses, short pulses with $PW = 0.3$ ms are followed by a short break of $PB = 7$ ms resulting in a frequency of $f = 137$ Hz. In contrast, the tested pDC waveform operates at a much lower frequency of 10 Hz. Snyder (2003b) reported an increased risk of injury for pDC if $f > 30$ Hz are used. The large break between pulse groups ($BB = 196.8$ ms) is believed to allow muscles to relax and thus reduce the incidence of injuries (Snyder, 2003b) for gpDC compared to pDC with the same frequency. However, this does not seem to be the case for the tested gpDC waveform or is not sufficient to compensate the high frequency used within the pulse groups. Pulse frequencies exceeding 30 Hz should thus be avoided not only in pDC applications, but also within gpDC configurations.

Interaction mode

Since the setups R4_pAC and DS1_pDC were not tested for non-passage interaction, no definitive conclusions can be drawn. However, a lower or similar incidence of injuries as for the respective passage interaction is expected based on the distribution of electric field strength and the reduction in injury incidence observed for non-passage interaction for the other tested setups.

It is unclear why more discolourations were observed for non-passage compared to passage interaction for setup DS2_pAC, as it does not align with the observations from the other setups. However, all observed discolourations for setup DS2_pAC were small, in the order of one 5 mm wide streak over the height of the fish or smaller, down to slightly enlarged normal dot pigmentation of Brown Trout. Thus, it is possible that discolourations were missed or had already vanished upon evaluation.

Engineering application

Based on experimental studies evaluating fish protection efficiencies of electrified racks, where no externally visible injuries or abnormal behaviour were reported, no or very low incidences of injuries were expected for the tested setups (Meister et al., 2021; Haug et al., 2022a; Moldenhauer-Roth et al., 2025). However, in the present study no internal injuries were observed only for DS1_pDC. This setup is thus the only setup that should currently be recommended for use at pilot plants. Since the use of pDC has the potential to cause electrochemical corrosion, further tests are necessary to determine the applied voltage and intensity of the electric field at which the incidence of injuries can be reduced to zero if pAC is used (DS2_pAC). The same principle applies to R4_pAC (40 V), where the injury rates were low, but not zero. However, Brown Trout are a comparatively sensitive species with respect to electrically induced injuries due to their fusiform shape and high number of small vertebrae (Soetaert et al., 2018). Therefore, the observed injury incidences for R4_pAC and DS2_pAC should be interpreted as conservative estimates. These setups may be acceptable for rivers dominated by less injury-prone species such as cyprinids or European Eel, or at sites where alternative passage routes (e.g. turbine or spillway passage) are associated with substantially higher mortality risks. However, further tests with different fish species and lower voltages are urgently needed.

Conclusion

This study provides the first systematic assessment of both external and internal injury risks associated with electrified bar rack configurations under controlled experimental conditions for Brown Trout. Observed internal injury rates varied widely between setups, ranging from zero up to 65%. The incidence of externally visible discolourations varied from zero to 90%. These results demonstrate that the design of the electrification including electrode placement, waveform, and voltage, is a critical determinant of biological safety. Among the tested six rack setups, only one setup, the rack electrified as an electrode with an additional row of electrodes downstream, a voltage of 44 V and a pDC waveform with $PW = 2$ ms and $f = 10$ Hz resulted in zero injuries (DS1_pDC). Therefore, this setup is a promising candidate for pilot studies at hydropower plants. For three other setups with pDC and pAC waveforms (R3_pDC, R4_pAC, DS2_pAC), injury rates between 5 and 15% were observed and the severity of spinal injuries was low. For these setups, further reduction of the voltage and thus electric field strengths may further reduce the risk of injury while still providing high fish protection efficiencies.

The waveform type proved to be a key driver of injury risk: pAC resulted in higher incidences of internal injury than pDC, although the differences were not statistically significant. These findings demonstrate that the results obtained for pDC cannot be directly transferred to pAC, even when the total number of pulses is kept constant. The tested gpDC waveform resulted in notably higher incidences of internal injuries than the tested pDC and pAC waveforms and is thus not recommended for use in electrified bar rack applications. The elevated risk of injury is attributed to the high intra-burst pulse frequency of $f = 137$ Hz.

A significant association was identified between externally visible dark skin discolourations and the presence of internal injuries This suggests that such discolourations may serve as a potential indicator of fish injuries in monitoring campaigns of electrified bar racks involving Brown Trout. However, these marks faded quickly after exposure and were sometimes only observed on one side of the fish. In addition, over all experiments, ten fish did not show any dark discolourations, but had internal injuries. These observations thus confirm that visual inspection alone is insufficient for assessing fish health post-exposure.

In general, this study highlights that electrified bar racks cannot be assumed to be injury-risk-free based solely on their effectiveness in protecting or guiding fish and the absence of externally visible injuries in such studies. Before pilot deployment, new electrified bar rack configurations should be evaluated using comparable study designs that explicitly assess the risk of internal injury to the target fish species.

Supplementary material

The supplementary material and all data respective to this study is provided under `https://doi.org/10.5281/zenodo.18404157`

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Ethics statement

All live fish tests conducted within the present study met the ethical guidelines and legal requirements (Swiss animal welfare act) under permission from the veterinary office of the canton of Zurich (animal experimentation license No. 37532, laboratory animal husbandry license No. 180).

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