FINAL PROGRESS REPORT

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List of Terms and Abbreviations

ISO – International Organization for Standardization
Hz – Herz (cycles per second)
MSD – musculoskeletal disorders
HAVS – hand arm vibration syndrome
ANSI – American National Standards Institute

Abstract

This research sought to characterize shock wave vibration and investigate its ability to damage nerves in an animal model simulating hand arm vibration exposure. These studies cannot be performed on humans because of the high potential for hand injury. Shock waves from impact tools contain kHz vibration energy that is 10-50 fold greater than that in the low frequency (30-250 Hz) range typical of sinusoidal nonimpact tools. The ISO 5439 exposure risk calculation reduces acceleration above 16 Hz by progressive frequency weighting so that contributions from frequencies 1.6 kHz (reduced 100 fold) and up are essentially nil. The present research findings challenge this approach because of the high energy generated by impact tools and the occurrence of nerve damage. These results are being used by others working on expanding ISO 5349 with options to factor in kHz vibration. We repurposed an inexpensive piezoelectric sensor to enable measurement of the 5 Hz to 25 kHz power spectrum of vibration magnitudes. This technology has been shared with other researchers investigating shock wave vibration contributions to hand arm vibration syndrome. Instrumenting tools in the work place with broad band sensors has the potential to improve the accuracy of daily vibration exposure and thereby, aiding adjusting work practices to stay below the exposure action value. An intermediate outcome is that workers using impact tools and wearing antivibration gloves can block kHz vibration energy generated by the tool.

SECTION 1
Highlights/Significant Findings

Summary of major contributions and accomplishments
The present research sought to understand the mechanisms by which vibration from nonimpact and percussive power tools damage nerves and arteries. The research and associated educational activities align with NIOSH priority goals for extramural research to reduce the incidence and severity of musculoskeletal disorders in the workplace. The findings are applicable to the Construction and Manufacturing sectors: **Construction** strategic goal 7: reduce the incidence and severity of work-related musculoskeletal disorders among construction workers in the U.S. and **Manufacturing** strategic goal 3: reduce the number and severity of musculoskeletal disorders (MSDs) among manufacturing sector workers. The **Cross sector** strategic goals for musculoskeletal health are also impacted: Strategic Goal 1: Identify unique sources of surveillance data to identify the areas of needed

musculoskeletal research, Strategic Goal 2: Reduce the incidence of work-related musculoskeletal disorders by implementing cost-effective workplace interventions to reduce musculoskeletal health risk factors and Strategic Goal 3: Reduce the incidence of work-related MSDs through widespread and targeted dissemination and communication of safety and health information and effective education and training.

Contributions to the vibration field This grant generated 6 peer reviewed publications, 3 manuscripts in preparation and 9 extended abstracts/platform talks at national and international scientific meetings. Safety and health education on power tool vibration was disseminated through workshops presentations invited by organizers of Safety Conferences and via platform talks at national and international scientific conferences on vibration.

Invited Speaker, Riley DA, 2012 Indiana Safety and Health Conference & Expo, “Power Hand Tools: Understanding and Lowering the Risk of Hand-Arm Vibration Injury”, Indianapolis, IN, March 13-14, 2012. Session evaluation score 3.81 which is above the average of 3.75. Attendee written comments: “Best session of the day. Very informative. Real world examples and study. Excellent material, excellent presentation. Great information, great presenter!”

Invited Speaker, Riley, DA. 2014 Understanding and lowering the risk of hand-arm vibration syndrome, Presented in Worker’s Comp: Injuries, Analysis and Prevention, “Solutions for Tomorrow’s Safety Challenges”, Indiana Health Safety WC4, 2014 Indiana Safety and Health Conference & Expo. Indianapolis, IN, 2014.Riley’s speaker score ranked above average. Attendee comments: “He was knowledgeable on subject; good subject matter; expert in the field and very interesting; good discussion with audience; learned new important information”.

The principal investigator organized and hosted the 6th American Conference on Human Vibration http://www.mcw.edu/achv2016 which bought together over 75 scientists, engineers, health professionals, and students to discuss hand arm vibration, whole body vibration and impact vibration as published in the proceedings http://www.mcw.edu/FileLibrary/Groups/ACHV/ACHV-Program-Proceedings-Book-060816.pdf .

The published findings from our research advance the understanding of the mechanisms of vibration injury and further validate the rat-tail vibration models as a beneficial for studying vibration injury mechanisms and prevention.

Translation of Findings and Outcomes/Relevance/Impact

Research to practice strategies The basic research provides insights (research to practice strategies) to reduce the risk of hand arm vibration syndrome in workers by increasing the bandwidth of vibration energy measured and considering antivibration glove use with impact tools.

Do not reply solely on ISO 5349 frequency-weighted acceleration for calculating risk exposure because high frequencies are not considered and the high vibration energy damages nerves. The risk of vibration injury goes up with increasing vibration acceleration (m/s^2) energy. The European exposure risk calculator based on ISO 5349 determines exposure using frequency-weighted acceleration. The calculator reduces acceleration level for frequencies greater than 16 Hz. This weighting underestimates the injury potential of higher frequencies and gives a false sense of safety. Higher frequencies are just as damaging, if not more damaging, to tissues. Measuring a broader bandwidth of vibration energy will more accurately predict exposure risk.

Avoid bare hand contact with the tool of an impact powered tool and the work piece during grinding to prevent exposure to vibration shock waves High frequency components are extremely hazardous, producing the earliest onset of HAVS based on clinical reports. Shock waves contain high acceleration energy in the high frequencies (>1000 Hz) which are not perceptible in the hands. Donning ISO Standard 10819 (ANSI S3.4-2002) approved antivibration gloves should protect hands from high frequency shock wave injury.

SECTION 2

Scientific Report

Background

Vibration injury of workers using powered tools has been recognized for more than a hundred years but remains a risk today for musculoskeletal heath. Persistence of this musculoskeletal injury risk has, in part, resulted from a lack of understanding the mechanisms of vibration injury. The present research has advanced mechanistic understanding by developing rat tail vibration models simulating power tool exposure. Accomplishing the aims of the present research has contributed to improved understanding of vibration exposure duration, frequency and amplitude in the injury process. Sharing and discussing the findings with basic researchers, bioengineers, health professionals and students participating in the 6^{th} American Conference on Human Vibration Milwaukee, WI organized and chaired by the principal investigator generated new insights into hand arm vibration, whole body vibration and impact vibration. For years, ISO 5349 frequency weighting vibration risk calculation has been discussed as beneficial but inadequate because it does not consider the large amount of vibration energy in the high frequencies (kHz) emitted by impact tools. The growing evidence for kHz vibration contributing to injury has finally resulted in expanded paradigms that consider the wider bandwidth of vibration energy in risk calculation.

Specific aims Publications are listed under each aim, and the impacts are described.

Aim #1 To investigate the dose response of duration, frequency, acceleration and amplitude on the induction of persistent vasoconstriction in the rat-tail sinusoidal (nonimpact) vibration model

Rowe DJ, Yan J-F, Zhang LL, Pritchard KA, Kao DS, Matloub HS and Riley DA. The preventive effects of apolipoprotein mimetic D-4F from vibration injury-experiment in rats. Hand 6:64-70, 2011. This study reveals that vibration-induced free radicals produce tail artery injury and that a free radical scavenger D-4F reduces injury. The importance of this study is that prevention of vascular injury may be accomplished by removing free radicals during vibration power tool use.

Krajnak K, Riley DA, Wu J, McDowell T, Welcome DE, Xu XS and Dong RG. Frequency-dependent effects of vibration on physiological systems: experiments with animals and other human surrogates. Industrial Health 50:343-353, 2012. This review points out the importance of the rat tail vibration models for investigating the frequency-dependent mechanisms of vibration-induced vasoconstriction that occur in humans.

Riley DA and Bain JLW. Is the mast cell a key player in vibration disease? Conference Proceedings 4th American Conference on Human Vibration, Hartford, CT, pp. 55-56, 2012. This is the first study demonstrating that vibration induces mast cell degranulation (secretion). Mast cell secretions regulate vasoconstriction and inflammation. This observation is important because vibration-induced mast cell dysfunction could cause excessive vasoconstriction and ischemia that manifests as white finger and white toe in the hand-arm (foot) vibration syndrome.

Krajnak K, Raju SG, Miller GR, Johnson C, Waugh S, Kashon ML and Riley DA. Long-term daily vibration exposure alters current perception threshold (CPT) sensitivity and myelinated axons in a rat-tail model of vibration-induced injury. J Toxicol Environ Health A. 79(3):101-111, 2016. Vasoconstriction is regulated in part by nerves. The noninvasive perception threshold test can detect damaged nerve function and provide early recognition of vibration injury and warn of potential disruption of blood vessel regulation before the condition becomes irreversible.

Aim #2 To define the dose response relationship of shock wave vibration exposure duration with the levels of nerve and artery tissue injury

Raju SG, Rogness O, Persson M, Bain J and Riley D. Vibration from a riveting hammer causes severe nerve damage in the rat tail model. Muscle Nerve 44:795-804, 2011. This study shows that a single 12 min exposure of shock vibration can damage nerves. The relatively brief exposure to vibration and resulting tissue damage raises awareness the threat of kHz shock wave energy and the importance of including it as a musculoskeletal injury factor.

Zimmerman J, Bain JL, Persson M, and Riley DA. Effects of power tool vibration on peripheral nerve endings. International J Industrial Ergonomics (in press, 2016). The publication reports increased nerve fiber degeneration with increased vibration exposure duration per day. The single 1 minute exposure generated no detectable damage. This is encouraging because riveting hammer use in the aerospace industry averages a total of 1 minute per day. The single 6 and 12 minute exposures produced measureable damage. Limiting the daily use of riveting to less than 6 minutes per day is recommended. The vibration energy in the kHz range is 10-50 fold greater than that in the lower frequency Hz range. This implicates kHz vibration in the nerve injury process. ISO 5349 does not consider kHz energy when calculating risk of injury. Going forward, the risk calculator should be appended to factor in kHz energy to achieve a more accurate assessment of risk and setting exposure limits.

Xu XS, Riley DA, Persson M, Welcome DE, Krajnak K, Wu JZ, Raju SRG and Dong RG. Evaluation of anti-vibration effectiveness of glove materials using an animal model. Bio-Med Mater Eng 21:193-211, 2011. Antivibration glove material absorbs kHz vibration energy, potentially preventing tissue injury. Direct evidence supporting the use of antivibration gloves will require a future study evaluating glove material and showing a reduction in nerve damage.

Riley DA and Bain JLW. Is the mast cell a key player in vibration disease? Conference Proceedings 4th American Conference on Human Vibration, Hartford, CT, pp. 55-56, 2012. Sinusoidal and impact shock wave vibration both stimulate mast cell secretion (degranulation). The secreted products are known to stimulate nerve secretory activity and degradation of vasoconstrictive peptides as well as regulating inflammation and healing. Further research on mast cells is necessary because vibration injury of these cells could promote hyper inflammation and failed healing, leading to nerve and artery dysfunction.

Riley, DA and Bain JLW. Interpreting HAVS based on rat tail vibration injury data. Proceedings 5th American Conference on Human Vibration. University of Guelph, Ontario, Canada, pp. 11-12, 2014. The rat tail vibration model is verified for studying nerve fiber degeneration. Subtypes of nerve fibers innervating arteries are demonstrable. If there is degeneration and regeneration of vasoconstriction nerves but less regrowth of vasodilation nerves, this would favor vasoconstriction and explain the vasospasticity component of hand arm vibration syndrome. Continued research on vibration injury of specific nerve types is necessary to understand the mechanism of vasomotor dysfunction and reveal novel targets for disease prevention.

Aim #3 To evaluate the occurrence and recoverability of vibration-induced **structural** deficits in the innervation and blood supply of the rat-tail following 12 minute shock wave vibration per day for 1 day, 1 week and 10 weeks

Xu XS, Riley DA, Persson M, Welcome DE, Krajnak K, Wu JZ, Raju SRG and Dong RG. Evaluation of anti-vibration effectiveness of glove materials using an animal model. Bio-Med Mater Eng 21:193-211, 2011. This study demonstrates that antivibration glove material blocks the high frequency (kHz) vibration energy. To lower vibration energy exposure and injury, gloved hands rather than bare hands should be contacting the metal tool piece and metal bucking bar when riveting.

Zimmerman J, Wu C, Bain J and Riley D. Sensory nerve ending structures after 5 weeks of vibration exposure. American Society for Peripheral Nerve, Waikoloa, Hawaii, January 13-15, 2017, Abstract accepted 2016. This study found that after 5 weeks of shock wave vibration, nerve fibers did not exhibt severe extensive degeneration. This was surprising because a single day of vibration produced nerve damage. The nerves of rats have a high capacity to regenerate. Peripheral nerves in humans are also known to regenerate vigorously, and this is possibly one reason why it takes 8 months or longer for nerve degeneration (loss of feeling) to manifest in workers using impact power tools. The eventual onset of loss feeling is thought to represent a reduction in the ability of nerves to regenerate. In this report, daily vibration was performed for 5 weeks, based on the severity of nerve damage after a single exposure. Five weeks in a rat with a 2 year lifespan is roughly equivalent to 150 weeks or 5 months in a human. Based on the reported onset of nerve degeneration in humans, future rat studies should investigate 10 weeks or 10 human months to reach the period of nerve regeneration failure.

Zimmerman J, Bain JL, Persson M, and Riley DA. Effects of Power Tool Vibration on Peripheral Nerve Endings. International J Industrial Ergonomics (in press, 2016). In this study, we report that the magnitude of vibration energy in the kHz range is 10-50 times that in the low Hz range. The nerve damage is likely due to this high energy component. The kHz energy should no longer be ignored when calculating vibration risk. A piezoelectric sensor was repurposed for measuring a wide bandwidth (Hz to kHz) of vibration energy. This technology can be used by future researchers seeking to define the mechanism of vibration injury and developing means to protect workers from the offensive vibration. Protection may also be developed by tool manufacturers reducing the offensive frequencies, and personal protection equipment companies producing antivibration gloves and tool shields to prevent the vibration energy from entering the hands.

Aim #4 To evaluate by repeated measures the occurrence and recoverability of vibration-induced **functional** deficits in the innervation and blood supply of the rat-tail following 12 minute shock wave vibration per day for 1 day, 1 week and 10 weeks

Functional testing was not completed because the structural studies of vibration exposure and recovery required all of the effort during the no cost extension. As a result, the carryover funds were not completely expended.

Publications

1. Rowe DJ, Yan J-F, Zhang LL, Pritchard KA, Kao DS, Matloub HS and Riley DA. The preventive effects of apolipoprotein mimetic D-4F from vibration injury-experiment in rats. Hand 6:64-70, 2011.
2. Raju SG, Rogness O, Persson M, Bain J and Riley D. Vibration from a riveting hammer causes severe nerve damage in the rat tail model. Muscle Nerve 44:795-804, 2011.

3. Xu XS, Riley DA, Persson M, Welcome DE, Krajnak K, Wu JZ, Raju SRG and Dong RG. Evaluation of anti-vibration effectiveness of glove materials using an animal model. Bio-Med Mater Eng 21:193-211, 2011.
4. Krajnak K, Riley DA, Wu J, McDowell T, Welcome DE, Xu XS and Dong RG. Frequency-dependent effects of vibration on physiological systems: experiments with animals and other human surrogates. Industrial Health 50:343-353, 2012.
5. Riley DA and Bain JLW. Is the mast cell a key player in vibration disease? Conference Proceedings 4th American Conference on Human Vibration, Hartford, CT, pp. 55-56, 2012.
6. Riley, DA and Bain JLW. Interpreting HAVS based on rat tail vibration injury data. Proceedings 5th American Conference on Human Vibration. University of Guelph, Ontario, Canada, pp. 11-12, 2014.
7. Zimmerman J, Bain J, Wu C and Riley D. Five-week exposure to riveting hammer vibration. Proceedings 6th American Conference on Human Vibration. Medical College of Wisconsin and Marquette University, Milwaukee, WI, USA, June 8-10, pp 101-102 2016.
8. Krajnak K, Raju SG, Miller GR, Johnson C, Waugh S, Kashon ML and Riley DA. Long-term daily vibration exposure alters current perception threshold (CPT) sensitivity and myelinated axons in a rat-tail model of vibration-induced injury. J Toxicol Environ Health A. 79(3):101-111, 2016.
9. Zimmerman J, Bain JL, Persson M, and Riley DA. Effects of Power Tool Vibration on Peripheral Nerve Endings. International J Industrial Ergonomics (in press, 2016).

Presentations/contributions

1. Presentation, Riley DA, Raju SG and Bain JLW. Assessing impact-tool vibration damage of tissues in a rat-tail model. 12th International Conference on Hand-Arm Vibration, Ottawa, Ontario, Canada, June 13-17, Abstract 2011.
2. Invited Speaker, Riley DA, 2012 Indiana Safety and Health Conference & Expo, “Power Hand Tools: Understanding and Lowering the Risk of Hand-Arm Vibration Injury”, Indianapolis, IN, March 13-14, 2012.
3. Presentation, Riley DA and Bain JLW. Is the mast cell a key player in vibration disease? 4th American Conference on Human Vibration Hartford, CT, June 13-15, Abstract 2012.
4. Invited contribution, Riley DA. Provided descriptions of vibration risks and HAVS in the article authored by Johnson, A. ‘Complacency is real’ Educating workers about the risks of nail guns and other power tools, Safety+Health Magazine, Vol 188, Sept 1, 2013.
5. Invited Speaker, Riley, DA. Understanding and lowering the risk of hand-arm vibration syndrome, Presented in Worker’s Comp: Injuries, Analysis and Prevention, “Solutions for Tomorrow’s Safety Challenges”, Indiana Health Safety WC4, 2014 Indiana Safety and Health Conference & Expo. Indianapolis, IN, 2014.
6. Presentation, Riley, DA and Bain JLW. Interpreting HAVS based on rat tail vibration injury data. 5th American Conference on Human Vibration. University of Guelph, Ontario, Canada, June 10-13, Abstract 2014.
7. Presentation, Zimmerman J, Bain J, Persson M, Riley D. Effects of Power Tool Vibration on Peripheral Nerve Endings. 13th International Conference on Hand-Arm Vibration. Beijing, China, October 12-16, 2015.
8. Presentation, Zimmerman J, Bain J, Wu C and Riley D. Five-week exposure to riveting hammer vibration. 6th American Conference on Human Vibration. Medical College of Wisconsin and Marquette University, Milwaukee, WI, USA, June 8-10, Abstract 2016.
9. Presentation, Zimmerman J, Wu C, Bain J and Riley D. Sensory nerve ending structures after 5 weeks of vibration exposure. American Society for Peripheral Nerve, Waikoloa, Hawaii, January 13-15, 2017, Abstract accepted 2016.

Manuscripts in preparation

1. Riley, DA and Bain JLW. The mast cell is a key player in vibration injury. Muscle & Nerve (2016).

2. Zimmerman J, Wu C, Bain J and Riley D. Sensory nerve ending structures after 5 weeks of vibration exposure. Muscle & Nerve
3. Zimmerman J, Wu C, Bain J and Riley D. Five week vibration and 5 week recovery induced changes in dorsal root sensory neurons. Muscle & Nerve

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Prepared by Danny A Riley, PhD on this date