**Laboratory and WorkplaceAssessments of Rivet Bucking Bar Vibration Emissions**

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**Supplemental material**

**S1. Development of the laboratory-based bucking bar assessment method**

One of the specific aims of this study was to develop a laboratory-based method for evaluating rivet bucking bar vibrations similar to standardized methods for evaluating powered hand tool vibrations in the ISO 28927 series. As stated in those ISO standards, the primary function of such a standardized method is to compare the acceleration levels of tools within a tool group ([e.g., ISO 28927-10, 2011](#_ENREF_4)). The assessment of HTV during the riveting process presents some unique challenges. Unlike most powered hand tools that are commonly assessed via steady-state data collection periods that last several seconds while the tool is continuously operated against a workpiece or a steady load, the riveting process employs periodic impulsive accelerations to complete the task. The durations of such pulses are controlled by the riveting hammer operator and can range from 0.5 s to over 2.0 s per rivet ([Dandanell and Engstrom, 1986](#_ENREF_2); [Cherng *et al.*, 2009](#_ENREF_1); [McDowell *et al.*, 2012](#_ENREF_5)). Naturally, the pulsing sequence of rivet bucking bar vibrations will follow that of the riveting hammer. It is very challenging to collect meaningful riveter vibration data that do not include periods of ‘off time’. Obviously, the amount of time that a tool is actually operating during a data collection period is critical to the integrated total value. Because the ‘trigger time’ of the riveting hammer varies by operator, tool efficiency, and task, it is difficult to quantify daily HTV exposures or to compare the vibration levels of riveting tools in work environments. Because of these difficulties, the ISO standard for evaluating riveting hammer vibrations calls for the vibration data to be collected while the riveting hammer is operated continuously against a load for several seconds as is prescribed for other powered hand tool groups. However, riveting hammer designs are optimized for periodic impulses; these tools are not designed for the continuous operation set by the standard. Furthermore, tool efficiency is neglected by the standardized method; a tool that can perform a task faster in an actual work environment is assessed over the same prescribed time period as less-efficient tools which negates the exposure reduction afforded by the more effective tool design.

The ISO 28927 standards caution users that tool vibrations vary considerably in typical use, and that actual workplace vibration exposures may be higher or lower than laboratory-measured values (ISO 28927-10, 2011). Those laboratory-based standards are not ideal for quantifying workplace exposures. However, the ISO 28927 standards are intended to provide reasonable simulations of actual workplace activity. The NIOSH laboratory-based rivet bucking bar vibration evaluation method was designed with this in mind. The NIOSH method uses features of two earlier laboratory-based bucking bar vibration assessment methods. The first method was developed by engineers at Atlas Copco Tools AB ([Treskog, 1994](#_ENREF_6)). As is the case with most actual riveting tasks, the Atlas Copco method requires two operators; one operator controls the riveting hammer while the second operator presses the bucking bar against a simulated rivet. However, the use of two human operators introduces more variability as the applied forces and system mass could vary substantially depending on the operators. The Cherng*et al*. ([2009](#_ENREF_1)) test fixture method effectively eliminates such variability by removing both human operators from the system. However, because the dynamics of the human play an important role in the amount of vibration transmitted to the operator ([Griffin, 1990](#_ENREF_3)), this important variable is confounded by rigidly-mounting both the riveting hammer and the bucking bar to the test fixture; it is questionable whether or not a fixture-based method can produce realistic or representative accelerations. Furthermore, it would be expensive and difficult to design and fabricate a complex, bar-specific test fixture with mechanical impedance comparable to that of the human hand-arm system. To avoid these difficulties, the NIOSH method is closer to typical standards contained in the ISO 28927 series where a single operator operates the tool and applies a target feed force against a simulated workload. Unlike the ISO riveting hammer evaluation standard ([ISO 28927-10, 2011](#_ENREF_4)) which calls for continuous tool operation during data collection trials, the pulsing operation sequence employed by the NIOSH method is a more realistic simulation of a typical workplace riveting pattern.

To determine the target push force for the bucking bar evaluations, a pilot test was conducted using a simulated work station where rivets were set to fasten sheet metal to frames constructed of the same materials used in actual aircraft sheet metal riveting tasks. The bucking bar feed force required to fully set the rivets was measured with a force plate. It was observed that a push force of about 80 N was required to fully set the rivets. It was also observed that some dampened bucking bars could bottom-out which defeated their dampening mechanisms if the push force was greater than 90 N. Therefore, 80 ± 10 N was used as the target push force in the proposed laboratory test.

Tool vibration magnitudes can vary greatly in actual workplace conditions. It is not feasible to design a standardized laboratory test method that can fully represent all workplace environments. Operating tools against a stable load seems to be a reasonable approach for standardizing tool evaluations for the purpose of comparing and ranking tools in terms of vibration. From this point of view, the tool loading method prescribed by the NIOSH bucking bar vibration HTV assessment method seems reasonable for the following reasons: (i) the apparatus and procedure are similar to existing standards in the ISO 28927 series; (ii) the apparatus is relatively simple and can be easily reproduced by other laboratories; and (iii) the riveting hammer and control station provide stable vibration stimulus, as reflected by the easily-achieved intra-subject variation (CV<15%) and the consistent weighted and unweighted acceleration measurements presented in Table 4.

The single-operator technique employed in the NIOSH method seems to offer a reasonable replication of typical workplace riveting operations. This first iteration of the NIOSH laboratory-based bucking bar assessment method produced similar tool rankings to those generated through the workplace assessments. However, the laboratory acceleration averages were substantially lower than the workplace measurements. There could be a number of reasons for this. First of all, the applied bucking bar feed force was not measured in the workplace evaluations. The feed force prescribed in the NIOSH laboratory tests may need to be adjusted to better reproduce typical feed forces used in actual riveting tasks. The effect of feed force on bucking bar vibration remains a topic for further study; bucking bar feed force should be further evaluated and optimized for the NIOSH method. Secondly, the volume of hardened steel balls contained in the energy absorber might need to be adjusted; it could be that the energy absorber dissipated too much energy during the lab evaluations and failed to deliver sufficient vibration stimuli to the simulated rivet. Lastly, the on/off timing sequence can be adjusted to better mimic the average pace of actual riveting tasks. In any case, we believe the NIOSH method can be fine-tuned to improve its ability to rank-order and identify bucking bars that can be expected to exhibit reduced HTV exposures to their operators in workplace environments and to provide better predictions of actual bucking bar HTV exposures.

It should also be noted that typical lab-based vibration emission tests defined in the ISO 28927 standards call for five trials per tool per operator. The tools are typically operated continuously at a constant speed during the data collection periods. Different from the ISO 28927 tests, the proposed bucking bar test closely mimics real workplace tasks; the test simulates the rhythmic tool operations typical of actual workplace riveting. The results of the current study suggest that three, five-rivet trials are sufficient to provide representative data. However, to be consistent with standardized laboratory-based tests for other tool types and to increase the statistical power of test results, five trials may also be considered for a standardized bucking bar laboratory test.

**S2. Control circuit for the simulation of a riveting sequence**

During the laboratory tests, the on/off operation of the riveting hammer mounted on the test apparatus was controlled remotely via a control station manned by the NIOSH investigator. The control station comprised a repeat-cycle timer that was programmed to automatically cycle power to the tool supply air solenoid valve which cycled the riveting hammer on and off in order to simulate the typical pace of the workplace airframes riveting tasks. Figure S1 shows a schematic diagram of the control circuit. The simulated riveting cycle consisted of 2 seconds on time and 3 seconds off time per rivet. To mimic the workplace evaluations, a trial in the NIOSH lab test simulated the setting of 5 rivets in 30 seconds.



Figure S1. Schematic diagram of the control circuit for the on/off operation of the pneumatic riveting hammer in the laboratory simulated riveting trials. A repeat cycle timer was programmed to cycle the riveting hammer’s air supply solenoid valve on for two seconds and off for three seconds per rivet. A simulated riveting trial consisted of five on/off cycles.

**S3. Protection against DC shifts**

The measurement of vibration of percussive tools often yields significant direct current (DC) shifts in the piezoelectric accelerometer output ([Griffin, 1990](#_ENREF_10)). These DC shifts are a source of measurement error and should be mitigated. Consequently, a layer of synthetic rubber was used as a mechanical filter for each bucking bar accelerometer to minimize or eliminate the DC shift. This synthetic rubber layering technique has been proven to be successful in several earlier experiments involving impact tools ([Dong *et al.*, 2004](#_ENREF_6); [McDowell *et al.*, 2009](#_ENREF_17); [McDowell *et al.*, 2012](#_ENREF_18)). The effectiveness of this accelerometer installation technique was verified in the NIOSH laboratory by conducting a series of simultaneous vibration data collection trials with each bucking bar using a laser vibrometer along with the installed accelerometers. (Measurements from a laser vibrometer are immune to the DC shifting problem.)