CORRELATION OF SEGMENTAL VIBRATION WITH OCCUPATIONAL DISEASE

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ABSTRACT

Many diverse problems have arisen in attempting to obtain valid and reliable measurements of segmental, tool induced vibrations. Almost all of the approaches possible have been tried in one form or another including animal experiments, use of cadavers, accelerometry, electromyography—both clinical and surface, physical and mathematical modeling of the hand-arm system and the entire body, as well as a variety of subjective responses and epidemiological techniques. Each of these approaches has encountered serious drawbacks, but prior investigators have achieved a noteworthy modicum of success in their efforts to explain how the body attempts to absorb and dissipate the energy created by the tools' external forces, and how these mechanisms break down when trauma begins. Taken together, the sum of this knowledge has still not provided us with the type of comprehensive information required to establish vibratory tool design and operating standards, as well as safe limits for both time and environmental exposure. The lack of such definitive information virtually assures continuing scientific investigation in this subject such as has been reported at this conference. This paper critically reviews and summarizes a number of the more pertinent recent efforts to further and perhaps accelerate progress in an important research area.

INTRODUCTION

It is generally agreed that a number of occupational disabilities are related to long term or repeated exposure to segmental vibration created in the operation of certain industrial power tools, although minimal damage thresholds for amplitude and limits for frequency characteristics of the offending forces are neither well charted nor universally understood. The connection between the above normal incidence of certain ailments in workers using particular tools has been well documented.[1-4] Chain saws, rock drills, and pneumatic hammers are among those tools that have been investigated. Here the vibration spectra generated can usually be measured at the source. Yet the method and degree of energy absorption by the various segments and joints of the hand-arm system remain unclear. Similarly unknown are which components of the vibratory input are responsible for eroding the normal absorption chain and how this breakdown accelerates the eventual onset of trauma. The pertinent factors here are highly interrelated so that discerning all the details of the process is difficult. Many unique parameters can apply in each given situation, the most important of which are tool mass and its distribution, ambient environmental conditions, amplitude and frequency characteristics of the forcing function, handle configuration, grip used, force applied, protective clothing worn.[5]

Certain degrading processes favoring the development of disease appear long term—typically measured in years of exposure, and therefore virtually impossible to measure in a laboratory environment. Perhaps this task is best left to the epidemiologist because many extraneous, off-the-job factors can combine to obscure how trauma actually develops. The trauma mechanisms are unknown, but if the vibration trauma could be reliably recorded, then differences between unaffected workers and those suffering from certain occupational vibration diseases could be charted. These differences could in turn be used for hypothesizing both the patterns and physiological techniques of vibration absorption by the hand-arm system and the methods by which the hand-arm system is impaired by long term or excessive exposure.

HISTORICAL BACKGROUND

In the United States, relatively little work has been reported on Raynaud's phenomenon and similar vibration maladies of occupational origin. This is most likely because of the generally low awareness of these diseases among nonspecialists leading to incomplete diagnosis. Because etiology is uncertain, only general treatment is prescribed. This consists of either a temporary or permanent change of occupation that may only alleviate symptoms rather than provide a cure.

The mechanisms by which vibration related diseases arise are obscure. Much of the early work done was based on subjective responses furnished by the workers themselves.[6] These authors were the first to state that the nonoperating hand, usually the left, is subjected to greater vibration stresses and is, thus, more susceptible to Raynaud's phenomenon and related afflictions. The greatest incidence of disease is claimed to lie between frequencies of 33 to 50 Hertz (2,000 to 3,000 strokes per minute). They believe the left hand is twice as vulnerable as the right, not only because it is much closer to the action point, but it is also subject to a secondary vibration component in the horizontal direction. This is in addition to the primary axial vibration that affects both hands to the same degree.

Several more recent studies[7,8] have attempted to determine which vibration frequencies are absorbed in which segments of the hand-arm system. As shown in Table 1, both sources generally confirm that the higher frequencies are absorbed in the fingers. These digits represent the smallest mass and are the most directly exposed anatomical segments. As the waves pass up the arm, proximal elements tend to absorb the high end of the remaining energy spectrum. Thus, the lowest portion of the wave, 20 Hertz and below, is all that remains for absorption by the shoulder or for dissipation into the body.

The precise mechanisms explaining why and how such vibration causes stresses to arise in the hand-arm system (stresses that eventually lead to discomfort and trauma) are unknown. Reynolds and Jokel[7] attribute the problem to an inability of hand and arm tissues to transfer all of the energy induced by the tool at the system interface, e.g., the tool handle. It is theorized that since there is a great deal of natural damping present in these anatomical structures, perfect transfer is an impossibility. Most of the energy is absorbed by the hands and arms, and only a small remnant is dissipated by the rest of the body. Such imperfect damping results in a buildup of friction and heat. This buildup, in turn, leads to increased local blood flow, peripheral tissue irritation, fatigue, and eventual partial tissue destruction. Soon the adjacent blood vessels lose some of their elasticity and, with it, the ability to absorb further vibration. If the process is allowed to continue, cyanosis will probably set in. This blanching of the fingertips is due to a loss of peripheral circulation and is the classic precursor of Raynaud's phenomenon. Kampik[9] has noted that short term exposure to certain adverse conditions of as little as 1 hour can result in the swelling of hand tissues. This may be accompanied by a temporary loss of tactile sensitivity indicative of nervous system involvement. Streeter[10] attempted to verify such losses in sensitivity. He used vibrating frequencies between 30 and 480 Hertz, and correlated these inputs with three levels of power and with grip strengths of 6, 12, and 18 pounds. From subjective verbal responses, he confirmed a temporary loss of tactile sensitivity. No clear relationship, however, could be established with grip strength. This parameter had previously been held to be a significant factor in discomfort and trauma formation. Reynolds and Jokel[7] attempted to explain the well known relationship between Raynaud's phenomenon and exposure to cold, a stimulus that provokes attacks. They also established a relationship with excessive grip pressure and showed how both tend to accelerate the degenerative process. It should be noted, however, that recordings of segmental vibration sensitivity were based on a range of subjective responses.

It appears that some workers are relatively sensitive to vibration inputs, whereas others, working under similar conditions, are virtually immune. What is responsible for this difference remains uncertain. Reynolds and Jokel[7] attribute at least part of it to such diverse factors as method and tightness of grip, body type, muscle tone, and work posture.

On the other hand, Teisinger[11] attributes Raynaud's and related diseases to the involvement of the nerve endings in the walls of the digital arteries and arterioles. He reviews several historical theories and dismisses them one by one: for example Magos and Okos[12] who claimed that, in cold climates, the blood vessels lose their ability to remobilize certain chemicals and Stewart and Gorda[13] who blamed the problem on callosites, formed in the subcutaneous layers by friction, that decreased digital circulation. The official Soviet standard[14] claims that it is impossible to differentiate the adverse effects of vibration, noise, and extreme environments on workers. It negates definitive causations based mainly on mathematical or physical modeling, subjective responses, or laboratory experiments. Soviet rationale holds that Raynaud's and related diseases are a result of the breakdown of "the regulating functions of the central nervous system." Teisinger gives short shrift to such arguments. In his own analysis, he also minimizes the impact of animal experiments such as those conducted by Rudin et al.[15-17] He states that tying guinea pigs onto shaker tables so stresses the animal that it is impossible to attribute any resulting trauma exclusively to vibrations. Teisinger claims that low frequency vibration or shocks experienced in using tools such as the riveting hammer lead directly to joint diseases because they strongly involve both the bones and tendons. Vascular diseases, on the other hand, result from exposure to higher frequency vibrating tools such as drilling hammers and chain saws. These devices generate spectra in the range of from 20 to 1,000 Hz. Besides the amplitude and frequency characteristics of these vibrations, he confirms many of the previously cited ancillary factors needed for establishing design and exposure standards. The critical avoidance frequencies, he claims, also depend on the various segment response resonances of the hand-arm system. These are more properly characterized as points of minimum mechanical impedance. As already noted, they depend upon the position of the hand, the muscle tension exerted, type of grip used, and the orientation of both wrist and elbow joints. These variables may account for many of the differences noted by investigators in their efforts to compute resonance points. Teisinger's sole resonance is given for the hand, 30 to 80 Hertz, which generally agrees with other sources (Table 1).

The spectra of tool forcing functions encountered is similarly quite varied. It depends on the type of tool, characteristics of the material being worked, orientation of the handle, and certain personal factors relative to the operator. Teisinger[11] hypothesizes that vasoneurosis may be the primary mechanism by which cyanosis develops, although he offers neither further details nor supporting evidence to substantiate this view.

Nerem[18] focuses on the role of arterial wall shear stress and its relationship to Raynaud's disease. He relates its etiology to the buildup of local friction forces between arterial blood flow and the endothelium. Nerem notes that vibration can produce serious variations in flow that directly affect wall shear. It is generally accepted that wall shear, in turn, has a direct influence on the transport of blood elements. If shear becomes too high, this can result in endothelial damage. The author contends that such damage is linked to the formation of Raynaud's disease. He notes that shears of magnitude exceeding 1,000 dynes/cm^2 are necessary to produce damage. Common vibrating tools such as jack hammers and pneumatic chisels produce frequency spectra of 20 Hz at a corresponding displacement amplitude of 5.0 cm. Using these tools will produce shear stresses in excess of 1,200 dynes/cm^2. This level of shear was predicted even after a 50% natural attenuation rate was allowed for the hand-arm system. The physiological model used was based on an attenuated oscillatory wall motion superimposed on normal pulsatile arterial flow. These deductions may be conservative in that they make no provision for the aggravating effects of extreme environments, excessively tight tool grips, or any other of the previously cited artifacts.

Pelnar[19] generally agrees with this hypothesis. He used finger plethysmography as his measuring technique in studying digital circulatory phenomena. He traced the basic cause of occupational cyanosis to arterial spasms. These were found in the digital arteries whenever low frequency impact loads were introduced and in the smaller arterioles when higher frequency oscillations were encountered. Magos,[20] too, concurs and succinctly lists the probable chain of events he believes is followed in the development of occupational Raynaud's disease: buildup of shear stress, transformation of vibrational energy into heat, increased capillary permeability, release of biochemically active substances, and formation of elastin and fibrin within the vessel wall.

In attempting to explain the wide differences found in individual sensitivity, Magos notes that there are no differences in the first phase of the defense mechanism that the body sets up against cooling. All workers exhibit similar degrees of vasoconstriction whether or not they suffer from Raynaud's disease. In the second phase—cold dilation—the blood vessels of the fingers and hands of individuals sensitive to Raynaud's phenomenon are unable to react appropriately to allow for sufficient dilation in cold environments. This thesis could explain the relatively high degree of variability between workers.

MEASUREMENT TECHNIQUES

In addition to subjective responses, several other techniques have been explored in the measurement of segmental vibrations. It has been theorized that cadavers can provide an acceptable substitute for in vivo recording. This approach would be valid if the bone structure bore the major responsibility for absorption. However Carlsoo and Mayr[21] point out that this is applicable only for low frequency vibration such as that produced by impact type tools. For tools that oscillate at higher frequencies, most of the absorption depends upon the elasticity of both joints and tendons, as well as the arterial structure of the hand-arm system. Abrams and Suggs[22] actually used a cadaver arm to measure the transmission of a vibrating joint. They found that low frequencies are transmitted with minor attenuation up the arm, whereas higher frequencies are mainly absorbed in the hand and forearm.[23] In this respect, it should be noted that cardiovascular elasticity decreases rapidly after death and is virtually gone by the time of onset of rigor mortis. Positive proof is lacking that residual elasticity in cadavers is sufficient to simulate adequately in vivo responses.

Two of the more promising newer techniques for real time measurement are accelerometry and electromyography (EMG). Carlsoo and Mayr[21] used these instruments to study how the recoil forces produced by reciprocating tools are absorbed by the joints and segments of the hand-arm system. Angular and linear piezoelectric accelerometers (one each) were attached to the forearm and to the upper arm while simultaneous muscle activity was being recorded from an appropriately placed EMG needle and surface electrodes. Results when using a pneumatic hammer and a bolt gun showed that most of the shock load had been damped before reaching the wrist. Some of the force was spent accelerating the forearm; the remainder was transferred to the elbow where it was either expended in accelerating the upper arm or transferred to the shoulder. Load distribution was in general agreement with previous conclusions, i.e., primary losses occur between the hand and elbow and smaller secondary losses occur between elbow and shoulder. The authors found little difference in the magnitude of load imposed and only slight intersubject variations. Only tightness of grip was found to be an important factor. The need to prescribe shock load limits and to investigate the effects of recoil on joint degeneration was stated; however, no details were given. The major contribution of this work was its demonstration of a measurement technique.

Chaffin[24] confirms the feasibility of using electromyography as a general diagnostic tool in occupational settings. He shows that EMG can be applied wherever there is significant muscular involvement in task performance. Because of their consistency, repetitive tasks are best suited to such analysis. Investigations can include both amplitude and frequency responses, as well as power spectrum analysis. Tichauer[25] has shown that a process akin to integration of the muscle action potentials will eliminate many of the artifacts that limit EMG analysis to specialists. The signal produced here represents an analog of the firing rate, which is indicative of the total instantaneous activity in a given muscle mass. He observes that surface electromyography can be applied to "the objective measurement of physiological and pathological responses to physical work stress." Recordings obtained are both valid and reliable since all high frequency spikes have been eliminated and the signals then become compatible with the response characteristics of a normal oscillograph.

Mather et al.[26] conclude that such electromyographic recordings can provide a valid indicator of muscle usage and body exertion. They also note that these signals can be used for objective comparisons of the effects of such work stresses — those produced by vibrating hand held power tools. Because the forces are repetitive, EMG can prove valuable by monitoring the real time reaction of key muscle groups in the hand and arm.

Ortengren et al.[27] demonstrated the practicality of this approach by investigating the power spectral density response of repeated test loadings during assembly line work. There is a shift towards the lower end of the frequency spectrum as work proceeds. It may be possible to correlate such shifts with corresponding states of vibration absorption. Wright et al.,[28] however, caution about the use of the EMG as an indicator of muscular fatigue.

A major source of difficulty involved in applying accelerometers to record a worker's instantaneous responses to vibration lies in the method of attachment. Implanting the instruments or fixing them solidly to a bone to eliminate all relative movement with the skeletal structure would be ideal. With the exception of animal or cadaver experiments, however, this is impossible. Hence, we must be satisfied with less than perfect approaches such as rigid attachment to tightly fitting velcro cuffs.[29]

The mass of these transducers themselves must be insignificant when compared with the mass of the hand-arm segment whose response they are recording. Electrical characteristics should stress the low end of the frequency spectrum. The body itself, being a physical system with definite mass and inertial properties, is often unable to respond adequately to higher frequency inputs. How the body actually handles these components is uncertain. They may either be stored as potential energy or dissipated rapidly near the surface of the skin.

Animal experiments using guinea pigs such as those carried out by Rudin et al.[15-17] are of necessity artificial situations involving whole-body rather than segmental inputs. They are, therefore, of limited value in this area. One potentially more promising approach in this regard would be to use animals whose musculo-skeletal structure is equivalent to man's such as the chimpanzee. To produce meaningful results, the animals would have to be harnessed so they would be forced to grip the handle of a vibrating tool, with the accelerometers rigidly attached to their bones. Such a highly restrictive set up would not, however, bear much resemblance to man at work.

Several newer techniques appear to hold promise for real time recording of workers using vibrating tools. Slow motion roentgen cinematography may be able to show the relative displacement of bones under different combinations of amplitude and frequency. Also thermography can exhibit the real time distribution and buildup of body heat. These patterns may then be correlated with vibration data.

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