

MATERNAL AIRCREW FETAL NOISE AND VIBRATION EXPOSURE RISK MODEL

Aim 1 Literature Search

FY20 Report

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Abstract

All Military personnel will likely be exposed to extremely loud noises such as various weapons (impulse noises > 180 dB), as well as ground, water, and air transportation platforms at some point in their career. However, it is challenging to assess the overall timeline of noise exposures of military personnel, especially during missions and deployment. Extreme noises have auditory and non-auditory effects on health. Unfortunately, military noise may not only induce adverse changes in psychological and physiological well-being and provoke hearing loss but may also affect the health and development of a pregnant female and her fetus. Unfortunately, the pathway and the level of exposure as well as outcomes of such exposure are not well understood. Computational models offer an ethical methodology to characterize the risk from military noise and vibration exposures to the mother and fetus and various stages of development. This information can then be used to inform policies on allowed duties for pregnant female aircrews.

This report summarizes a literature review of the information concerning military noise exposures, aircraft noise exposures, maternal and fetal noise outcomes, noise and vibration transfer to human tissues and the fetus, and computational models and data requirements for vibrational energy transfer to the mother and fetus. We collected over 1000 publications, of which 638 documents were selected for inclusion into the Mendeley database to be provided to the sponsor. After review, a total of 95 publications were included in the final report, 102 publications were reviewed in the report table and 57 included into a draft journal review paper. There is an immediate need for more scientific evidence regarding temporary and permanent noise effects and exposures as well as the development of an accurate, reliable, and predictive numerical modeling framework that would ensure the health and safety of maternal aircrew and their unborn children.

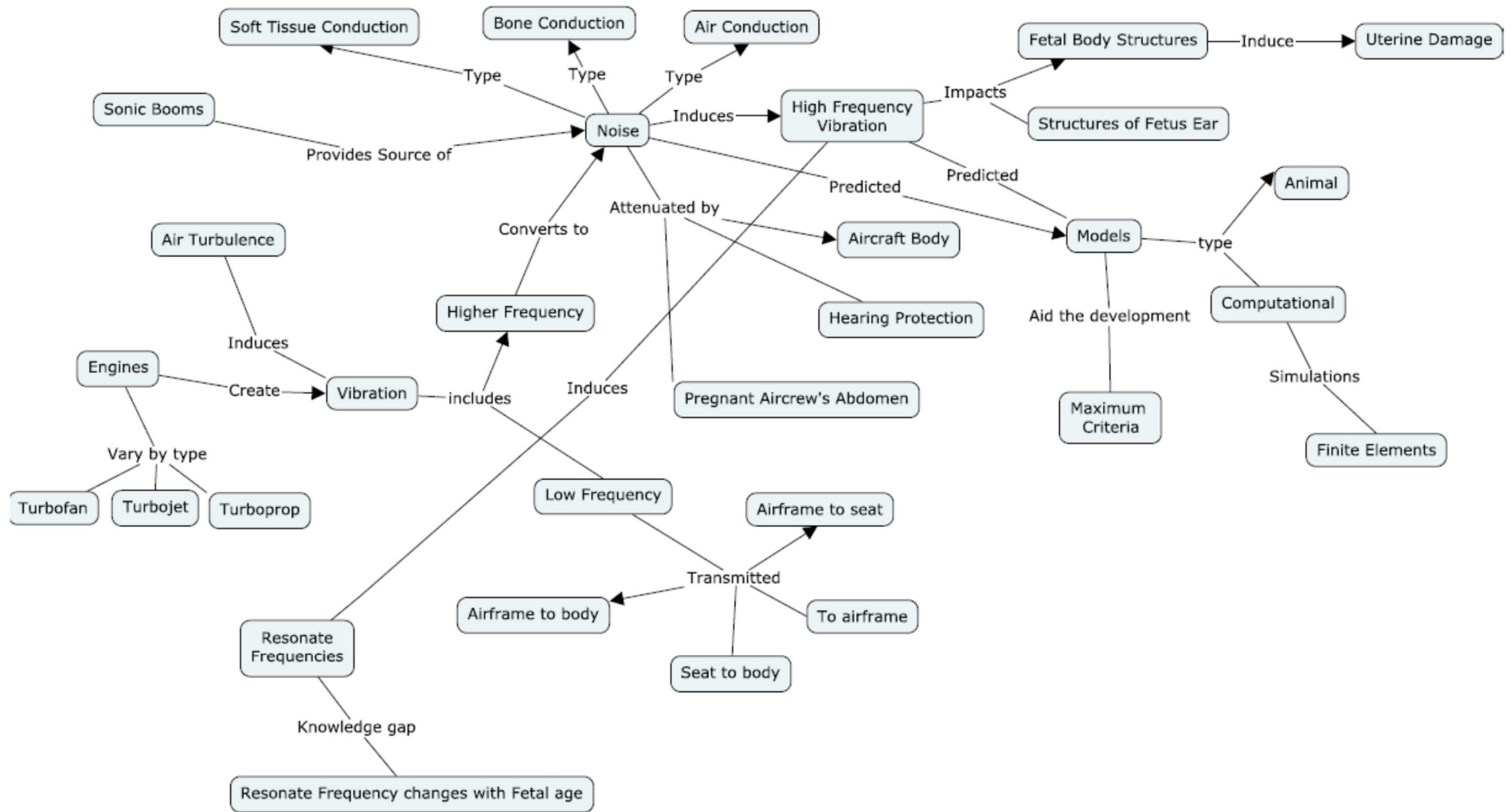
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Scheme 1. Fetal project Aim 1 concept map.



Summary

This report concentrates on the state-of-the-art in noise and vibration on fetus and pregnant female aircrew. Noise and vibration are generated from multiple sources inside and outside of the aircraft. As shown in Figure 1, these originate from the motion of the engines, hot jet exhaust mixing with still cool air, air flowing over external surfaces of the aircraft and turbulence. Vibration is then transferred through the aircraft to the seat and bodies of the aircrew. This vibration can result in vertical, horizontal, hand-arm localized or whole-body vibration. Vibration can also create noise as it is transferred to waves in the air. Noise can be transferred into the cabin to the crew. Both vibration and noise can then be transmitted through the pregnant female body, subsequently impacting the fetus

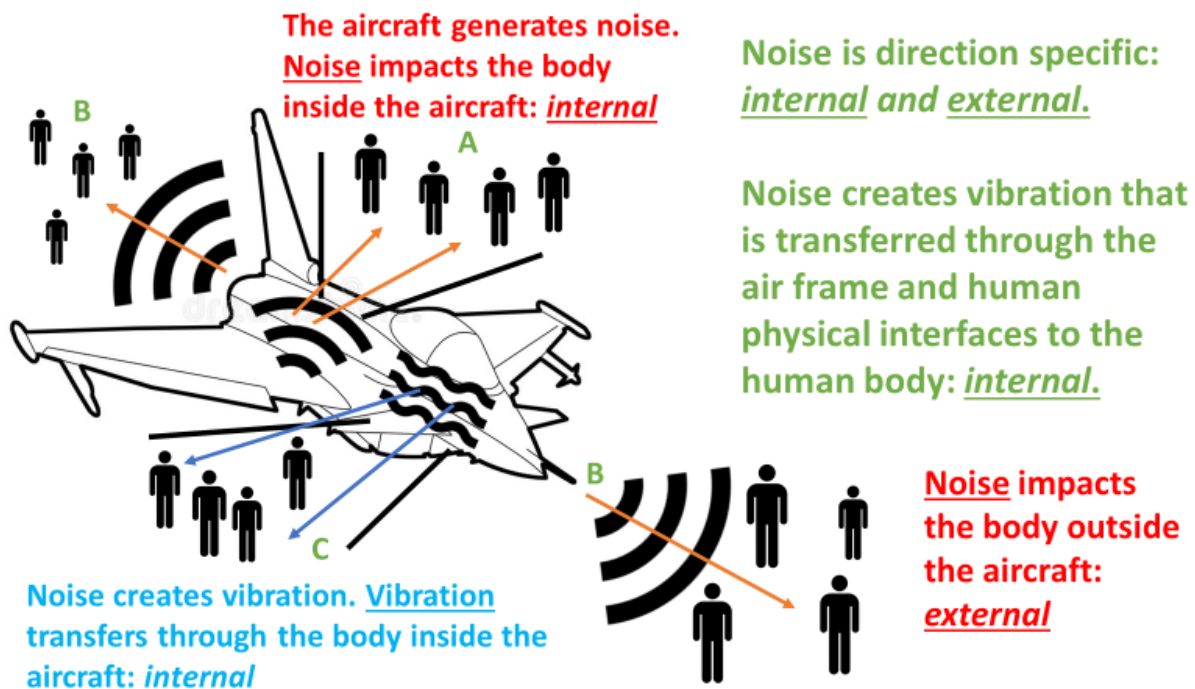


Figure 1. Internal and external noise impacts.

To understand and model the effect of noise and vibration, we must investigate how energy resulting in noise and vibration is transferred from the aircraft structure to the

seat, from the seat to the body and directly from the aircraft structure to the body. Subsequently, we must determine the pathways for transferring noise and vibration through the female body, including tissue, bones, muscles, etc., to the fetus. Also, we have to determine the frequencies of noise and vibration that are likely to reach and be transferred through the body to understand the effect on the pregnant female and the fetus. This effect can be explored using experimental or numerical methods.

Figure 2 shows the schematics of noise and noise-induced vibration between the aircraft, seat, and the body.

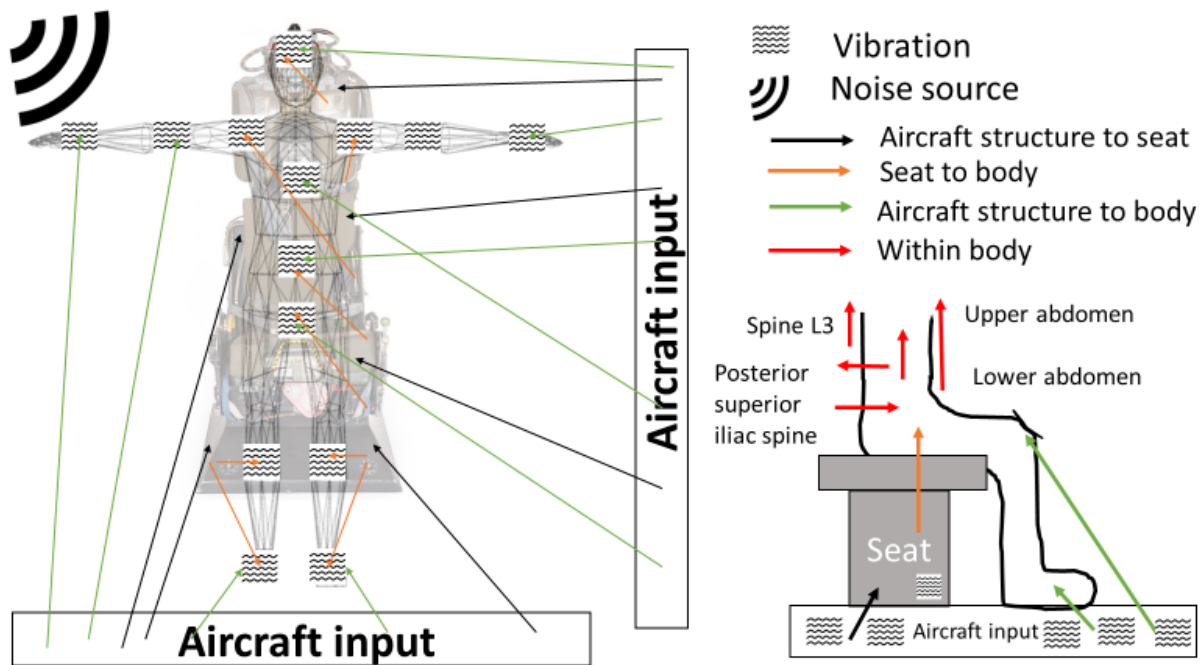


Figure 2. Noise and vibration effects on the body.

As human fetal experiments which might cause harm to the fetus cannot be performed due to ethical, practical, and safety reasons, experimental methods are primarily limited to animal models. However, none of the animal models can adequately represent the human fetal environment. Further, alternative physical models, such as anthropomorphic test devices, would be extremely expensive to construct due to the

need to model the fetal environment at various developmental stages. Therefore, this literature review suggests that scientific effort should be directed towards the development of accurate, reliable, and reproducible numerical models which apply, for example, Finite Element methods. This report summarizes the theoretical knowledge on noise and vibration exposures, discussion on animal, anthropometric, and computer simulation models, as well as challenges associated with these modeling approaches and future directions.

[Keywords used and literature search strategies](#)

A detailed literature search was conducted on noise and vibration effects on pregnant Air Force aircrew. This search relied upon several databases including: SCOPUS, Defense Technical Information Center (DTIC), PubMed, Embase, University of Cincinnati Library, Open Access Theses and Dissertations (OATD), Elton B. Stephens Co (EBSCO) database, PQDT Open, DART Europe, Deutsche National Bibliothek, Brown University Library Digital Repository, Cornell University Library Theses and Dissertations, Harvard Library Theses and Dissertations, MIT libraries, Google Scholar, and military.com. These sources were searched for journal articles, reports, theses, dissertations, and other peer reviewed scientific evidence published between 1970 and 2020. References in publications were also analyzed and screened for relevant publications to be included into a Mendeley database. The following keywords and/or search terms were used to look for relevant publications: noise AND health effects AND pregnant aircrew AND vibration AND exposure to noise AND pregnant AND pilots AND modeling OR flying when pregnant OR fetus OR pregnancy OR pregnant jet pilot(s) OR whole body vibration OR computational simulations OR pregnant uterus OR physical models of uterus OR pregnant abdomen OR animal models OR high frequency exposure OR low frequency exposure. Initially, over 1000 publications were found but after careful consideration, 638 documents were selected for inclusion into the Mendeley database. After review, a total of 95 publications were included in the final report, 102 publications were reviewed in the report table and 57 included into the

journal review paper. The criteria for publications to be reviewed and included into the review table, final report and/or review journal paper were: 1) it should directly address noise and vibration effects onto pregnant pilots, 2) it should address noise and vibration effects on the human or animal model fetus and 3) discuss the potential health outcome. The Mendeley database contains additional literature examples containing theoretical considerations, practical implications, and other information that will be important in any subsequent experimental and numerical simulation studies dealing with noise and vibration effects on health in military personnel.

Background

Noise and Vibration

Sound is a pressure wave that makes air vibrate such that it can stimulate the cochlea within the ear to produce neural impulses. Sound can be characterized by frequency, measured in Hertz and amplitude, measured in Decibels. Noise is unwanted sound that may induce adverse health effects in the adult human ear if it exceeds a time-weighted average (TWA) of 85 A-weighted deciBels (dBA) over 8 hours (1) or exceeds an impulse level of 140 dB. The A-weighting curve accounts for differential frequency sensitivity in human hearing. In broad terms, this scale adjusts the unweighted frequency spectrum of the noise or sound to account for the fact that the adult human ear is sensitive to sound between about 20 and 20,000 Hz and more sensitive to sounds with frequencies between about 200 and 20,000 Hz than frequencies between 20 and 200 Hz. Sound with an amplitude capable of producing greater than 85 dBA may significantly affect hearing or even induce permanent damage inside the inner ear. The vibration creating sounds are usually divided into two groups based on frequency. While higher frequency vibrations up to 20,000 Hz produce sound waves that can be heard by humans, lower frequency vibrations may not be heard but can induce stress in humans. Further low frequency vibrations transferred to the human body through the air or through mechanical coupling to a vibrating surface can induce vibration in a person's whole body or to specific body segments, i.e., arms, hands, or legs, and can impede

human physical performance and potentially cause injury to the structure of the human body.

Air that passes through an aircraft turbine produces friction and a turbulent flow, which causes sound waves and are described by pressure and flow velocity. The intensity of sound depends on many parameters, such as aircraft speed, engine modifications, aircraft type, etc. A person touching a vibrating surface experiences a localized hand-arm segmental vibration, which can be felt inside or outside the aircraft or a building, whereas person submerged into the vibrating environment, e.g., on a vibrating seat or inside an aircraft cabin during takeoff, flight and landing, experiences the whole-body vibration, which can be experienced inside the aircraft or a building. It is generally accepted that excessive noise and vibration are associated with long term hearing loss and other physical injuries in the military and the Air Force in particular.

Various aircraft generate noise during ground operations, take-off, flight, and landing (2). When researching noise generated by aircraft, it is important to either calculate or estimate how much noise “energy” reaches personnel located on the ground or inside the aircraft from the aircraft to induce measurable vibrations in humans to cause adverse health effects (3). Low frequency waves are much longer in comparison to high frequency waves. Therefore, they can travel farther, i.e., low frequency waves are not attenuated by air, can circumvent physical barriers, and do not lose energy as quickly as high frequencies. Low frequencies (< 200 Hz) and infrasound (< 20 Hz), usually produced by the engine on the ground, taking-off and during landing cause non-auditory undesired health effects such as cell damage, sleep disturbance, changes in blood pressure, nausea, fatigue, cardiovascular issues and thickening of the soft tissue (4). Also, it has been reported that the turbulent boundary layer between the hull of the aircraft and the surrounding environment is the primary contributor to excessive noise in aircraft during cruising (5).

Noise-induced vibrations are caused by the aircraft itself, including rotating fans, blades and vanes within the engines and surfaces such as flaps which induce air turbulence. According to Sadeghian and Bandpy (2020), the turbulence produced at the engine exhaust produces high frequency noise, whereas turbulence within the exhaust stream

distant from the engine nozzle, referred to as the lower exhaust, produces low frequency noise (6). Vibration can also be generated by runway characteristics and materials, wheel structure and imbalance, atmospheric conditions, unsteady aerodynamic flow, boundary layer noise and other parameters (7).

Aircraft noise and sonic boom characteristics

To effectively model noise exposures to aircrew inside and outside the aircraft, one needs to understand what processes and mechanisms govern sound wave distribution at noise sources.

Sources of aircraft noise

Subsonic noise

Turbofan, turbojet, and jet engines produce significant amounts of mixed frequency sound with low frequencies being predominant. Jet engines contribute the highest intensities that may be detrimental to the on-ground personnel and aircrew (8). In jet engines, the main source of noise is coming from the exhaust stream where turbomachinery, compressor, and blades produce the highest intensity noises (9,10). To calculate noise that is coming out of these engines, one needs to consider exhaust flow properties such as mass flow, temperature, pressure, velocity, and Mach number (11). In rotorcraft, noise is primarily generated by the rotors themselves as they generate vortices within the surrounding air (12).

Sonic booms

During supersonic flight, shock waves are generated from the front of an aircraft. When an aircraft reaches supersonic conditions, a pressure wave moves along the path of an aircraft that is called sonic boom (13). Flying aircraft at supersonic speed transmits

energy to the air as shockwaves, which can be heard and felt far away from the source (14).

Aircraft noise propagation

The pathway of aircraft noise depends on many factors such as the distance, atmospheric attenuation due to wind and humidity, temperature, and landscape (e.g. mountains, forests, tall-rise buildings) (15).

Atmospheric factors significantly affect noise propagation (16) and should be considered when modeling potential noise exposures (17). Also, it has been reported that water vapor in air absorbs high frequency noise (18,19). Temperature also affects aircraft noise propagation (20). When air temperature decreases with increasing altitude, the aircraft noise is directed upwards, therefore loud noises are not heard on the ground (13). On the contrary, when the temperature increases going up into the atmosphere, aircraft noise is directed downwards, thus producing high noise exposures on the ground (21). In addition to air, surface absorption and deflection may significantly alter the noise pathway. Thus these factors should also be taken into consideration during modeling efforts.

Noise and Vibration measurements

Sound waves are pressure waves that travel through air into the ear or towards a microphone and cause elements within these sensors to vibrate. This vibration is then converted to electrical signals, permitting the actual sound to be detected or heard. It is important to understand that sound power causes sound pressure, i.e., the source vibrates to produce sound power, which results in sound pressure in the air. Vibration can be comprised of a single frequency (e.g., a tuning fork) or multi-frequency (e.g., aircraft seat and body system) vibrations. Also, sound intensity is usually used to quantify the sound power per certain unit of an area and may be used in computer

simulations and modeling to define the level and vector as well as development of noise maps for target applications. Every aircraft produces noise that covers a wide range of frequencies and is measured in full or 1/3rd octave bands. An octave band is defined as a range of frequencies where the highest frequency is two-fold higher than the lowest frequency in the band. To calculate the noise level from aircraft or machinery, one needs to add the sound levels from each octave band.

On the other hand, vibration is quantified using an accelerometer that measures dynamic and steady state acceleration forces, e.g. the movement of a target object or structure.

Sound pressure and intensity: Sound pressure is often measured in pascal (Pa). The intensity of a sound wave can be defined in terms of the change in atmospheric pressure induced by the sound. Sound pressure level (SPL) is the change or oscillation in pressure induced in air as the sound wave passes through the air and is usually measured in decibels (dB). SPL is usually measured with a sound pressure level meter, where sound comes into the meter through an opening where a microphone is positioned and the output signal is shown in decibels. Sound pressure depends on the distance from the sound source, environmental characteristics, such as the size of the space, absorptive capacity of all the surfaces, volume of the space and other physical parameters. The close to zero values of the SPL scale represents the lowest level sound that an average person can hear [about 20 micro-Newtons per square meter ($\mu\text{N m}^{-2}$)]. On the contrary, ≥ 120 dB on the scale is where the sound exposure is high enough in amplitude to induce pain in the ear and may cause immediate adverse health effects.

The combination of noise levels produced by two similar jets is typically only 3 dB higher than the sound produced by these jets separately (21). Furthermore, when one jet produces significantly higher noise level than another jet, the combined effect will be insignificantly higher than the noise produced by the louder jet.

The noise has another unique characteristic, which is called a pitch. Pitch is a dissemination of sound pressure as a function of frequency. Importantly, human

perception of noise depends on frequency with pitch increasing as the frequency of the sound increases from 20 Hz to 20 kHz.

Noise and Vibration health effects

High sound pressure (amplitude) may induce hearing damage or permanent loss through damaging cochlea hair cells (22). For example, extended exposure to 100-125 dB sounds (e.g., thunder, military jets, gunfire, rock concert) may cause direct damage to the structure in the ear, leading to long term hearing loss (23). High frequency sounds (> 2000 Hz) may induce temporary or permanent hearing threshold shifts and cause general annoyance whereas low frequency sounds (< 200 Hz) can induce various adverse cardiovascular effects, cell damage, lack of concentration, headaches, blood pressure, tissue damage and other non-auditory effects (24).

While we refer to waves traveling through air which are induced by vibration as noise, vibration, especially low frequency vibration can also travel through the structure of the aircraft and impact members of the aircrew. This vibration can be measured using accelerometers which are attached to vibrating parts of the aircraft structure.

Vibration enters the body through a point-of-contact, for example hand-arm segmental vibration can occur when an individual places their hand onto a vibrating surface. Vibration can also impact the entire body as whole-body vibration when an individual is standing or sitting on a vibrating surface. Similar to sound, vibration health effects depend on the duration, intensity, and frequency of vibration. Whole-body vibration is reported to have adverse physiological effects such as discomfort and pain on the human body (25). For example, horizontal vibration at frequencies < 1 Hz may induce motion sickness, which is characterized by different symptoms than motion sickness experienced at higher frequencies. Of course, the severity of these effects depends highly on the age and gender of the person, duration of exposure and activity type, among others (26). On the other hand, the effect of vibrations > 80 Hz depends highly on position and the area where vibration occurs and dampening by external factors

such as clothing. To adequately determine the effect of vibration on the human body, it is important to know the resonance frequencies of certain anatomical features. For instance, the natural baseline frequency of the lumbar spine is between 1 and 6 Hz, usually considered at 3.5 Hz (27,28). Also, it has been determined that the resonance oscillation of the eyeball is governed by the solution that fills the eyeball, with the resonant frequency of the eye to be 18 Hz (29,30). Furthermore, it is important to point out, especially for the subsequent computer simulations to determine the effect of noise and vibration on the pregnant human body, that the resonant frequency of the skull ranges from 300 to 400 Hz and the fusion frequency of extra-ocular muscles is around 350 Hz (31). Also, the resonance frequencies of the head (axial mode) is from 20 to 30 Hz, shoulder girdle from 4 to 5 Hz, lower arm is from 16 to 30 Hz, spinal column (axial mode) is 10 to 12 Hz, chest wall is from 50 to 100 Hz, arm is from 5 to 10 Hz, hand is from 30 to 50 Hz, abdominal mass is from 4 to 8 Hz and legs from about 2 Hz (bent knees) to 20 Hz standing (32).

Policies on pregnant aircrew - are they allowed to fly?

Before 1993, all aircrew were removed from duty when pregnant and would need to ask for a medical waiver to remain on duty between 1 and 34 weeks of pregnancy. Also, pilots from dual-seat non-ejection aircraft would have to apply for a medical waiver between the 13th and 24th week of pregnancy if they wanted to continue their flying duties. In 1993, the United States Armed Forces began permitting women to serve in combat roles. In 2019, The Air Force updated its policies governing the flight duties of pregnant aircrew. Currently, remotely piloted aircrew, missile duty crews and pilots are permitted to do their jobs while pregnant, without asking for the medical waiver (33). In addition, pregnant aircrew can fly from 12 to 28 weeks of pregnancy without asking for the medical waiver. However, flying in the first trimester of pregnancy and deployment overseas to fly ejection-seat aircraft is still prohibited (34).

Fetal hearing and risks

During the 20th through 24th week of gestation, the fetal peripheral auditory system develops enough for the fetus to detect and distinguish sounds (36). Therefore, during the last 15 weeks, fetal exposures to high and low frequency sounds may have a significant and sometimes negative effect on fetal behavior and central nervous system development (37).

Figure 3 shows a diagram of vibrations during bone and soft tissue conduction.

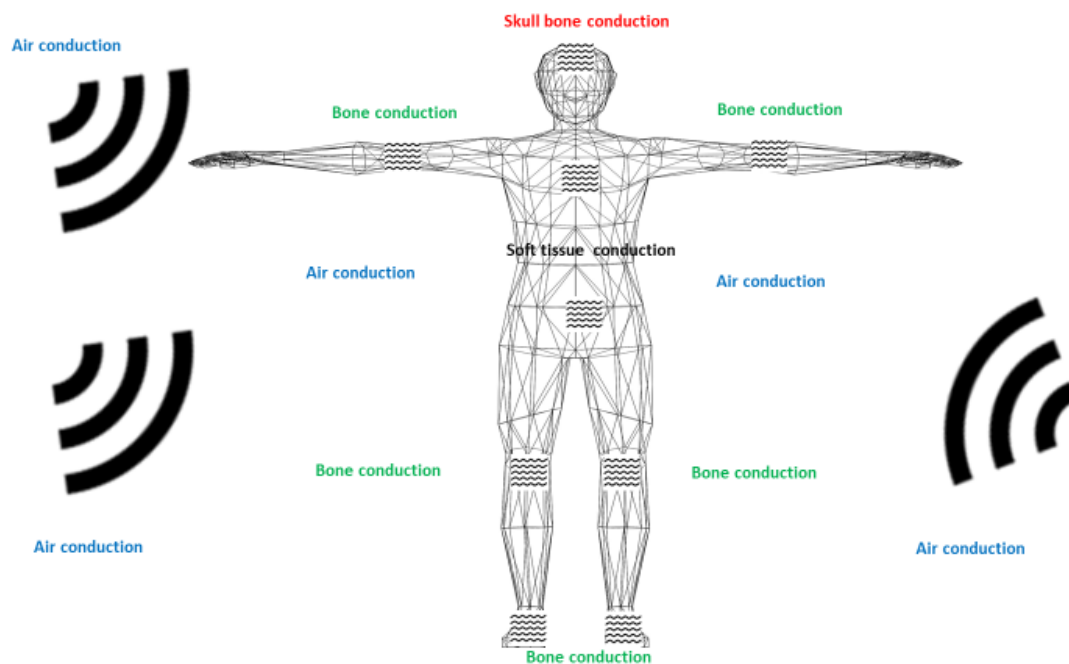


Figure 3. Soft tissue and bone conduction according to (38).

During sound exposure, external sounds move through the maternal abdominal wall into the uterus through the amniotic fluid towards the fetal ear. The cochlea reacts to

vibration from the amniotic fluid at the ear drum as well as vibration transferred from fluid contacting the skull. Anywhere the fetal body contacts the uterine wall, vibration can also transfer through tissue and bone conduction rather than via the eardrum. Importantly, high-frequency noises are attenuated by the maternal body (amniotic fluid, uterine environment), whereas low-frequency noises penetrate tissues successfully (39). According to Thurston (2008), the maternal body has a capacity to attenuate external noises up to 10 dB at frequencies < 1.0 kHz and about 20 to 30 dB at frequencies > 1.0 kHz (40). It has been reported that the resistance to noise transport across the tissues and fluids depends on frequencies, thus actual noise that reach the fetal ear may be of different intensity and carry different effects than original sounds (41). Unfortunately, there is no clear agreement of the prioritization of pathways for the external sound that reaches the fetal ear. For instance, there is no clear evidence whether the sound which reaches the fetal inner ear via soft tissue or bone conduction contributes more to the cochlear hair cell reactions when the mother is exposed to loud external noises. Also, none of the studies provide any scientific evidence on the risk to noise exposures through different conduction routes at different stages of pregnancy. Despite the fact that fetal hearing is not fully developed by the 20th week of pregnancy, there may still be adverse effects of extreme external noises observed on the development of fetal hearing in earlier weeks of pregnancy (42,43). The scientific reasoning behind these statements are the following. The otocyst embryonic stem cells produce hair cell-like cells that may react to loud sounds (44). Indeed, when exposed to loud noises for some time, mammalian cochlear outer hair cells shrink in size, proving that there are cellular changes in the presence of loud external noises (45). If fetal cells react in a somewhat similar way to external noises, especially before the formation of the hearing system, the ability of the fetus to hear may be affected by external noises and therefore scientific evidence is required to support this hypothesis.

Internal and external sounds to fetus

Inside the pregnant abdomen, the fetus is continuously exposed to cardiovascular, respiratory, and intestinal sounds, which are considered “background noise” (low frequency noise < 0.1 kHz with an intensity of less than 90 dB). These background noises are always complemented by additional external noises such as mother’s speech, body sounds, and movements (36). Importantly, vibrations from outside the maternal body (hand-arm or whole-body vibrations) can induce sounds inside the pregnant abdomen. Important parameters to consider when assessing the vibration induced sounds inside the uterus are the static and dynamic forces of the vibrating source and the distance from the source to the fetus.

Key frequencies in the uterine environment

High frequency sounds (> 0.5 kHz) are attenuated by the uterine environment and are almost inaudible to the fetus, whereas low frequency sounds at about 300 Hz reach the fetus and may induce undesired changes in development and health. For instance, frequencies above 300 Hz and up to 4 kHz are attenuated by ~ 20 dB at a rate of 6 dB/octave (46). Furthermore, exterior sounds of up to 70 dB with a frequency of 200 Hz travel through tissues, the uterine wall, and membranes to the fetus with a low attenuation of around 5 dB (47). According to Gerhardt and Abrams (2000), sound pressures at low frequencies inside the pregnant abdomen are enhanced by the characteristics of the uterine environment and can be significantly higher than outside the pregnant abdomen (46).

Animal modeling: pregnant ewe studies

Animal models are important to strengthen our understanding of the mechanisms that may occur during pregnancies that are associated with health, development, exposures, and risks (Andersen et al., 2018). There is a great number of available animal models that are used to research various diseases or the effects of stressors such as noise and vibration to fetuses. Unfortunately, many animal models do not result in reproducible

results, therefore minimizing their use in *in vivo* tests (48). Despite the fact that no animal study truly mimics human pregnancies, sheep and pig models are used to research potential interactions between the mother and the fetus in the presence of various stressors (49,50). Challenges in using animals for these models include the inability to place instruments such as catheters, microphones, and other equipment to collect information on responses to stressors without anesthetics (51).

Even with these challenges, sheep are widely used for noise exposure research, because sound attenuation characteristics in sheep abdomens are remarkably like those of humans (52). In addition, sheep have precocial hearing similar to humans and sheep hearing is only slightly worse than humans for frequencies greater than 8.0 kHz (46).

The first models that used pregnant sheep to evaluate potential effects of noise exposure and risks to fetus were developed in the 1980s (53). For instance, results showed that during sheep exposure to extreme noises, there were high rates of glucose use noticed across the fetal hearing pathway (54,55) indicating that there may be a comparable approach to assess risks to stressors without the need to use humans.

However, the question remains, whether fetus exposure to noise is uniform, or the distance and the direction of the noise source compared to the fetal head position affects the sound pressure and fetal responses. To answer this question, Gerhardt and Abrams (56) took pregnant ewes between 130- and 136-days of gestation and placed a hydrophone close to the ear of the fetal lambs. Catheters were positioned in the fetal brachiocephalic artery and in the maternal iliac artery. The ewes were placed in a sound field. The sound pressure detected in air at 2 inches was 103 dB. Ewes were sacrificed five to eight days after surgery. Noise exposure mapping of the pregnant abdomen was done using an electronic artificial larynx. During experiments, the electronic larynx was pushed all over the pregnant abdomen looking for spots that generated the highest internal sound pressures.

It was found that sound levels produced by the larynx varied with the distance from the hydrophone. When the larynx was positioned directly over the hydrophone, the average sound pressure was 134.9 dB, whereas it dropped to 114.3 dB and 101.4 dB at 3 and 6

inches from the hydrophone, respectively. Authors argued that this drop in sound pressure may be attributed to the attenuation of sound due to absorption by the tissues and fluids inside the body. This was confirmed by the work of Gerhardt and coworkers (1990), where they concluded that varying sound pressure levels were due to the attenuative capacity of amniotic fluid. The study placed a hydrophone into the amnion of a pregnant ewe and exposed them to various frequency high level sounds. It was observed that the closer the hydrophone was to the sound source and the outer surface of the abdomen, the smaller transmission loss was observed. Also, previous experiments with pregnant ewes and noise exposures showed that internal noise was almost only low frequency, whereas energy above 0.5 kHz was effectively attenuated by 40 to 50 dB (52).

In another study, fetal sheep were used to assess the effect of noise exposure on physiological responses. Two groups of ten fetuses at 115 and 125 days of pregnancy were subjected to extreme noise and their electrocortical activity, heart rate and evoked potentials were analyzed (36). Results showed that there were 7.3 dB less sound detected in uterus than in air. Also, there were frequencies of 315 Hz and 160 Hz measured in air and uterus, respectively, detected from 1/3rd octave bands. High frequency sound pressures were attenuated by soft tissues and amniotic fluid of the ewe by 25 dB. Furthermore, results from another study determined that exposure to extreme noise had a capacity to affect the auditory brain stem response and significantly damage cochlea hair cells (58). In addition, 32 seconds of extreme noise induced changes in fetal electrocortical activity and altered heart rate patterns (Bauer et al., 1997).

Unfortunately, despite worrying results, there is no strong evidence suggesting that human fetuses exhibit the same susceptibility to noise as sheep, or that human fetuses are at risk to inner ear damage by extreme noises to which pregnant women might be exposed in everyday life.

Noise and Vibration energy transfer to human body: seated versus standing position

Most studies investigating vibration effects on human bodies choose to study the sitting body and its biodynamic response to vertical vibration and only a few studies report results on biodynamic responses to horizontal vibration (59). Also, for reliable results, it is important to consider the seated body posture and seat characteristics such as height, hand positions, backrest, and seat pan angle to get a reliable response to vertical whole-body vibrations in all the calculations (59).

To evaluate noise and vibration exposures (especially at low frequencies in 0.5 to 20 Hz range), one must determine body, particularly the pregnant abdomen's, biodynamic responses to vibration. It is important to note that each organ in the human body has its own background frequency and resonance induced by the whole-body vibration which may cause adverse health effects (60). Biodynamic responses can be performed through quantification of acceleration and power of vibration absorbed by a seated or standing body exposed to whole-body and/or hand-arm vibration through measurements of body-seat and body-aircraft interactions (61). Also, the power of vibration absorbed may also be obtained from calculating power absorption density, stress, and the strain rates within the tissues.

Measurements of Noise and Vibration transfers to body

Sound transmission (SPL) into the fetus and uterine environment is measured in humans and animals using an underwater microphone, i.e., hydrophone, that is placed on the fetus head for animal models, inside the cervix for human models or inside the intact uterus for other animal models (46).

Accelerometers are used to detect vibration energy, which is recorded in decibels or Gs. Furthermore, noise and vibration exposure levels are measured using dosimeters and human vibration data loggers (60).

Noise and Vibration pathway to the fetus

Soft tissue conduction

Soft tissue conduction is a type of skin and soft tissue stimulation by sound or vibration. These vibrations are travelling through soft tissue into the ear (38). It is hypothesized that sound travels from the sound source into the mother's abdomen, transfers through the amniotic fluid and membranes to reach the eardrum and the inner ear of the fetus (42). The sound may damage fetal hearing through destroying inner and outer hair cells inside the cochlea (62). Another hypothesis is that the sound is conducted from the air to soft tissue and bone conduction routes, especially when the fetus is > 20th week. First, sound is transferred to the mother's body by air from the sound source. Then it migrates through the abdominal wall, uterus, and finally through amniotic fluid where it reaches the fetal head via soft tissue conduction routes. Then, bone conduction takes place when the sound moves through cartilaginous fetal skull bones. Subsequently, soft tissue conduction takes place again stimulating the structures of the inner ear, permitting the sound to be detected (63).

Bone conduction

Bone conduction takes place when the sound provokes skull bone vibration and is subsequently transmitted to the temporal-petrous bone, which leads to the vibrations of the inner, middle, and outer ear walls (64). This, in turn, causes several mechanisms of bone conduction such as inner ear fluid inertia, compression of the bone, ossicular chain inertia and the occlusion effect (38). Importantly, all these mechanisms induce pressure differences across the basilar membrane, which results in a passive traveling wave, which is governed by the same laws as air conduction (65). Some scholars argue that external sounds predominantly reach the fetus by the bone conduction mechanism, which has been substantiated by animal experiments (36,66).

Soft tissue or Bone conduction?

It is also important to determine what sound conduction pathways are predominant to conduct sound to the fetus in pregnant adult females to accurately research the noise exposures to the fetus. There is a possibility that the soft tissue vibrations make the fetus “hear” by inducing actual vibrations of skull bone (i.e., bone conduction-related mechanisms) (38). However, there is a large difference between the target acoustic impedances: bone ($7.8 \times 10^6 \text{ kg/m}^2\text{sec}$); water and gel ($1.5 \times 10^6 \text{ kg/m}^2\text{sec}$); typical soft tissues ($1.6 \times 10^6 \text{ kg/m}^2\text{sec}$); air ($0.0004 \times 10^6 \text{ kg/m}^2\text{sec}$) (67). It is reported that when there is a large acoustic impedance difference between two medias, for example air and skull bone, sound is not transferred but reflected at the boundary between these two media (38). For instance, for the two medias comprising air and skull sound intensity from surrounding air is attenuated by approximately 70 dB at the bone interface. Thus sounds with an intensity of less than 70dB will not induce bone conduction directly and sound is not anticipated to be transferred by a bone conduction. Instead this sound will be reflected and remain airborne.

Computer modeling for Noise and Vibration energy transfer

Finite element analyses/Multiphysics

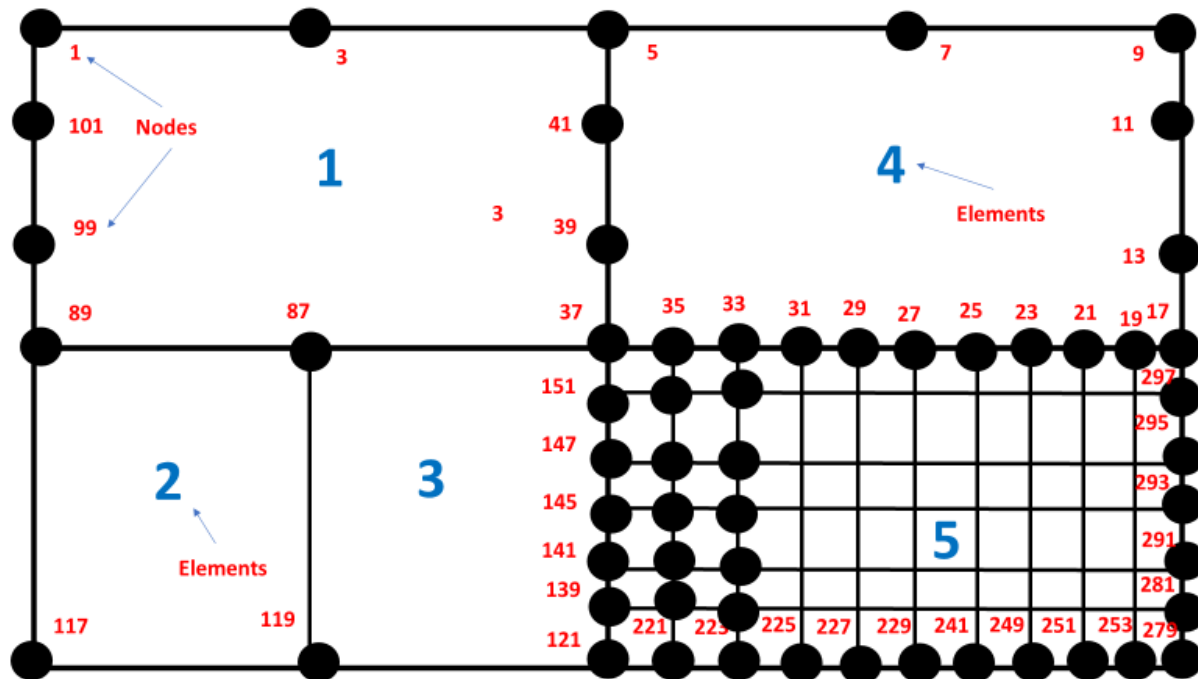
In addition to animal models, numerical modeling is warranted to predict, understand, and design preventative measures to noise induced hazards to the female body and fetus.

Most problems in physics and other quantitative sciences can be expressed and quantified using differential or partial differential equations (PDEs). These equations have a capacity to describe natural phenomena and solve engineering problems encountered in a target field. For example, they can be used to determine the structural behavior of buildings under stress, evaluate the heat capacities of a given object, flows,

wave propagation, vibrations, etc. However, when solving PDEs, one needs to provide initial conditions as well as to determine the boundary conditions. Some examples of PDEs are the Poisson equation, wave equation, and Fourier law. In general, PDEs provide a framework to solve many physical theories such as elasticity, quantum mechanics and hydrodynamics

To numerically solve the PDEs, one may use so called “Finite element” methods (Finite element analyses, or FEA) utilizing relevant equations such as Maxwell, Laplace, Yang-Mills, Euler, Navier-Stokes or others. Thus, a simplified FEA is a method used to forecast how a system (e.g., uterine environment, human head, human body) behaves under certain conditions and in the presence of stressors. Basically, FEA looks for the “weak” and problematic spots in the “design” of the system to provide necessary optimizations. To solve the PDE, it is necessary to develop a mesh (1D, 2D or 3D representation of the object, like a uterus), find the most applicable and relevant solver/equation (e.g., Navier-Stokes) and identify boundary conditions that would connect that solver (or equation) with a particular area in the object. Importantly, this object is comprised of small parts called “finite elements”. The outcome is usually a 2D or 3D solid model of the “system” (body, uterus, abdomen), for example showing the amplitude of the acoustic wave distribution or vibration over the uterus at certain conditions. Other examples include a model of a pregnant abdomen under acoustic pressure, noise and/or vibration pathways through amniotic fluid, or temperature changes at different heat inputs.

Figure 4 shows an example of a mesh. This is a plate-type component modeled with several mostly rectangular or triangular elements with a uniform thickness that could be ~ 2 mm.



Challenges in using FEA for human body simulations

To effectively and accurately model the pregnant body and fetus system, one needs to account for all the noise and vibration effects that reach the body from various external and internal sources. Also, one must include potential interactions between the organs and fetus as well as consider external surface contributions (e.g., seat to body interactions and/or aircraft to seat to body to fetus interactions). In addition, physiological and physicochemical factors should be taken into account when modeling, such as the age and position of the fetus and its head in the uterus, uterus geometries and mechanical properties of uterine walls and membranes, volume of amniotic fluid at certain periods of gestation and the interactions between the uterus, walls, fluid, membranes and the fetus. Also, sound and vibration pathways need to be identified considering sound attenuation and dissipation in the uterine environment.

Currently, several physical experimental approaches exist to study the biomechanics of human tissues. For example, biological tissues are used in animal and *in vitro* (cadaver) experiments (68). Unfortunately, animal experiments are not always effective, because animal tissue structure and functions are quite different from humans (69). Human cadaver tissues would be a good candidate for physical experiments as they have similar structure and characteristics of the living body, unfortunately, the cost is too high to account for numerous experimental variables and simultaneous effects of stressors (68). Some other experimental approaches include the detection of mechanical changes in human tissues under stress. Unfortunately, most of these models are not realistic and are unable to quantify tissue damage under imposed stress from external sources (68).

However, there may be a way to solve current challenges by coupling 3D imaging (mesh), finite element simulations and biomechanical multibody models. Recently, FEA combined with the Human Body Models (HBMs) have become increasingly popular to study passive and active safety systems (e.g., car and jet seat), interior car and jet designs, etc. Such combinations provide complementary information to conventional “dummy” models, when physical experimental limits are reached (70). However, these efforts are still at a very early stage of development and have to overcome multiple

challenges associated with accurate model development, complex human geometries, heterogeneity of the human body, tissue representation accounting for their anisotropic and viscoelastic characteristics (71), potential kinematics and interactions between the organs, bones and internal and external stressors and selectivity in terms of gender and size (68,72). As of today, there is a limited amount of FE-HBMs available, including PAM-CRASH, HUMOS1 and HUMOS2 and THUMS, which were mostly developed to investigate automotive crash injuries (72–75).

Challenges associated with human tissues

The effect of noise and vibration on biological tissues, especially at low-frequency exposures, is unclear. Despite the fact that the human body is a viscoelastic-composite material (acoustic coupling is not detected outside the human hearing range), it is usually modeled as Hooke elastic (76). However, according to Flynn and co-workers (2017), viscoelastic materials do not exhibit all the properties of Hookean elastic models. For example, they dissipate energy when under stress, exhibit hysteresis and creep (77).

Herein, some of the limitations associated with tissue representation in currently available FE models are presented:

Hard tissues

Bones can be modeled as viscoelastic materials (78). Data and FE models on bone behavior under stress is available (79). However, simplified FE models that require much less computational power and provide the same accuracy of prediction under stress (e.g., acoustic waves, ultrasound) is warranted. For example, a lumbar spine simplified FE model could be developed to study the effect of vibration and noise on the female body (80).

Soft tissue

Soft tissues are skin, muscles, blood vessels, fatty tissue, and cartilage. Also, internal organs such as kidneys, lungs, liver, and brain are classified as soft tissues (81,82).

Unfortunately, these are overly complex structures with complex biomechanical (non-linear, heterogeneous, anisotropic) properties (83). Therefore, the actual representation of soft tissues to be included in FE models is challenging.

Ligaments

Ligaments are defined as connective tissues that hold together bones and allow movements through joints (84). However, their accurate representation is challenging due to anisotropy (85).

Tendons

Tendons are collagen-structures that connect skeletal muscle directly to the bone (82). Parameters available in the literature that are essential for FE models include: the effect of strain rate on tendon response (86), specimen holder (87,88) and pre-conditioning (89).

Other computer modeling approaches

Currently, there are several computer-based approaches that may assist scientific efforts, especially FE models, to accurately quantify uncertainties and model noise and vibration exposures in pregnant aircrew, both on the ground and inside the aircraft.

FLULA2

Aircraft noise prediction methodology was developed at the Swiss Federal Laboratory for Materials Testing and Research (EMPA) in 1988 (90). FLULA2 is based on a library containing a large amount of data on power and energy requirements during takeoff and landing, noise-induced vibrations, etc., from various commercial and military aircraft and their flight trajectories at various distances from airports (91). Such a model could be

employed to predict the noise produced outside various aircraft under different environmental conditions.

MICRO-CAP II

It is hypothesized that mechanical vibrations may alter organ functions based on their location inside the body, duration of pregnancy and the type (horizontal vs. vertical) of vibration (92). For example, horizontal vibrations have a stronger effect on arms, head, torso, and spine, whereas vertical vibrations have a stronger effect on the thorax. Therefore, to investigate the effect of vibrations on human bodies, A linear spring-mass-damper model was developed using MICRO-CAP II. Although this modeling program was originally developed to support modeling of electrical circuits, this program permits modeling of amplitude as a function of frequency. This model provided estimates of low frequency vibration on various body parts which was consistent with measurements made using accelerometers placed on various body segments as it was induced from a seat or steering wheel within a motor vehicle. This approach might be coupled to FE modeling to investigate noise and vibration effects on pregnant aircrew especially at low frequencies by using this model to understand vibration induced on the uterus by the pelvic floor and diaphragm, then using the FEA to understand the transmission of this vibration through the amnionic fluid to the fetus.

Next-Generation Aircraft Noise Prediction Program (ANOPP2)

NASA's Advanced Air Vehicles Program (AAVP), Integrated Aviation Systems Program (IASP), and Transformative Aeronautics Concepts Program (TACP) developed the Aircraft Noise Prediction Program (ANOPP and ANOPP2) to analyze and predict aircraft generated noise levels by quantifying sound pressure levels (93). This model assists in determining the noise exposure to ground crews (94).

Data needs and Future directions

When reviewing the existing publications, it is clear that low frequency sound and vibration will be transmitted through a female crew member's body to a fetus and there is reason to believe that the sound may alter the hearing of the fetus. The literature which was reviewed provided little discussion of other health or wellness concerns associated with the effect of low frequency vibration. However, this topic deserves further research. Since, experimentation with humans or even animal models is not justifiable, it is important to leverage advances in modeling to further our understanding of the likely effects of sound and vibration upon the structures of the fetus.

Models can be constructed to various levels of fidelity, to answer different questions. The literature review revealed that there are several questions worth exploring. These include the following:

- 1) How are sounds of various frequencies transmitted or attenuated as they pass through the mother's abdomen to the fetus at various stages of gestation?
- 2) How is vibration of various frequencies transmitted from the seat, floor, and controls transmitted or attenuated as they pass from the aircraft through the mother's body to the fetus at various stages of gestation?
- 3) How are pressure waves in the amniotic fluid conducted to the inner ear of a fetus once the structure of the ear is formed?

It is important to understand that models such as these will likely permit the understanding of the types of sound or vibration that are most likely to affect the fetus, these models only provide information on the types of exposure which are most likely to result in risks to the fetus but are unlikely to reveal exposure limits or clear policy guidance regarding flight restrictions.

Currently, modeling of the structural, thermal, or acoustic response of the human body (e.g. pregnant abdomen, uterine environment, etc.) to various external and internal stresses is rather limited due to inaccurate and inefficient modeling approaches. While models such as the spring-damper model implemented in Micro-Cap II provides apparently robust estimates of acceleration of the abdomen from pathways through the pelvic floor and the diaphragm, it does not include any

modeling of the transmission of this signal through the amniotic fluid to the fetus itself.

A modeling approach which appears worth pursuing involves the combination of human body scans to understand differences in physical structure across humans at different stages of gestation with FE models which include different parameters for each type of material in these different body structures. Ideally, these computational models should include detailed human anatomy and physiology data not limited to tissues, ligaments, muscles, bones, and amniotic fluid. However, models which include all of these body structures are extremely difficult to achieve. For example, when slicing medical images, for example computer tomography (CT) scans, for application in mesh development, blood vessels, nerves and intestines may not be accurately segmented or even identified, thus reducing the accuracy of the model. Amniotic fluid is extremely important in evaluating noise and vibration exposures to address the questions we posed earlier. Unfortunately, amniotic fluid is not visible in medical images, therefore it will likely be difficult to segment it from certain surrounding structures. Another challenge is that some of the currently used anatomical human body models are developed using proprietary software that does not allow modifications, such as Semcad X (Switzerland).

FE models should be simple enough to satisfy the accuracy requirements but not to require extensive computational resources and complex modeling efforts. Therefore, platform independent COMSOL, ANSYS, Autodesk, NSC, SolidWorks methods should be a good starting point in researching noise and vibration exposures to humans. The highly warranted research must focus on the development of an accurate and simplified pregnant abdomen and uterus model first, followed by the whole body anatomical models to evaluate the effect of sound and vibration at various frequencies on the fetus to understand the frequencies which are most likely to be transmitted to the fetus and thus have harmful effects on the development and health of the fetus. Furthermore, the development of some sort of a library for uterine walls, membranes and amniotic fluid “deformation” during any period of pregnancy including the nearby organs such as bladder, intestines, stomach is necessary to account for fetus growth, position in the

uterus and fetal and maternal movements (fetal movement in the amniotic fluid, mother walking, sitting, breathing) throughout pregnancy (95).

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Appendix 1. Maternal Aircrew Fetal Noise and Vibration Exposure Risk Model – Aim 1 Literature overview

General information on exposures		
References	Subject Terms	Description / Implications / Findings
Alves-Pereira M, Rapley B, Bakker H, Summers R. Acoustics and Biological Structures. In: Intech [Internet]. IntechOpen; 2019. p. 13.	Low frequencies Biological effects of noise	This chapter provides information and experimental evidence on noise effects on health, to biological tissues at low frequencies. It is generally accepted that human body is a viscoelastic material that can be modeled as Hooke elastic. It is important for the subsequent Multiphysics simulations where accurate human biomechanical models will be created. Hooke elastic means acoustical coupling at frequencies outside the human range do not exist and are not taken into modeling consideration. According to authors, there are numerous challenges associated with acoustic stimulus and penetration through tissues. For example, when tissue samples are assessed for mechanical properties, acoustic stimulation is not regarded as pressure waves in air. Also, response of biological tissue to acoustic stimulus such as noise highly depends on frequency, amplitude, time and the accuracy and reliability of assessment methods and approaches. Authors provide good background information

		and theoretical background on viscoelastic properties of biological tissues, present challenges, and ways to overcome these challenges when biological tissues are exposed to low frequency sounds.
Pierson LL. Hazards of noise exposure on fetal hearing. Semin Perinatol. 1996;20(1):21–9.	Loud noises Animal studies Noise exposure mechanism	It is important to know how the noise exposure affects the development and/or health of the fetus and when during gestation it happens. Author argues that due to the uterine environment (amniotic fluid, position of the fetus during gestation, external and internal noises etc.) and the development of the ear at about 22-24 th week, it is possible that noise effects to the fetus are different in comparison to those of mothers. For instance, there were some early evidence collected during animal (sheep) studies, indicating that changes in hearing and/or maybe even loss of hearing is possible when fetus is exposed to loud noises.
Van Dyke P. A Literature Review of Air Medical Work Hazards and Pregnancy. Air Med J. 2010 Jan;29(1):40–7.	Female flight nurses Miscarriages Noise and vibration exposures Modeling	This literature review presents good information on miscarriages among female flight nurses and paramedics at one air medical transport company in 2008. Risks of premature birth or losing baby were discussed in terms of exposures to vibration, jet fuel, noise, and other stressors. According to the review, modeling showed that pregnant women exposed to whole body vibration experience greater spinal load than nonpregnant women. Authors recommend that subsequent studies of the air medical and non-medical community at large exposures to various stressors are highly warranted as there are not enough reliable sources of information on actual effects in addition to outcomes such as low birth weight and loss of hearing in newborns.

<u>Tompkins OS. Major Exposure Hazards for the Frequent Flyer Business Traveler [Internet]. University of North Carolina at Chapel Hill; 2003.</u>	Frequent flyer Noise and vibration exposures Physical, chemical, biological hazards	This Master thesis provides important information on various environmental exposures of frequent flyer business travelers. This information is valuable as some sort of a baseline when discussing potential exposures to noise and vibrations in pregnant aircrew. Data collected include biological, chemical, enviro-mechanical, and psychosocial hazards and associated risks as well as few recommendations for risk prevention.
<u>Passchier-Vermeer W, Passchier WF. Noise exposure and public health. Environ Health Perspect [Internet]. 2000;108(SUPPL. 1):123–31.</u>	Health effects and diseases No accurate noise exposure mechanism exists	Authors present good introductory information on potential risks associated with exposures to loud noises. They discuss potential health effects such as hearing impairment, heart diseases, sleep disturbances, physiological changes in immune system and potential birth defects, among others. Unfortunately, accurate mechanisms of noise exposure pathways were not known at that time and is not known now in 2020. Research is needed to determine the actual relationship between noise and cardiovascular disorders. Authors present good background information and theory on sound pressure levels and sound levels, sound exposure levels and exposure settings as well as present information relevant to direct and indirect noise induced health effects that are valuable in noise effect modeling studies.
<u>American Academy of Pediatrics. Noise: A hazard for the fetus and newborn. Committee on Environmental Health. Pediatrics. 1997;100(4):724–7.</u>	High intensity noises Pregnancy	It is reported that loud noises and especially high intensity noises have adverse effects on health (when considering both, auditory and non-auditory noise effects). According to regulations, “the standard for the workplace is no more than 8 hours of exposure to 90 dBA, 4 hours to 95 dBA, 2 hours to

	Decreased weight at birth Risks from 65 dBA to 140 dBA	100 dBA, with no exposure allowed to continuous noise above 115 dBA or impulse noise above 140 dBA". Authors report that cochlea and peripheral sensory end organs fully develop by 24 weeks of pregnancy. The hearing threshold at 27 - 29 weeks is about 40 dB. Furthermore, when exposed to loud noise (80 dB in 8-hour shift), the risk of premature birth significantly increased. Also, loud noise was associated with decreased birth weight, especially in the areas of 60 to 65 dB noise exposures.
Barba-Vasseur M, Bernard N, Pujol S, Sagot P, Riethmuller D, Thiriez G, et al. Does low to moderate environmental exposure to noise and air pollution influence preterm delivery in medium-sized cities? Int J Epidemiol. 2017 Dec 1;46(6):2017–27.	Premature birth rates Environmental stressors: noise and air pollution	Environmental stressors such as noise and air pollution highly affect the premature birth rates. It is important to note that multi-exposures may have a combined effect on the pregnancy duration. Authors researched the relationship between the premature births and multi-exposure rates to noise and air pollution in medium-sized cities in France with 121671 to 243936 inhabitants with 302 cases and 1204 controls. Exposures to noise and air pollution were monitored at female addresses. To evaluate relationship, conditional logistic regression models were implemented, and sensitivity analyses were performed. Authors found no significant correlation between the premature births and noise/air pollution.
Basner M, Brink M, Bristow A, De Kluizenaar Y, Finegold L, Hong J, et al. ICBEN review of research on the biological effects of noise 2011-2014. Vol. 17, Noise and Health. Medknow Publications; 2015. p. 57–82.	Biological effects of noise on health No pregnant women included	This is a review from the International Commission on Biological Effects of Noise (ICBEN), which analyzed a great number of available literature sources from 2011-2014 to assess the effect (biological) of noise on human health. They found that occupations and transport were the main sources of noise that may have detrimental effects on health. According to the review, noise is likely underestimated danger

		for auditory and non-auditory systems and preventative measures must be in place to avoid risks and hazards to human health.
Bauer, Herbig - 2019 - Occupational Stress in Helicopter Emergency Service Pilots From 4 European Countries	Noise exposure Helicopter pilots	This study discusses helicopter emergency medical services pilots' work conditions and its effect (e.g. noise exposures, etc.) on health. This study has been done in 2015-2016 by distributing cross-sectional questionnaire to 72 European pilots (mean age of 51.9) and examining stressors such as noise and how these stressors affected overall health and wellbeing. Study presents detailed answers to the questionnaire and data collected could be used to inform subsequent models that predict the effects of stressors onto the human body.
Bentur Y, Koren G. The three most common occupational exposures reported by pregnant women: An update. Am J Obstet Gynecol. 1991;165(2):429–37.	Knowledge gaps: occupational exposures and pregnancy	According to the study, there are numerous gaps in knowledge regarding occupational exposures and pregnancies. It may be attributed to extremely scarce pieces of information of the reproductive toxicological effects of stressors, lack of safety standards that are used to protect the unborn child and limitations in assessing the actual levels and determining pathways of exposures.
Beutel ME, Jünger C, Klein EM, Wild P, Lackner K, Blettner M, et al. Noise annoyance is associated with depression and anxiety in the general population- the contribution of aircraft noise. PLoS One. 2016 May 1;11(5).	Noise effect on general population in Germany	Noise is regarded as one of the important environmental stressors. Authors performed a cross-sectional study with 15010 participants aged 35 to 74 in Germany in 2007 to 2012. Noise sources from traffic, outdoors, aircrafts, railroads and industry were assessed separately during a day and night and graded on a 5-point scale from “not at all” to “extreme”. It was found that aircraft noise was the highest stressor affective almost 60% of people who participated in this study.

Brueck SE, Aristeguieta C, Ramsey J. Exposures of Helicopter Pilots and Gunners to Firearm Noise and Lead During Gunnery Target Training Exercises. 2014.	Noise effects Helicopter pilots and gunners	Authors collected time-weighted average (TWA) personal noise exposure measurements over 2 days on helicopter pilots and gunners. They measured exposures to noise from shooting and from helicopter flights during gunnery target training. In addition, vibration measurements were also performed. Authors found that noise exposures from helicopters and gun shooting significantly exceeded National Institute for Occupational Safety and Health exposure limits. Peak levels during shooting were higher than safe limits and were loud enough to damage the hearing. Interestingly, helicopter pilots reported fatigue and headaches from loud noises during shooting, whereas gunners did not report any adverse health effects during the shooting.
Dijk FJ. van. Epidemiological research on non-auditory effect of occupational noise exposure. Environ Int. 1990; 16:405–9.	Noise effect 80 to 85 dBA No clear evidence that noise affects pregnancies	Three longitudinal studies are reviewed here that discuss the effect of noise on pregnancies (80 dB(A), with 40% of the women exposed to 85 dB(A) or more). Only one study showed the negative effect of noise on birth weight. Also, there were no relationship found between noise exposure parameters and pregnancy duration, birth weight and other parameters.
Douglas, Janet B. A cross sectional study of the associations between health beliefs, hearing acuity and use of hearing protection in noisy work environments. 1989. Boston University	Noise exposure and self-perceived health effects	In this thesis, author performed cross-sectional study (192 out of 2016) to examine the relationships between the perceived loud noises the effects on health and self-reported comfort zone when hearing protection is being used in noisy environment such as power generation plant. Statistical treatment of data has been performed using paired t test comparisons. It was found that 12% of subjects told they were always wearing hearing protection and 7% never used it despite they had to. Stepwise multiple regression analysis

		was used to analyze the relationships among variables. “Findings were that perceived barriers, susceptibility, benefits and hearing acuity accounted for 26% of the variance of Peruse, and that perceived barriers, susceptibility and hearing acuity accounted for 16% of the variance of visual analogue scale (VAS)”.
Lee LJ. Maternal Workplace Emotional Stressors and Physical Activity and Adverse Birth Outcomes. The University of Texas; 2015.	Premature births Occupational exposures: noise included	In this thesis, author discusses the premature birth and the effects that causes it. Maternal occupations such as extremely loud environments and heavy lifting significantly contribute to premature births and/or loss of child. Questionnaires were distributed to U.S. Department of Labor’s Occupation Information Network (O*NET) where women self-reported their jobs and occupations. Factor analysis was used to find correlations between individual occupations.
Navy and Marine Corps Public Health Center. Reproductive and Developmental Hazards: a Guide for Occupational Health Professionals Reproductive and Developmental Hazards: a Guide for Occupational Health Professionals Reproductive and Developmental Hazards: a Guide for Occupational Health Professionals. 2010.	Reproductive hazards	This study evaluates reproductive and developmental (ReproDev) hazards in the workplace.
Ristovska G, Laszlo HE, Hansell AL. Reproductive outcomes associated with noise exposure - A systematic review of the literature. Int J Environ	Noise exposure Premature birth	Authors determined that loud noises during pregnancy are stressors that may potentially result in dysregulation of placentation, increased risks of premature birth and decreased uterine blood flow. Herein authors present evidence that reproductive outcomes are highly associated

Res Public Health. 2014 Aug 6;11(8):7931–52.	Lower weight at birth Epidemiological studies	with occupation and environmental noise exposure. This study has been done collecting information and literature sources from various databases from 1970 to 2014. Collected data shows somewhat positive correlations between occupational noise and low weight at birth (less than 2500 g) and/or premature births. Five epidemiological studies found significant correlation between the low birthweight and high noise exposures. However, there were several studies that did not show any positive or negative correlation between the noise exposures and birth weight.
Uran SL, Gómez-Casati ME, Guelman LR. Long-term recovery from hippocampal-related behavioral and biochemical abnormalities induced by noise exposure during brain development. Evaluation of auditory pathway integrity. Int J Dev Neurosci. 2014;37:41–51.	Noise exposure Reversible and irreversible damages 85 – 97 dB SPL	Loud noises may lead to reversible or irreversible damage of auditory and non-auditory systems. Authors reported that “noise-exposed developing rats elicited hippocampal-related histological, biochemical and behavioral changes”. Study was done with male wistar rats of 15 days that were exposed to moderate noise levels of 95-97 dB SPL for 2 hours a day for one day (acute noise exposure) and for 15 days (sub-acute noise exposures). The moderate acoustic overexposure suggested that auditory and extra-auditory tissues are at risk even in low level everyday acoustic environments.
Sittig SE, Nesbitt J, Krageschmidt DA, Sobczak SC, Johnson RV. Noise levels in a neonatal transport incubator in medically configured aircraft. Int J Pediatr Otorhinolaryngol. 2011;75(1):74–6.	Noise exposure Critically ill neonates Air transport	Authors assessed the effect of noise exposures to critically ill neonates during medical evacuations by air. Experiments were performed in specially designed incubators and noise levels were measured in incubators and cabins. It was found that incubator lessens noise exposures by ~6 dBA, unfortunately, the noise level in incubator was still above the safe recommended levels and was as high as 83 dBA in BK-117, followed by 82 dBA in Bell 222 and 80 dBA in Pilatus PC 12. On the contrary, the noise levels in the cabin was 90, 88

		and 86 dBA, respectively. Thus, it is recommended to perform more detailed studies on noise exposure to pregnant aircrew to assess the actual effect of noise to fetus.
McIntosh TK, Ritting AN, Saatman KE, Hoshino S, Russ AB. Concussive Effects of Low Frequency Sound Exposure. 19999.	Low frequency Underwater noise exposure Concussion Acoustic trauma Rats	In this 2-fold study, 96 male Sprague Dawley rats were put into water and subjected to various frequencies. Part 2 study was performed with 11 rats that were submerged into water and 11 rats that were no submerged into water and both groups subjected to the 150 Hz, 180 dB and 250 Hz and 194 dB noise. After the tests, all rats were sacrificed, and their cardiovascular and neurological characteristics were assessed. Rats subjected to 150 Hz underwater did not show any cognitive problems, whereas rats subjected to 250 Hz showed significant learning deficit. No histological harm was observed regardless the frequency.
Dalecki D. Response of Biological Tissues to Low Frequency Underwater Sound. 2002.	Low frequency Underwater Biological effects Mice	In this report, the author found that low frequency noise (~200 dB over 100 – 2500 Hz range) adversely affects tissues that have gas (e.g. lungs) underwater in mice. Study was performed with traveling waves, pure pressure and pure velocity waves. The outcome was recorded using an acoustic scattering technique. It was found that acoustic pressure is the main parameter to assess the damage of low frequency noise to lungs underwater.
Yu F, Xu X, Ren Z, Yang J, Kong F. Maternal high-decibel acoustic exposure elevates prenatal stress, impairing postnatal hearing thresholds associated with decreasing ribbon synapses in	High decibel exposure Pregnant rats Prenatal stress	Authors argue that high-decibel (65 to 95 dB) induced stress affect fetal hearing system significantly more than a direct noise exposure. During this study, authors exposed pregnant rats (Sprague-Dawley rats (275 ± 15 g), n = 60) to 2 hours/day loud (65 to 95 dB) music from 15 th day to delivery. The outcome was measured using auditory brainstem

young rats. Reprod Toxicol. 2019;89:21–7.		response. It was found that loud noise induced hearing loss in rats.
Meta and systematic analysis of noise effects on pregnancies and birth outcomes		
References	Subject Terms	Description / Implications / Findings
Selander J, Rylander L, Albin M, Rosenhall U, Lewné M, Gustavsson P. Full-time exposure to occupational noise during pregnancy was associated with reduced birth weight in a nationwide cohort study of Swedish women. Sci Total Environ. 2019 Feb 15;651:1137–43.	Occupational noise Premature birth and low weight at birth <75, 75-85 and >85 dB	To evaluate the effects of occupational noise on premature birth and low birth weight, a cohort of 857.010 single birth has been started (FENIX study). All information has been collected starting pregnancy week 10. Authors classified noise exposures into three main categories: <75, 75-85 and >85 dB. Odds ratios were adjusted for anthropometric and physico-chemical data like BMI, smoking, education, physical activity and job requirements and low job control. It was found that high levels of noise (>85 dBA) affected the weight of the child at birth if compared to <75 dBA. Unfortunately, there was no well-defined association between the premature birth and high levels of noise. Authors concluded that high levels of noise were mostly associated with slightly lower weight at birth but not with the premature birth. Intermediate noise (75 to 85 dBA) showed no statistical significance associated with low birth weight and/or premature births.
Gehring et al. - 2013 - Environmental exposure assessment in European birth cohorts results from the ENRIECO project	Noise, air, and water pollution	It is generally accepted that single birth cohort studies may not be sufficient to conclude that one stressor or another has statistical significance when compared between selected outcomes. Thus, combination of several studies would be

	37 European studies	beneficial. Numerous studies have been combined in ENRIECO (Environmental Health Risks in European Birth Cohorts) project focusing on noise and air pollution, water contamination, allergens, metals, pesticides, etc. occupational exposures. This project contains data on various exposures from 37 European birth cohort studies. Study has a highly informative table called “Description of exposure assessment in the birth cohorts by exposure topic Exposure” and contains information on Noise exposures and data collection methods. Also, Table 2 titled “Recommendations for methods, evaluations of collaboration with existing data, and areas of interest for future work including new data/new methods by exposure topic” provides information on noise propagation models and other information that is extremely helpful to inform noise exposure modeling efforts.
Lie A, Skogstad M, Johannessen HA, Tynes T, Mehlum IS, Nordby KC, et al. Occupational noise exposure and hearing: a systematic review. Int Arch Occup Environ Health. 2016 Apr 1;89(3):351–72.	Noise induced hearing loss Literature review	Authors present a systematic review of information and data available on noise-induced hearing loss in occupational environments. They collected over 22413 articles from MEDLINE, Web of Science, Scopus and other databases and selected 698 articles that were reviewed in detail and selected 187 articles that were relevant to this review aims and were included into this systematic review. It was reported that there are up to 21% of people that experience hearing loss in various occupations. Unfortunately, not many articles provided a clear distinction between the hearing loss due to exposures to extreme noises or hearing loss due to the old age. According to the review, there are numerous factors that affect hearing loss such as socioeconomic characteristics, genetics, and numerous other factors such as high index of air

		pollution, exposure to firearms and military aircrafts, smoking, diabetes, high blood pressure, simultaneous exposure to noise and vibration and acute or chronic exposure to chemical/biological substances in the work place. Authors concluded that some occupational groups that are at risk include military, construction crews and agricultural workers.
Hartikainen-Sorri AL, Sorri M, Anttonen HP, Tuimala R, Läärä E. Occupational noise exposure during pregnancy: a case control study [Internet]. Vol. 60, International Archives of Occupational and Environmental Health. 1988.	Occupational noise Pregnancies 81 dBA	Authors performed case-control study with 77.8% employed women (284 women with preterm deliveries, 299 women with low child weight at birth and controls. The whole study was performed with 1166 women in total) to analyze the effect of occupational noise exposure on pregnancies. Study found that only 3.5% women reported they were exposed to occupational noise more than 81 dB in 8 hours during their pregnancies. This study showed no correlation between the noise exposure and weights at birth or preterm births and was concluded that there is no association between the occupational exposures and health problems at birth in Finland.
Polańska K, Hanke W, Gromadzińska J, Ligocka D, Gulczyńska E, Sobala W, et al. Polish mother and child cohort study - Defining the problem, the aim of the study and methodological assumptions. Int J Occup Med Environ Health. 2009 Jan 1;22(4):383–91.	Stressors Pregnancy outcomes: health, morbidity, mortality	Prospective cohort study has been performed in Poland (REPRO_PL) with 1300 mother-child pairs in 2007-2011 to evaluate the various exposures to stressors during pregnancies. The outcomes selected were children health, morbidity, and mortality. Women were monitored and checked every trimester and notified study organizers of their pregnancy outcomes. During each check women were given questionnaires and biological samples were collected. One of the outcomes of this study was the relationship between the occupation and stress.

Dzhambov AM, Dimitrova DD, Dimitrakova ED. Noise exposure during pregnancy, birth outcomes and fetal development: meta-analyses using quality effects model. Folia Med (Plovdiv). 2014;56(3):204–14.	Noise exposures Fetal development >80 dB	This systematic review attempts to summarize information on the current state of the art relationship between occupational and residential noise and pregnancy outcomes and fetal development. Authors collected information on women exposed to high levels of noises throughout their pregnancies and study included 29 studies. It was found that noise exposures at > 80 dB during pregnancies have a higher risk for lower weight at birth, may experience gestational hypertension and have a child born with congenital malformations. However, there were no correlation with noise exposures and preeclampsia, premature birth, and perinatal births.
Sadoun E, Leventakou V, Casas M, Ahmed HF, Kogevinas M, Fthenou E. A birth cohort study in the Middle East: The Qatari birth cohort study (QBiC) phase i. BMC Public Health. 2017 Oct 23;17(1).	Stressors: noise, air pollution, radiation Pregnancy outcomes	This cohort study (The Qatari Birth Cohort) is designed to analyze the synergetic effects of environmental stressors such as air pollution, noise, radiation, social factors along with genetic factors and their outcomes on mother and child' health, stillbirth, gestational diabetes and hypertension. There were about 3000 families (15th week of pregnancy) included over 2 years (5 years follow up is scheduled) in this cohort. They were provided with questionnaires and submitted biological samples in each trimester. Authors conclude that this study provides invaluable information into the early life factors such as genetics, environmental and socioeconomic conditions that affect mother and child's health.
Zare Sakhvidi MJ, Zare Sakhvidi F, Mehrparvar AH, Foraster M, Dadvand P. Association between noise exposure and diabetes: A systematic review and meta-	Noise exposure Diabetes mellitus	This systematic study aims to evaluate relationship between the excessive occupational and transport noise exposures and diabetes mellitus. Authors performed the study following MOOSE guidelines and assessed literature sources and information using the Newcastle–Ottawa Scale. The study

analysis. Vol. 166, Environmental Research. Academic Press Inc.; 2018. p. 647–57.		indicates that random effects metanalysis was used to estimate the risks of diabetes with increasing noise. Heterogeneity was assessed using Cochran's Q test and quantified using 12 statistics. Sources of heterogeneity were analyzed using meta-regression analyses. Bias was assessed with funnel plots and Egger's test. Inclusion criteria was met by 15 studies that included 5 prospective cohorts, 2 cross-sectional and 2 case-control studies that included in total of 444460 adults and 17430 diabetes mellitus cases. There were 6% increase in diabetes mellitus cases with increasing noise exposures. Source analyses suggested strong associations for air traffic noise, followed by road traffic noise exposures. These findings are important in researching cumulative or synergistic effects of overall pregnant female health and pregnancy outcomes when exposed to excessive noises.
Kollock R, Games K, Wilson AE, Sefton JM. Effects of vehicle-ride exposure on cervical pathology: A meta-analysis. Ind Health. 2015;53(3):197–205.	Vehicle rides Cervical pathologies	This meta-analysis (1980 – 2014) is performed to evaluate the effect of vehicle-ride exposures on cervical pathologies. There were 12 studies that met inclusion criteria and the outcome was that vehicle-ride exposures (ground-based vehicles: operator and fixed-wing aircrafts: fighter pilots) is likely to increase the risk of cervical pathology.
Keith L, Luke B. The Association Between Women's Work, Working Conditions and Adverse I Pregnancy Outcomes: A Review of the Literature and Directions for Future Research. WHI. 1991;l(3).	Noise exposure Pregnancy outcomes	Authors performed a detailed review collecting scientific evidence on occupational exposures and adverse pregnancy outcomes.
Selander J, Albin M, Rosenhall U, Rylander L, Lewné M, Gustavsson	Occupational noise	This FENIX study concentrated on determining relationships between the occupational noise exposures and fetal and child

P. Maternal occupational exposure to noise during pregnancy and hearing dysfunction in children: A nationwide prospective cohort study in Sweden. Environ Health Perspect. 2016 Jun 1;124(6):855–60.	Fetal and child health < 75, 75-85 and > 85 dB	health. This study included 1422333 single births from 1986 to 2008. Information on occupations, socioeconomic factors, smoking habits, gender, ethnicity, genetics, etc. was collected during 10th of pregnancies from mothers registered in national registry in Sweden. Occupational noise exposures were divided into three groups, < 75, 75-85 and > 85 dB. Associations were determined using Cox proportional hazard models. Study found strong evidence that exposures to loud noises and hearing problems in children are correlated.
Magann EF, Chauhan SP, Dahlke JD, McKelvey SS, Watson EM, Morrison JC. Air Travel and Pregnancy Outcomes: A Review of Pregnancy Regulations and Outcomes for Passengers, Flight Attendants, and Aviators. Obstet Gynecol Surv. 2010;65(6):396–402.	Air travel Associated health issues: premature birth, low weight at birth	Authors analyze available literature on air travel (pregnant passengers, flight attendants and aviators) and associated health problems (premature birth, low weight at birth) and spontaneous pregnancy losses during gestation. 9 articles were selected in this review that directly discussed the relationship between air travel and pregnancy outcomes. For instance, the risk of premature birth or losses was greater (odds ratio 1.62) in flight attendants than in control group. The risk of premature birth was higher (odds ratio: 1.44) in passengers than in the control group. However, no other associations such as low weight at birth, preeclampsia were found. Authors also provide good information on medical issues such as cabin pressurization, thromboembolism, cosmic radiation, and infectious diseases associated with flying. Also, there is a section on health effects of aircraft noise that could be effectively used in modeling efforts.

Skoder H, Pettersson H, Norlen F, Gustavsson P, Rylander L, Albin M, et al. Occupational exposure to whole body vibrations and birth outcomes – A nationwide cohort study of Swedish women. Sci Total Environ. 2021;751(10):141476.	Whole body vibration Transportation and construction	The aim of this prospective cohort study was to determine whether the exposure to whole body vibration results in preterm birth and low weight at birth. The Fetal air pollution exposure cohort (babies born 1994-2004, n = 1,091,080) was used to assess the effects. It was found that those women who were not absent from work where whole-body vibration were present (construction and transportation) were in a greater risk to have a premature birth. However, no increase in low weight at birth was observed.
Argys LM, Averett SL, Yang M. Residential noise exposure and health: Evidence from aviation noise and birth outcomes. J Environ Econ Manage. 2020;103:102343.	Noise exposure NextGen Fetal health Low weight at birth	This literature review assessed the effects of >55 dB noise exposure to pregnant female (babies born between 2004 to 2016 in New Jersey) and the subsequent outcomes as low weight at birth. It was found that low weight at birth was 1.6% higher for women who lived close to the airports (exposed to both, aviation and road noise) in comparison to the ones who lived away from noise sources exceeding 55 dB. Also, the study also took into account the air pollution, which was used as a confounder in this review.
Military exposure-related literature		
References	Subject Terms	Description / Implications / Findings

Fouts B, Mortimer D. Stresses of Flight during Aeromedical Transport: An Integrated Review. 2018.	Noise, vibration, pressure exposure Aeromedical transport	Authors present a detailed literature review on challenges associated with the aeromedical transport and health effects. Literature sources reviewed include the effect of pressure, noise, vibration, hypoxia, fatigue, thermal changes, dehydration, gravitational forces, and combination of all stresses. Authors emphasized the knowledge gaps and the lack of scientific evidence available especially on noise and vibration as well as cumulative effects during aeromedical transport.
Castelo-Branco NA. Low Frequency Noise: A Major Risk Factor in Military Operation. In: Aging Mechanisms and Control Symposium Part A - Developments in Computational Aero- and Hydro-Acoustics Symposium Part B - Monitoring and Management of Gas Turbine Fleets for Extended Life and Reduced Costs. Manchester, UK; 2001.	Low frequency Noise exposure Pathology	It is generally accepted in the military that high frequency noise (> 500 Hz) is a health concern, which may induce temporarily and/or permanent hearing damage or loss and should be taken care of. However, low frequency (< 500 Hz) and non-audible frequencies such as ultrasound (< 20 Hz) are ignored despite alarming results showing tissue and cell damage, reduced cognitive abilities, acute respiratory problems, neurological disturbances, mood swings and other health concerns among military personnel. One of the adverse outcomes of low frequency noise exposures is early retirement which is rather costly for the Military in general. Authors discuss the potential health problems associated with low frequency noises and approaches to minimize the health effects.
Muhr P, Johnson A-C, Selander J, Svensson E, Rosenhall U. Noise Exposure and Hearing Impairment in Air Force Pilots. Aersp Med Hum Perform. 2019;90(9):757–63.	Noise exposure Military pilots Hearing impairment	This longitudinal study to assess the noise exposure to Swedish military pilots (born between 1945 to 1980 and enrolled between 1963 and 2000. They were followed during their active service from 1963 to 2010 and subjected to testing every 5 years) and determine whether loud noises affect hearing. It was found that over 41% of pilots were constantly

		exposed to > 80 dBA. Also, it was determined that the most of hearing damage happened during the first 10 years of exposure.
Cheng H, Sun G, Li M, Yin M, Chen H. Neuron loss and dysfunctionality in hippocampus explain aircraft noise induced working memory impairment: A resting-state fMRI study on military pilots. Biosci Trends. 2019;13(5):430–40.	Noise exposure Memory losses Cognitive impairment	This study is aimed at determining the relationship between the long-term aircraft noise exposure and health effects such as memory losses and cognitive impairment in pilots. Authors selected 30 fighter jet pilots and compared the effects of noise exposures to 30 controls. Correlation analyses were done to find associations between the neural imaging and neural performance. Pilots showed significantly worse results than controls in verbal and visual memory tests. Structural MRI data also suggested neuron dysfunction of the hippocampus in military pilots indicating that prolonged exposure to noise adversely affect the working memory accuracy.
Delisle JM, Riddle E. the Effects of Fatigue Relating To Female Airline Pilots. Embry Riddle Aeronautical University; 1995.	Airline pilots (females) Fatigue	This thesis present information on the effect of occupation (airline pilots) on their health (fatigue). There were 121 pilots (divided into two groups: with and without children) included into the study who were asked to provide information on their usual workday and other factors that may affect their health, especially how their occupation and raising a child and performance is affected by fatigue. The outcome of the study included data on the levels of fatigue that were directly influenced by body biochemistry and responsibilities. This information can be effectively used in research where synergistic effect of noise and occupational performance should be determined and evaluated.
Engebretsen SLG. Birthweight of infants related to psychosocial profiles of military mothers.	Military duty (females)	This prospective exploratory study analyzed association between active military duty (219 women from 8 th to 42 nd week of pregnancy) and pregnancy outcomes such as weight

[Internet]. Birthweight of Infants Related to Psychosocial Profiles of Military Mothers. The University of Utah; 1996.	Pregnancy outcomes: weight at birth	at birth. Independent variables were psychosocial risk factors such as stress, self-esteem and social inclusion and support. Other variables were associated with biomedical risks, lifestyles, and genetics. Data showed that stress was the most statistically significant variable in predicting low weight at birth.
Gilbert RH. Low birth weight and the natality experience of female aviators in the US Air Force Military airlift command and strategic airlift command. University of Texas; 1997.	Active military duty (females) Low weight at birth	Main finding of this thesis is that low weight at birth is directly associated with being active duty military compared to civil personnel. According to the author, there are twice as many low weights at birth cases when military personnel are compared to their civil counterparts. However, there was not association found when military pilots were compared to civil counterparts. However, author argues that this no association maybe due to the extremely low numbers of deliveries by military pilots in comparison to civilians.
Greenwell BM, Tvaranas AP, Maupin GM. Risk factors for hearing decrement among U.S. Air Force aviation-related personnel. Aerosp Med Hum Perform. 2018 Feb 1;89(2):80–6.	Occupational settings: noise Hearing problems	Longitudinal retrospective cohort study (2013) analyzed 167 253 available audiogram records from 10 567 personnel to determine associations between occupational settings on hearing problems in US Air Force aviation-related personnel. Variables of interest were age, time since the last audiogram, gender, and occupation. The outcomes were detected changes in hearing sensitivity. Random forest analyses were performed to determine predictor variables. Out of all the variables, only time since the last audiogram and age were associated with hearing sensitivity. Aircraft type or occupation were not linked to hearing losses or sensitivity.
Guski R, Bochum R, Richard I. Aviation Noise Impacts White Paper State of the Science 2019 : Aviation Noise Impacts [Internet]. 2019.	Aviation noise Health problems	This white paper presents information on aviation noise (helicopter, military aircrafts, supersonic aircrafts, etc.) effects onto surrounding communities considering health effects such as sleep disturbance, annoyance level and discuss economic

		effects of aviation noise. Review also provides mitigation strategies based on effects.
Hansen MCT, Schmidt JH, Brøchner AC, Johansen JK, Zwisler S, Mikkelsen S. Noise exposure during prehospital emergency physicians work on Mobile Emergency Care Units and Helicopter Emergency Medical Services. Scand J Trauma Resusc Emerg Med. 2017 Dec 6;25(1).	Noise exposure >80 dBA Health effects	Study provides information on the risks of hearing loss in pre-hospital (specifically helicopter emergency medical service and emergency care units) personnel who are exposed to loud noises (> 80 dBA) during their regular workday. Collected noises were analyzed and compared against 94 dB and hospital controls of 70 dBA. Before the tests, all the study participants were tested for hearing quality to establish a baseline. Also, participants were tested after the loud noise episodes to calculate actual effect of noise on hearing. No occupational hearing loss was found using audiometry testing. As reported in the article: “A significant level shift of the Distortion Product Otoacoustic Emissions at 4 kHz for HEMS crew compared to MECU physicians was found indicating that noise affected the outer hair cell function of the inner ear, thus potentially reducing the hearing ability of the HEMS crew”.
Issarayangyun T. Aircraft noise and public health; 2005.	Airport noise Health effects Pregnancy outcomes	This thesis provides insights into the Sydney Australia airport noise pollution and its effect on human health. Main questions that are investigated in the thesis are associated with comparison of health status of communities around airports to communities away from airports. Also, whether noise exposure directly correlates with high blood pressure and level of stress in communities close to the airports. Research was performed in the form of distributed questionnaires and self-administered health surveys with the follow up questionnaires to “exposure group” and “control group”. Total sample size was 1500 (ages from 15 to 87) with over 40% response rate. It was found that health quality in terms of

		general health, vitality as well as mental health was significantly lower (odds of 2.61 of having chronic noise stress and 2.74 of exhibiting hypertension) in the exposure group compared to the control group.
Jahnke SA, Poston WSC, Jitnarin N, Haddock CK. Maternal and Child Health Among Female Firefighters in the U.S. Maternal Child Health J. 2018 Jun 1;22(6):922–31.	Occupational stressors (firefighters): noise included Health effects	This study researches the effect of occupation (firefighters) on mother and child health. Questionnaires were distributed to 1821 women firefighters with questions on occupation effect on their pregnancy and outcomes (weight of a child, diseases, injuries). 25 to 30% of participants reported miscarriages or premature births during their service. Unfortunately, more quantitative data is warranted to associate miscarriages and premature births with firefighting duties.
Mestre V, National Research Council (U.S.). Transportation Research Board., Airport Cooperative Research Program. Effects of aircraft noise : research update on selected topics. Transportation Research Board; 2008. 90 p.	Noise exposure Health effects Modeling	Authors provide analysis of aviation noise health effects. This information maybe subsequently used in modeling where theoretical considerations are necessary to consider single or synergetic effects. Unfortunately, they also note that a complete separation of noise effects from other effects (genetics, stress) on health is quite an impossible task. Also, majority of articles published in the last few decades provide sometimes contradictory information when assessing loud noise health effects. Also, there is no single internationally accepted research methodology and/or standards in analyzing noise effects on health. Furthermore, vast majority of literature sources claim that despite some evidence that loud noises may have adverse effects on fetal health and development, no strong evidence suggest that this is the case.
Tomei F, De Sio S, Tomao E, Anzelmo V, Baccolo T, Ciarrocca M, et al. Occupational exposure to	Noise effect Male pilots	The main aim of this study was to assess the effect of noise parameters such as intensity, duration and type on hypertension in male pilots (n = 77 flying turboprop planes,

noise and hypertension in pilots. Int J Environ Health Res. 2005;15:99–106.	Hypertension	exposed to 93 dBA and n= 224 flying jets, exposed to 79 dBA) measuring their blood pressure and the heart rate. It was found that pilots exposed to 93 dBA had higher blood pressure. Unfortunately, only male pilots were tested and therefore it is difficult to extrapolate the results such noise would have on pregnant female aircrew.
Mcquiston BK. Accommodation and Occupational Safety for Pregnant Military Personnel. 1997.	Size and shape of pregnant women Occupational restraints	25 pregnant military personnel were evaluated collecting anthropometric data (and 3D scans) for changes in shape and size during pregnancy. Collected data was evaluated in terms of changes and potential accommodations when the person is sitting, standing, and working. The potential movements of the fetus were also recorded.
Brubaker PA. Can aircraft noise > 115 dBA adversely affect reproductive outcome in USAF women? University of Texas; 1985.	High frequencies Adverse reproductive outcomes	The comparative literature study was performed to look for associations between high frequencies (>115 dBA) and adverse pregnancy outcomes. Study included active Air Force women who delivered (~17-20 delivered each month) in selected 6 months interval at selected hospital. The outcomes were selected: low weight at birth and premature births. Study showed insignificant association between high frequencies and adverse health outcomes. However, as the n was too small, these results cannot be used to conclude that noise exposure does not have any effect on pregnancy outcomes.
AGARD. Recruiting, Selection, Training and Military Operations of Female Aircrew. In: AGARD Conference Proceedings No 491. 1990.	Training aspects of female pilots	This conference proceedings present information from various sources on what are the main parameters, factors and specifics regarding female aircrew training and retention. Information on anthropometry, training aspects, personal equipment, and physiological considerations is provided.
Flindell IH, Inskip H, Coggon D, Finegold LS, Huot PE. Assessing the	Aircraft noise	This is a collaborative effort between the UK, Canada and the US, which researched the potential health effects of low-

<u>Feasibility of a Prospective Epidemiologic Study of Possible Effects of Military Aircraft Noise on the Health of Overflowed Populations. United Kingdom; 1998</u>	Exposures	altitude and high-speed military aircraft generated noises to the general public. During this study, exposed and non-exposed group of people were assessed taking into account numerous confounding variables such as stress, and other health effects that may occur during a day without taking into account general annoyance and sleep disturbance that usually occur during night. It was found that no individual aircraft noise was over 120 dB. It was found that due to variability and unpredictability of data or so called “patterns of aircraft operations”, it was rather impossible to determine the long-term effects of noise exposures to general public. The conclusion was that it may be feasible to conduct prospective epidemiological study of aircraft generated noise effect if bigger sample size is selected and longer time frame is used.
<u>Pearsons KS, Wilby JF. Possibility of Hearing Loss from Exposure to Interior Aircraft Noise. Los Angeles, CA; 1981.</u>	Hearing loss Aircraft noise Noise exposure Sound Pressure	This is an early report on hearing damage by extreme noises in commercial and military aircrafts developed by the Committee on Hearing, Bioacoustics and Biomechanics (CHABA). It presents levels of interior noise that can be found in various types of aircrafts during takeoff, cruising, and landing. During 80s, there was an intent from FAA to develop new damage risk criteria (based on temporary threshold shift, all exposures and permanent threshold shifts) using information collected from 8 hour per day noise exposure data. Most of the noise measured in various aircrafts fall into the 80 to 85 dB range from 31.5 to 8000 Hz octave band center frequencies.
<u>Spenser RH, Sternfeld JH. Noise survey HU-1A Helicopter with</u>	Acoustic properties	During this effort, Army HU-1A helicopter 9-1632 had a modified exhaust system and was compared to a standard exhaust system 58-2080 at ambient conditions. It was found

<u>modified exhaust system. Morton, PA; 1961.</u>	Noise exposure Exhaust systems Helicopter Sound Pressure	that exhaust system modification does not provide a significant acoustic shield with a slight improvement in high frequency range (1200-2400 cps and 2400-4800 cps, respectively) during takeoff and landing. There was no difference observed during lower frequencies. Also, there was some internal sound pressure difference but that was attributed to interior configuration of HU-1A aircraft.
<u>Thomas GB, Williams CE. Noise Susceptibility: A Comparison of Two Naval Aviator Populations. Pensacola, FL; 1986.</u>	Noise exposure Naval aircraft carrier Health effects	The main idea of this effort was to determine whether all aviators are equally susceptible to loud noises. There were 56 naval aviators tested for potential hearing loss or damage and other health effects including blood pressure, etc. There was strong statistical correlation between the noise and tobacco use, high blood pressure and cholesterol. It was found that noise-susceptible group exhibited higher cholesterol and triglyceride levels and had less aviators in the group that smoked.
<u>Webster JC. Noise Levels on Aircraft-Carrier Flight Decks, and Their Effects. San Diego, CA; 1971.</u>	Hearing Noise effects Jet fighter	Measurements were performed on the flight deck of USS Kitty Hawk and it showed that crew was exposed to high levels of low-frequency noises (at octaves ranging from 62 to 125 Hz). It was found that these levels affected speech communication and presented a risk of hearing damage or even loss to the crews.
Noise basics: soft tissue, air, and bone conduction		
References	Subject Terms	Description / Implications / Findings

Ziskin MC. Fundamental Physics of Ultrasound and its propagation Propagation in Tissue. RadioGraphics. 1993;13:705–9.	Ultrasound Propagation in tissues	Authors present information on ultrasound (> 20 kHz) propagation in tissues. It is reported that ultrasound is attenuated when it travels throughout the soft tissues and bones due to absorption and deflection of acoustic energy that is coming from the beam. Ultrasound is regarded as non-ionizing, unfortunately, at high intensities, it may generate excessive heat, induce mechanical and chemical effects and cavitation. Authors provide good theoretical background on ultrasound waves, propagation and chemical as well as biological effects that could be used in computer simulations. Various attenuation data and parameters are presented which would be later used in Multiphysics calculations to evaluate the effect of noise, acoustic wave traveling through tissue and potential health effects associated with these phenomena.
Sohmer H. Soft Tissue Conduction: Review, Mechanisms, and Implications. Trends Hear. 2017;21:2331216517734087.	Noise propagation mechanism Pregnancies	It is important to understand the mechanisms of noise propagation in the human body, thus important to understand actual noise conduction pathways when analyzing noise effects on fetus. For instance, authors provide examples of soft tissue conduction such as delivery of acoustic vibrations to the skin via clinical bone vibrators. These vibrations are transmitted through the soft tissues until they reach the ear. Unfortunately, many unknowns exist in the field of fetal “hearing” mechanisms and attenuation, especially when fetus is affected before 24th gestation week.
Antonets VA, Kazakov V V. On noninvasive assessment of acoustic fields acting on the fetus. Acoust Phys. 2014;60(3):342–7.	Non-invasive methods Pregnancies	This study focused on evaluating a non-invasive method to assess acoustic field (maternal voice, external sounds, and vibrations). The outcome could provide important information on researching how acoustic sounds travel (e.g. are either dampened or intensified) through mother’s body into uterine

		environment and to fetus. Similar research would also important question what, low or high frequency sounds are dampened and/or intensified and whether external sounds such as music, voice recordings help for the fetus to develop or are detrimental for fetal health. Unfortunately, current practices do not include standardized methods for measurement of acoustic signals, and it is not clear whether these signals are dangerous or beneficial for the fetal health and development. Authors inform that acoustic pressures at < 1 kHz in the uterus can be measured noninvasively using hydrophone placed in a soft capsule in liquid. Authors also found that at frequencies up to 1 kHz, external sounds can reach uterus without any dampening or intensification, i.e. sounds are of the same amplitude-frequency inside as well as outside uterus. Furthermore, at frequencies > 1 kHz, sounds are attenuated in the uterine environment, which is like the previous published studies where authors claimed that at frequencies above 500 Hz, maternal voice and sounds are not recognized by the fetus.
Smith A. A review of the non-auditory effects of noise on health. Work Stress [Internet]. 1991;5(1):49–63.	Non-auditory effects of noise	Review is about non-auditory effects (blood pressure, sleep, illnesses, mental health, and annoyance) of noise to human health. It provides insights into what additional noise effects should be considered when performing experimental work and computer simulations to assess all adverse effects of noise exposures to humans.
Chao PC, Juang YJ, Chen CJ, Dai YT, Yeh CY, Hu CY. Combined effects of noise, vibration, and low temperature on the physiological	Cumulative effect of noise Vibration	This study provides information on the cumulative effect of noise, vibration and extreme (low) temperature on the performance of workers (23 individuals 19 to 22 years of age). To evaluate these cumulative effects, Taguchi method has

parameters of labor employees. Kaohsiung J Med Sci. 2013 Oct;29(10):560–7.	Low temperatures	been employed to simulate various exposure conditions and effects measured. Results indicate that the most significant parameter that affected external surfaces (skin, organs) was temperature, exposure time was second important parameter in assessing the effects. Also, noise contributed the most to hearing problems and loss, whereas vibration and temperatures did not have any effect. Cumulative parameters did not show any significant effects on health; however, authors indicate that this might have been because boundary conditions were not carefully selected.
Murata M, Takigawa H. Teratogenic effects of noise in mice. J Sound Vib. 1989;132(1):11–8.	Noise, teratogen exposure Cumulative effect on health	Two-fold study is performed to evaluate how excessive noises and combined noise and teratogens (cadmium sulfate or tryptan blue) impact the development of fetus in mice. Mice were exposed to 100 dB for 6 hours a day either continuously on 7 th day of pregnancy, intermittently (every 15 min on 7 th day of pregnancy) and continuous noise from 7 th to 12 th days of pregnancy. Teratogens were injected on the 7 th day of pregnancy. On 18 th day of pregnancy mice were sacrificed and fetus examined. It was found that noise exposures alone or in combination with teratogens did not affect the growth of the fetus. Teratogenicity was not observed during continuous noise exposures in combination with teratogens.
Animal modeling		
References	Subject Terms	Description / Implications / Findings

Morrison JL, Berry MJ, Botting KJ, Darby JR, Gattford KL, Giussani DA, et al. Improving pregnancy outcomes in humans through studies in sheep	Sheep	Animal models can be used to mimic human pregnancies. Despite none of the animal models can truly reproduce human bodies, still it is generally accepted approach when actual physical experiments on humans are prohibited or unethical to perform. For example, sheep can be used to research the development of the fetus and its health. Authors summarize current efforts in using animals as models for human pregnancies. Also, from economic standpoint, sheep models are the most economical and effective way in researching health problems during pregnancies.
Huang X, Gerhardt KJ, Abrams RM, Antonelli PJ. Temporary threshold shifts induced by low-pass and high-pass filtered noises in fetal sheep in utero. Hear Res. 1997;113(1):173–81.	Pregnant ewes Health effects of noise	To evaluate the brain response to noise and evaluate potential health effects to loud noises, authors exposed 12 pregnant ewes (119 to 128 days pregnant) to 16 hours of low pass and high pass (cut-off frequency 1.0 kHz, ~120 dB in air) noises. Authors also assumed that sound travels through bone conduction. They confirmed that mostly low-frequency sounds reach fetal inner air.
Gerhardt KJ, Huang X, Arrington KE, Meixner K, Abrams RM, Antonelli PJ. Fetal sheep in utero hear through bone conduction. Am J Otolaryngol Neck Med Surg. 1996;17(6):374–9. Gerhardt KJ, Abrams RM, Kovaz BM, Gomez KJ, Conlon M. Intrauterine noise levels produced in pregnant ewes by sound applied to	External noise pathways to fetal ears	Despite it is generally accepted that sound travels to the inner air via air conduction mechanism, it is not the same pathway observed in fetal hearing. Authors proved that “external sounds can reach the fetal inner ear through the ear canal and middle ear system, bone conduction, or both”. The study involved exposure of 9 pregnant sheep to high intensities of 100 to 135 dB and measuring the response using cochlear microphonics.

the abdomen. Am J Obstet Gynecol [Internet]. 1988;159(1):228–32.		
Shannon GS, Moran W Al, Shackelford CL, Mason KT. Effect of Vibration Frequency and Amplitude on Developing Chicken Embryos. Fort Rucker, AL; 1994.	Chicken modeling Vibration amplitude	The effect of vibration amplitude in the rotary-wing aircraft environment on chicken was researched. Chicken embryos were exposed to 5, 10, 15, 20, 25, 30, 40, and 50 Hz. Vibrations varied from 0.15 to 2.88 G _z (rms). It was found that exposure to vibration > 2 G _z had a strong effect on fetal development and mortality. Exposures > 1 G _z were determined as harmful at certain frequencies.
Ashe WF. Physiological and Pathological effects of mechanical vibration on animals and man. 1964.	Rats Whole body vibration	Author exposed 6 male Sprague-Dawley albino rats to whole body vibration (20 cycles per second, 0.25 inch amplitude). It was found that vibration induced a significant weight loss
Finite Element (FE) modeling / computer simulations: biomechanical human models		
References	Subject Terms	Description / Implications / Findings
Zhao JZ, Narwani G. Development of a Human Body Finite Element Model for Restraint System R&D Applications. In 2005.	Biophysical model: thorax, abdomen, shoulders, head, neck	Authors developed finite element model (physical impact) of an adult (male) including thorax, abdomen, shoulders, head, and neck (based on NASS/CDS database from 1993 to 1999 with over 59,000 cases). It also have bone structure (skeleton, skull, spine, ribs, clavicles and other bones) and soft tissues such as muscles, ligaments, heart, liver, spleen, kidneys that are connected by various blood

		vessels like arteries and veins. The model was validated with Post Mortem Human Subject database with emphasis on frontal and side impacts, including safety belt and airbags under different loads. They looked at the force-deflection parameters and characteristics. It was also validated against chest belt data from NHTSA biomechanics database, #2860) and was in a good agreement with data presented there (especially in the range of 15-35 mph).
<u>Schwartz D. Development of a Computationally Efficient Full Human Body Finite Element Model. Virginia Tech – Wake Forest University; 2015.</u>	The Global Human Body Models Consortium (GHBMC) Biophysical models	In this master thesis, authors research vehicle injuries during vehicle crashes using Finite element model and by developing a full human body model. Author argues that FEA models have a capacity to aid in this research by collecting and analyzing (as well as predicting the outcomes) large volume of biomechanical data from crashes and injuries during vehicle accidents. Thesis introduces The Global Human Body Models Consortium (GHBMC), which has collected huge amount of data to develop human body finite element models with 1.3 million nodes and more than 2 million elements. Author propose to develop a simplified FE model of an adult male which would significantly reduce computer simulation time (35-fold reduction in required runtime) and could be used in various parametric studies without the need to have extensive computer resources. This was achieved by using a coarser mesh, homogenizing, or omitting structures from the original GHBMC model. All the deformable components for the model were collected from biomechanics literature. This simplified model had 11 contacts and 354 thousand elements, which was almost 8-fold reduction from the original model.

Fuchs, Therese Fressmann D, Mayer C, Pipkorn B, Segura R, Eber J, Yasuki T, et al. Challenges in using a finite element human body model in different crash codes. In: Proceedings of the 2014 International IRCOBI Conference on the Biomechanics of Injury. Meyrin, Switzerland; 2014.	Human Body Model Mesh	Authors discuss advantages and disadvantages of Human Body Models (HBM) based on FE models. Several challenges are associated with extreme complexity of the human body. Thus, to accurately create representative mesh, one needs to use imaging technology and slice images to later develop associated mesh. Authors discuss the importance to choose representative material and parameters that would represent biological tissues.
Mondal P, Arunachalam S. Unique Finite Element Modelling of Human Body Inside Accelerating Car to Predict Accelerations and Frequencies at Different Human Segments. J Appl Sci. 2020;10:1861.	Vibration effects Seated human body	This research reports findings associated with the vibration effect onto humans seated inside the moving vehicle. Generally, results are reported on the total vibration only to a certain human body part (e.g. effect of vibration on the back or pelvis) without considering the bigger picture like the whole body. However, during this research, finite element model is developed that determines vibration effects on human body parts but considering the whole human body. Instead of using real time and real-life vibration tests for the seated human, virtual model of entire human body has been created in finite element environment. Human body parts were shown as ellipsoidal sections using assigned shape-specific stiffness data to different human parts. Results focused on collecting data on vertical accelerations, displacement, and frequency. Models were validated through real time and life data from literature.
Yue X, Wang L, Wang R. Tissue Modeling and Analyzing with Finite Element Method: A Review for	Human body model	It is generally accepted that it is impossible to perform mechanical experiments in real life with actual human bodies. However, finite element models can be used to overcome this drawback. FE models can be developed to research various

Cranium Brain Imaging. Int J Biomed Imaging. 2013;2013:781603.		deformations in the human body (e.g. cranial deformations) in the presence of outside stressors such as vibration, blunt impacts, etc. This type of FE models using 3D approach and relevant FE solvers can provide insights into the biomechanical field quicker and without the need of real time real-life experiments.
Mukherjee S, Chawla A, Balaraman K, Soni A. Finite element crash simulations of the human body: Passive and active muscle modelling. Sadhana. 2007;32:409–26.	Human body model including muscles and limbs	It is rather impossible to use conventional dummy models and test procedures to effectively evaluate crash and direct hit impacts on human bodies. However, FE models can be used to describe and predict crash and vibration impacts on human bodies adequately and effectively. Authors describe soft and hard material properties and use these properties to develop FE model (40 lower limb muscles using the Hill model) and use it in dynamic loading experiments as well as the effects of reflexes of muscles and associated injuries during crash. They found that a single linear visco-elastic material law could not adequately estimate and describe the strain rate range. Therefore, other laws and models must be researched to solve this problem.
Tan XG, Kannan R, Przekwas A. A Comparative Study of the Human Body Finite Element Model Under Blast Loadings. In: ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE). 2012.	Biomechanical model 3D Blast loading	These authors also emphasize the lack of reliable biomechanical models to model human body biodynamics. To overcome this challenge, authors developed human body FE (CoBi solver) model (1D – 3D) adopted from 3D male anatomy model by the Zygote Media Group, Inc. The with face, skull, brains, spine, and lungs to research stress-wave propagation in humans under various stresses and load (e.g. blast loading) using conditions. Authors used DFT (using conservation of mass, momentum, and energy laws), and FE models to research the topic. Developed CoBi solver can

		simultaneously solve numerous unknowns, is scalable and generated meshes are of a particularly good quality.
<u>Moorcroft DM. A Finite Element Model of the Pregnant Female Occupant: Analysis of Injury Mechanisms and Restraint Systems. Virginia Polytechnic Institute and State University; 2002.</u>	Pregnancy Car accident Deformation	In the thesis, author reports that every year there are over 40,000 pregnant women involved in car accidents with 300 to 3800 losing a child due to that accident. Placental abruptions (~70%) are a leading cause for these fetal losses. The main aim of the work was to develop a finite element model to quantify stress and the strain on the uterus during car accident to subsequently predict the risks of injuries and fetal losses. The model of 28-week pregnant female uterus has been developed and integrated into the full human body model. Speeds that were considered ranged from 13 to 55 kph. It was determined that peak uterine strain (~75% risk) could be used as main predictor of fetal outcome followed by the head injury and viscous criterion. Model performance was validated through data found in literature and physical modeling experiments using dummies. Thesis provides good overview on female anatomy and details of pregnant uterus which could be used for subsequent experiments or for the development of other finite element models. Limitations are also discussed, like for example, human pelvis is elliptical is not a good representation of a female pelvis. Uterus can be modeled as a solid, however most models regard it as one material thick. Ligaments must be considered as well when performing finite element modeling.
<u>Chen Z-W, Joli P, Feng Z-Q, Rahim M, Pirró N, Bellemare M-E. Female patient-specific finite element modeling of pelvic organ prolapse</u>	Pelvic organ prolapse	Authors discuss the finite element modeling of Pelvic organ prolapse (POP). This is an important area of research because it provides information on the dynamic behavior of the pelvic organs based on magnetic resonance images (MRI,

(POP). J Biomech [Internet]. 2015;48(2):238–45.		12 frames). As pelvis is considered hyperelastic material, the Yeoh model (FER solver that takes into consideration deformations) of finite elements can be used to discuss the stress and strains (deformation gradient tensor) onto pelvis. In the future research, authors suggest adding soft biological tissues that are assumed to be anisotropic and hyperelastic and governed by anisotropic material laws. To improve the accuracy of the model, more realistic boundary conditions must be used.
Watson NJ, Hazlehurst T, Povey MJW, Drennan A, Seaman P. COMSOL modelling of the acoustoelastic effect. J Phys Conf Ser [Internet]. 2015 Jan;581:12008.	Acoustoelastic effects	To accurately perform FE modeling, ones needs to take acoustoelastic effects into account. Many materials (human body included) are affected by constant or temporal mechanical loads and methods needed to measure and analyze stresses and strains to ensure that materials (human body included) functions properly and safely. Acoustoelastic effects are defined as stress dependency on the acoustic velocity in an elastic media. Finite element model combines structural mechanics and acoustic models in COMSOL software.
Joyce EM, Diaz P, Tamarkin S, Moore R, Strohl A, Stetzer B, et al. In-vivo stretch of term human fetal membranes. Placenta. 2016;38:57–66.	Strains and stresses Pregnant uterus model	Strains and stresses onto the pregnant uterus are main problems associated with losing fetus at an early pregnancy stage. Losing fetus occurs when the Fetal membranes (FM, collagen fibers) fail due to external stress. Therefore, to understand how to prevent membrane failures, one needs to understand their biomechanical properties (in vivo stretches for example). Authors used high resolution MRI imaging to determine how FM fail under the applied stress. They researched 8 pregnant women from 2.88 days to ~38.4 weeks prior caesarean delivery. Software used in this research

		allowed to determine the surface area and all the related placental components. Stretches, tension, pressure and rupture were calculated at delivery.
Sigal IA, Flanagan JG, Tertinegg I, Ethier CR. Finite element modeling of optic nerve head biomechanics. Invest Ophthalmol Vis Sci. 2004 Dec;45(12):4378–87.	Deformations Mesh	Finite element models can also be used to research stresses and surface deformations of the optic nerve head biomechanics including neural tissues, lamina fibrosa, central retinal vessel). Authors found that scanning laser tomography is not effective in deformation estimation, therefore, if similar tissue research is needed, other sources to inform finite element modeling is warranted. Authors used two-dimensional, eight-node elements and various meshes with degrees of heterogeneity were investigated with element counts ranging from 217 to 41,604 and up to 44,537 degrees of freedom. Also, Poisson ratios from 0.49 to 0.499999 were investigated.
Myers KM, Feltovich H, Mazza E, Vink J, Bajka M, Wapner RJ, et al. The mechanical role of the cervix in pregnancy. J Biomech. 2015 Jun 25;48(9):1511–23.	Biomechanical model of uterus and cervix	Authors discussed various biomechanical (structural) models of uterine cervix to determine risks associated with spontaneous preterm birth. Furthermore, authors presented clinical, biochemical, and engineering concepts associated with cervix functioning mechanism during pregnancy.
Feltovich H, Carlson L. New techniques in evaluation of the cervix. Vol. 41, Seminars in Perinatology. W.B. Saunders; 2017. P. 477–84.	Parturition Deformation	Parturition process is not entirely understood, however, clearly cervix that is comprised of various muscle cells, fibroblasts, glandular cells, vascular cells, and immune cells as well as extracellular materials such as proteins, is one of the most important organs in the process. Thus, research has been performed to quantify cervical remodeling taking into account tissue deformability (strain elastography and shear wave elasticity imaging), and structure (attenuation and backscatter) such as orientation as well as concentration of microstructural

		components such as collagen. It is generally accepted that soft tissue deforms under compression.
van Rietbergen B, Weinans H, Huiskes R, Odgaard A. A new method to determine trabecular bone elastic properties and loading using micromechanical finite-element models. J Biomech. 1995;28(1):69–81.	Trabecular meshwork	Despite this research is dealing with trabecular meshwork that is not directly associated with pregnancies, it introduces a new type of finite element modeling that allows to analyze large regions of hard tissue (bones) in details. This approach uses 3D FE model by converting voxels to elements directly. 5 mm bone was modeled and consisted of 296,679 elements. In addition, upper and lower boundaries for the tissue module were calculated and was concluded that the main deformation mode of this bone was predominantly in bending. This provides invaluable information to research bone structures associated with pregnancies.
Myers KM, Paskaleva AP, House M, Socrate S. Mechanical and biochemical properties of human cervical tissue. Acta Biomater. 2008 Jan;4(1):104–16.	Cervical tissue modeling	It is important to maintain mechanical integrity of cervical tissue to have a healthy pregnancy. Stresses and strains as well as changes in biochemistry can affect the mechanical properties of a cervix. Authors present results from three clinical cases using cervical samples from hysterectomy specimens. Tissue samples were tested in the presence of confined and unconfined compression and tension as well as detailed biochemical analysis (cervical tissue hydration, collagen content and extractability as well as sulfated glycosaminoglycan content) performed. This data can be useful in researching vibration effects on cervix. For example, it was reported that nonpregnant tissue was a lot harder than the pregnant tissue if compared under various degrees tension and compression. Also, collagen content and extractability and sulfated glycosaminoglycan content was greater in the pregnant tissue. Future studies must include

		anisotropy of the tissue and collected statistically relevant data on electrical properties of sulfated glycosaminoglycans, as well as data on tissue swelling properties.
Woods JR. Reactive oxygen species and preterm premature rupture of membranes – A review. Placenta. 2001;22(SUPPL.1).	Premature rupture of membrane	It is important to research causes and consequences of premature rupture of membranes (PROM) to evaluate the risks of premature fetal lost. For instance, it is reported that one of the causes of PROM is the damage of collagen in the chorioamnion by reactive oxygen species (ROS). Knowing that, it is important to research whether there are the cumulative or combined effects of ROS and other external stressor sources such as vibration and noise. Furthermore, article presents a particularly good anatomic information on the composition of chorioamniotic membrane, which may be used in subsequent FE modeling studies.
Westervelt AR, Myers KM. Computer modeling tools to understand the causes of preterm birth. Vol. 41, Seminars in Perinatology. W.B. Saunders; 2017. P. 485–92.	Mechanical integrity and sensitivity Uterus and cervix	Authors research the mechanical integrity and sensitivity to external loads of the soft tissue structures, uterus and cervix that are supporting fetus in the pregnant female body. It is reported that many mechanisms and temporal mechanical loads in the uterus are unknown and many research publications rely on hypotheses. For instance, it is discussed that extreme stretching of these soft tissues may lead to tissue remodeling and even membrane rupture that in turn may lead to premature birth. Authors review recent findings found in literature on engineering and computational tools that evaluate and predict mechanical loads on fetal membranes, uterus, and cervix. Computational tools include biomechanical modeling and FE models that put emphasis on predictive development of tools that may be able to prevent premature births. Authors provide good body of information on boundary

		conditions, engineering and biomechanical variables that maybe used to inform FE models. This collection of data may be effectively utilized to develop or validate a plethora of models that require this type of information. Also, various limitations are proposed.
Roger W. Pryor P. Multiphysics Modeling Using COMSOL®: A First Principles Approach [Internet]. System. Jones and Bartlett Publishers; 2009. 852 p.	Theoretical background on FEA	This book presents all the necessary theoretical and computational background as well as hands on information how to build and solve models using COMSOL Multiphysics software in many areas of engineering and science such as behavior of various elastic and non-elastic or solid structures. All the models developed in this book are discussed and explained using first principles and relevant analysis techniques. Book also provides information on materials coefficients and solvers.
Dong R, He L, Du W, Cao Z, Huang Z. Effect of sitting posture and seat on biodynamic responses of internal human body simulated by finite element modeling of body-seat system. J Sound Vib [Internet]. 2019;438:543–54.	Whole body-seat biomechanical model Low frequencies	Authors developed an accurate 3D FE model of the whole body -seat system (vertical, reclined and seated body in driving posture as well as three varying stiffness seats) called biodynamic random response analysis to research the effect of the posture and physical seat on the biodynamic response of the human body. Initial boundary condition was determined using static analysis of the whole body under gravity. Also, random response analysis was performed at low frequencies (0 to 20Hz). Authors collected information on damping ratios. They also claim that such simulation model can be used to investigate the responses of the human body-seat systems and perhaps replace numerous and time-consuming physical experiments to design seats that significantly reduce injury risks to lumbar spine. They also provided a large amount of data associated with meshing of human body and all the

		relevant information important for any FE simulations involving human body and seat environment.
Yu C, Wang F, Wang B, Li G, Li F. A Computational Biomechanics Human Body Model Coupling Finite Element and Multibody Segments for Assessment of Head/Brain Injuries in Car-To-Pedestrian Collisions. Int J Environ Res Public Health. 2020;17(2):492.	Biomechanical model Head-brain injuries	Authors developed a new coupled pedestrian computational biomechanics model to investigate and accurately predict the outcomes of the head/brain injuries (that include both, hard and soft tissues, and the bones). They combined two already existing models such as the head-neck model from the Total Human Model for Safety (THUMS, Toyota Central R&D Laboratories, Nagakute, Japan) (Version 4.01) FE model and other body parts from the Netherlands Organization for Applied Scientific Research (TNO, The Hague, The Netherlands) (Version 7.5) multibody model. The newly developed model was validated by reproducing tests using cadavers from published scientific literature sources and a correlation and analysis objective rating tool to evaluate relevant correlations of targeted signals between the model predictions and the test results. Developed model and cited models from literature may greatly assist in noise and vibration effect studies on pregnant uterine environment because they provide valuable information on potential correlations and present main parameters (e.g. anthropometry parameters) that can be used in computer simulations.
Campbell JQ, Coombs DJ, Rao M, Rullkoetter PJ, Petrella AJ. Automated finite element meshing of the lumbar spine: Verification and validation with 18 specimen-specific models. J Biomech. 2016 Sep 6;49(13):2669–76.	Lumbar spine model	Authors developed human lumbar spine FE model using an automated algorithm that used segmented computer tomography scans (18 individual specimen, 216 simulations run and compared to 186 experimental data ranges in six primary bending modes) of lumbar spine and identified target areas as well as relevant surfaces. Mesh was validated analyzing changes in key output variables and by comparing

		results using relevant literature sources. Developed FE model used STL geometry of lumbar spine as input and identified 1306 landmarks considering key biomechanical features of each bone, like endplate contours, ligament attachment points, and surfaces. The annulus fibrosis was modeled using the Holzapfel–Gasser–Ogden formulations. The bones were characterized by 7470 elements for each vertebra and were modeled as rigid materials. The nucleus pulposus was described as a fluid cavity employing 2154 quadrilateral reduced integration surface elements per disc to define the nucleus boundary.
Hinz B, Seidel H, Hofmann J, Menzel G. The significance of using anthropometric parameters and postures of European drivers as a database for finite-element models when calculating spinal forces during whole-body vibration exposure. Int J Ind Ergon. 2008;38(9–10):816–43.	Whole body vibration Biomechanical model	This study presents a FE model of the human body and its biomechanical response to whole body vibration. Such information helps to understand the loads onto the lumbar spine and evaluate risks associated with this type of stressors. Authors researched literature for relevant data and performed experiments to develop a model including five typical postures and ten statures. 50 developed models were tested using white noise signals in x, y, z directions as input to buttocks, back, feet and hands. Results show a strong influence of spinal loads on changing statures and postures.
Lee-Sifakis-Terzopoulos: Comprehensive Biomechanical Modeling and Simulation of the Upper Body	Biomechanical model Human body	Authors developed biomechanical model of upper part of a human body (68 bones, 814 muscles, 147 jointed degrees of freedom) including all the major bones, spine, ribs, tissues, and muscles, and physics-based distortions of the soft tissues. Muscles were modeled as piecewise uniaxial Hill-type force actuators. Total of 354,000 tetrahedral finite elements were simulated to account for flesh deformations.

Harders M, Székely G. Using statistical shape analysis for the determination of uterine deformation states during hydrometra. Med Image Comput Comput Assist Interv. 2007;10(2):858–65.	Uterus deformation Pregnancy	To assess the uterus deformations during pregnancy, one needs to develop an accurate model that accounts for tension inside the uterine cavity, which is filled with hydrometra. Authors introduce FE model that accounts for deformations of hydrometra and 3D mesh for subsequent simulations.
Fernandez M. The Biomechanics of Pregnancy: Simulating Pregnancy Mechanics, Evaluating Preterm Delivery Interventions, and Measuring in-vivo Mechanical Properties. Columbia University; 2017.	Premature births	This thesis presents modeling efforts to predict premature births using FE analyses. Authors developed biomechanical model including organ geometry, tissue deformation behavior and potential biomechanical interactions between uterus, cervix, and fetal membranes.
Baah-Dwomoh, A., McGuire J, Tan T, De Vita R. Mechanical Properties of Female Reproductive Organs and Supporting Connective Tissues: A Review of the Current State of Knowledge. ASME Appl Mech Rev. 2016;68(6):060801.	Biomechanical model Female reproductive organs	This overview presents a biomechanical model characterization based on FE analysis on female reproductive organs (cervix, vagina, uterus, and ovaries) and connective tissues (ligaments, fasciae, and muscles). Authors provide good theoretical background, description and research challenges associated with every organ and tissue.
Buttin R, Zara F, Shariat B, Redarce T, Grange G. Biomechanical simulation of the fetal descent without imposed theoretical trajectory. Comput Methods Biomech Biomed Engin. 2013;111(2):389–401.	Biomechanical model Pregnant abdomen	Authors provide details and geometries on biomechanical modeling using FE analyses of all female reproductive organs interacting with fetus during birth. Importantly, fetus head is not modeled as rigid material but modeled in a flexible way without pre-defined moving trajectories or geometries. They also consider cycling contractions in the uterine environment and muscle movement in the abdomen. As well as include pressure that is modeled as residual muscle tone. Hooke's law was used to model elastic behavior. However, to account

		for hyper-elastic behavior, the Mooney-Rivlin model or Neo-Hooke laws can also be applied depending on the model requirements.
Irannejad M, Ahmadian M, Mohammadi H. Rigid-Bar Loading on Pregnant Uterus, and Development of Pregnant Abdominal Response Corridor, based on Finite Element Biomechanical Model. Int j numer method biomed eng. 2019;36.	Rigid bar traumas Pregnant abdomen	Authors use FE analysis to research direct “rigid bar” traumas onto the pregnant abdomen. They developed an accurate biomechanical model of pregnant womb during 3rd trimester with uterus, fetus, placenta, amniotic fluid, and ligaments. Geometries and mesh were developed based on computer imaging technique (Computer Tomography scans) and validated using anthropometric data from literature. Ogden hyper-elastic theory has been applied, which differs from other authors who based their research on ne-Hooke and/or Mooney-Rivlin theories. Results indicated that low up to 45 mm penetration into the pregnant abdomen, showed the same response as a non-pregnant abdomen, however, at larger penetrations, pregnant abdomen was much stiffer and more rigid in comparison to a non-pregnant abdomen. Authors postulate that this may be due to the occurrence and positioning of the fetus in the abdomen. Authors also provide a detailed uterus and fetus set table with all the relevant geometrical parameters included from model and anthropometric data. Also, they model uterus wall, placenta, amniotic fluid and fetus as four-node tetrahedral with # of elements ranging from 1500 to 2814 and ligaments as two-node 3D truss with 138 elements.
Other modeling for external outside aircraft exposures		

References	Subject Terms	Description / Implications / Findings
Boyle, Devin K. A study of the integration of an inlet noise radiation code with the A study of the integration of an inlet noise radiation code with the Aircraft Noise Prediction Program. Missouri University of Science and Technology; 2012.	Turbofan effect on health ANOPP	To understand and evaluate the effect of extreme sounds on the ground crew (external to the aircraft), numerical models must be developed. In this Master thesis, numerical model was developed that assessed the turbofan noise effects on the ground crews and turbofan inlet treatment using acoustic liners to somewhat minimize that noise. The modeling tool used was developed by NASA Aircraft Noise Prediction Program (ANOPP) with the fan noise propagation and radiation code developed at Missouri University of Science and Technology. This tool is utilized to predict the noise distribution from turbofan engines during flights, takeoff, approaching/landing and cruising at constant altitudes and speeds.
Hough JW, Weir, Donald S. Aircraft Noise Prediction Program (ANOPP) Fan Noise Prediction for Small Engines. Hampton, VA; 1996.	Predictions of noise pathways ANOPP	This ANOPP modeling tool includes improved predictions and updated Heidmann and GASP predictions to improve accuracy. Small engine upgrades are incorporated into fan noise module.
Lopes L, Burley C. Design of the Next Generation Aircraft Noise Prediction Program: ANOPP2. In: 17th AIAA/CEAS Aeroacoustics Conference 2011 (32nd AIAA Aeroacoustics Conference). 2011.	ANOPP2 Improved predictions Noise propagation	This study presents a second-generation improved Aircraft Noise Prediction Program (ANOPP2) from NASA for various configuration aircraft. It combines various available acoustic approaches and integrates noise prediction and propagation methods. It considers sources, installation, and propagation of sound through atmosphere (e.g. includes information on refraction and effect of terrain).

<u>Diwan G, Jauniaux E, Henriques J, Thibaut A, Gélat P. Computational studies on the acoustics of the womb. In 2019.</u>	Acoustic wave propagation Pregnant abdomen	Authors recognize the importance of physiological and non-physiological noise, especially during fetal development and early times after birth. Thus, computational modeling is proposed to evaluate and quantify the acoustic waves propagation from the external into the uterine environment and fetus. It is generally accepted that propagation of acoustic waves is governed by Helmholtz equation. Unfortunately, it is extremely difficult to accurately solve this equation due to complex interactions and parameters such as soft and hard tissues, temporal development of the fetus, geometrical positioning of fetus in the womb, varying acoustic densities and sound speed. It was found that uterine environment is subjected to resonance at frequencies within the human hearing range. Authors state that “this resonant behavior of the womb can result in unphysical pressure amplitudes if the attenuation effects are not considered”.
<u>Moreno M, Amorim P, de Moraes T, Silva J, Baylon K, Flores-Villalba E, et al. Soft Tissue Modeling For Virtual Surgery Simulation. In 2014.</u>	Exoskeleton structure model 3D mesh	This study presents the Exoskeleton Structure method used to develop 3D mesh and Equivalent Strain Energy Density (ESED) model for soft tissue that could be subsequently used in computer simulations of uterine environment. During this research, InVesalius software for slicing of medical images has been used in addition to mechatronic design.
<u>Walker E. Constructing a Noise Propagation Model to Assess Community Noise Levels Stemming From Road Traffic: The Case of Somerville, MA. Tufts University; 2012.</u>	Sleep patterns Noise exposure Numerical model	In this thesis, non-auditory noise effects on health have been assessed including disturbed sleep patterns, high blood pressure and general annoyance. Road traffic noise was researched (sample size = 204) employing noise propagation model. The outcome of a study and this model can be effectively used to analyze indirect effects of noise to pregnant crews on ground, i.e. external to the aircrafts. Spearman

		correlation has been employed to evaluate the relationship between the average noise exposures (road traffic noise) and its indirect effects like blood pressure, sleep, and general annoyance. It was found that participants living close to traffic noise sources were subjected to levels about 36% higher than WHO standards. Significant positive correlation was found between the general annoyance and traffic noise.
Pietrzko S, Butikofer R. FLULA - Swiss aircraft noise prediction program. In: Acoustics 2002 - Innovation in Acoustics and Vibration. Adelaide, Australia: Annual Conference of the Australian Acoustical Society; 2002.	Aircraft noise prediction FLULA	To predict the military and civil aircraft noise, FLULA model has been developed at Swiss Federal Laboratory for Materials Testing and Research (EMPA). According to the model: "The directivity patterns of aircraft noise radiation are estimated from noise records of the flyover noise gathered from an array of microphones, synchronized in time with tracking radar geometrical records of the flown flight path. The resulting one-third-octave noise spectra are used to identify coefficients of a polynomial, which describe the directivity pattern of the aircraft in flight. For the prediction of noise at various aircraft speeds the polynomial model is extended by a velocity dependent term adjusted for convection amplification. Using the adjusted measured directivity patterns the takeoff ground roll noise can be predicted accurately". This model can be effectively utilized in combination with computer simulations to accurately model noise exposes both, inside and outside the aircraft.

Appendix 2. Gap Analysis for Multiphase modeling

Gap analysis for Multiphase modeling

The problem	What needs to be done	Comments
Attenuation pathway and mechanism of sound in the uterus is unknown	Actual dampening effect of amniotic fluid is not known. What frequencies or intensities are dampened? Are these sounds dampened or intensified? What and how much attenuates sound: abdomen wall, amniotic fluid, or uterine wall? Also, question of how much noise is enough to affect the health of the fetus remains unanswered for now.	Describe the propagation of acoustic waves (governed by Helmholtz equation) from external sources into the uterine environment. However, the numerical solution of the Helmholtz equation is an extremely difficult task due to different tissues with densities that lead to scattering and attenuation of waves.

Biomechanical models to represent pregnancy are limited by the lack of time resolved data of the pregnant abdomen during gestation	Add knowledge of uterine environment during gestation	It can be done by obtaining of pregnancy data from non-invasive medical imaging (CT, MRI scans) to create solid models of the pregnant abdomen.
Mechanism and prevalence of soft tissue and bone conduction of noise are unknown	There is a controversy how fetus “hears” and what mechanisms are predominant at various gestation weeks	Geometry and mesh need to be developed for “time-resolved” studies in finite element analyses. Furthermore, determine what is the main pathway for the fetus to “hear” (air, bone, or soft tissue conduction) at low and high frequencies.
Energy transfer pathway <i>bone ↔ soft tissue ↔ air</i> is not adequately researched. Add energy (noise and vibration pathway): <i>air ↔ seat ↔ tissue ↔ muscles</i>	It is necessary to find out how the sound wave (energy) is propagated in human tissue and when attenuation and/or dissipation occurs. Then add <i>air ↔ seat ↔ tissue ↔ muscles</i> : what can fetus hear and how it is affected? Also, include jet cabin and seat	Three postures of human models (vertical seated body, reclined seated body, and seated body in flying posture and several types of seats (soft and hard) can be modeled with emphasis on the vibration and noise exposure. Change certain parameters of the wave to change the bioeffects of the sound waves. Also, to research when and how absorption/dissipation (i.e. conversion of acoustic energy to heat) happens. The Mooney–Rivlin hyperelastic isotropic material model (or neo-Hookean) can be used to simulate the large (especially non-linear) elastic distortion of the soft

	environment into the modeling framework.	tissue. In the model, an elastic strain-energy potential function can be used to characterize the nonlinear relationship between the stress and the strain.
Sitting vs Standing noise propagation is unknown inside and outside the aircraft.	Combine Noise propagation and prediction software like MICROCAP, FLULA2 and ANOPP2 with FEA to account for all internal and external noise effects.	Include three important factors that affect the propagation of sound: geometric spreading , atmospheric effects , and surface effects to FEA framework through prediction models.
Accurate models of reproductive system (cervix, uterus, membranes, and fetus) to be used in Finite Element Analyses are lacking	Soft and hard biological tissues represented as biomechanical models	Human body can be modeled as Hooke elastic material. Biological soft tissues can be represented by a homogeneous, isotropic linear material. Bioheat transfer in tissues can be simulated using Pennes equation for temperature change, and the damage of the tissues can be simulated by employing Arrhenius equation. Cervix can be modeled as viscoelastic tissue. Muscles can be represented by piece-wise uniaxial tension cable elements linking the insertion points
Acquisition of medical images of pregnant women (CT, MRI, ultrasound scans)	Fetal representation in 3D may need to be constructed from pregnant and, perhaps, non-pregnant images may	3D modeling technique Poly Modeling (polygon mesh) can be used to combine modeling with anatomical representations of non-pregnant adults.

	need to be simulated for pregnancies	
Reliable models of pregnant anatomy are lacking	Complex geometries for layers of different tissues and boundary conditions such as ligaments and fascia as well as simple geometries needs to be developed. Sensitivity studies must be performed to determine whether complex geometries are needed, or simple geometries are enough to accurately describe what is needed. Models also must be verified and validated prior the use.	Solid CAD models can be converted into numerical models applicable for biomechanical modeling. However, sometimes it may be too difficult due to high computational requirements. Thus, simplified geometries can be used to capture all the aspects of physiology
Mechanics of the human body to model various phenomena with emphasis	For reliable computer simulations one needs to model elasticity, flow, heat, electromagnetism, acoustic	Use Multiphysics to: Define and solve models for single-phase and multiphase flows

on noise and vibration exposure	waves, etc. and utilize Multiphysics concepts to account for all the effects and interactions	Analyze thermal effects by conduction, convection, and radiation Analyze and model deformation, stiffness, response to dynamic loads Analyze rigid- and flexible-body assemblies using multibody dynamics
Input parameters in biomechanical models are generally based on assumptions	New approaches or techniques for accurate data collection is needed.	Individual geometries can be obtained from CT, MRI etc. scans and combined with tissue-specific cellular models and mechanical information to develop person-specific models. Plane symmetric linear finite-element models can be used for the prediction of static and dynamic compression and shear forces acting on the lumbar discs during whole-body vibration in aircrafts.

Appendix 3. Review article

Exposure of pregnant female aircrew and their fetuses to noise

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Summary: How much noise is enough to affect the health of the fetus and what knowledge gaps exist? This review focuses on direct and indirect health effects of noise on pregnant female aircrew and fetus.

Disclaimer: The views expressed in this paper are those of the authors and do not reflect the official policy or position of the US Air Force, the US Department of Defense, or the US government.

Abstract

All Military personnel will likely be exposed to extremely loud noises (impulse noises > 180 dB), such as various weapons as well as ground, water, and air transportation platforms at some point in their career. However, it is challenging to assess the overall timeline of noise exposures of military personnel, especially during missions and deployment. Extreme noises have auditory and non-auditory effects on health. Unfortunately, military noise may not only induce adverse changes in psychological and physiological well-being and provoke hearing loss but may also affect the health and development of a pregnant female and fetus. We must understand that the fetus is constantly exposed to hazardous noise levels in aviation without adequate protection that may be available to mother. Unfortunately, the pathway and the level of exposure as well as outcomes of such exposure are highly unknown. There is an immediate need for more scientific evidence regarding temporary and permanent noise effects and exposures as well as the development of an accurate, reliable, and predictive numerical modeling framework that would ensure the health and safety of maternal aircrew and their unborn children.

Keywords: female aircrew, fetus, noise exposure, low and high frequency

1. Introduction

Sound is a pressure wave that makes air to vibrate and is always present in our professional and personal environments. Noisy equipment and loud processes are present during all military operations, exposing military personnel to risks of temporarily and permanent hearing damage or even loss. Most likely, military personnel will be exposed at some point to the most intense impulse noises > 160 dB that can be found in any occupation, such as various weapons as well ground, water and air transportation platforms ¹. An 8-h average level of 85 decibels, A-weighted (dBA), requires Hearing Conservation Programs to be active per the Occupational Safety and Health Administration (OSHA) (29CFR1910), and any exposure in the United States Department of Defense (DoD) to levels of 85 dBA (regardless of average levels) requires various levels of hearing protection to be used².

It is difficult to accurately assess the timeline, duration and intensity of military personnel noise exposures, especially during missions and deployment ³. According to Wells and co-workers (2015), jobs that military personnel have usually include exposure to impulse sounds (that are difficult to accurately measure in the field), therefore, it is difficult to understand the overall health effects regarding these exposures⁴.

Loud noises have auditory and non-auditory effects on health. Noise may physically damage the cells inside the ear, causing temporary and sometimes permanent hearing loss ⁵. Over the years, the risk of hearing damage or loss related to impulse noise has been linked to the number of impulse occurrences, the peak level of the noise, and to the duration of that impulse¹. Based on this data, the Department of Defense designed and approved the Design Criteria Standard for Noise limits (MIL-STD 1474E) ⁶.

In addition to auditory effects, exposure to loud noises may also trigger pathological effects, such as cardio-vascular disease due to the formation of high amount of adrenaline that narrows blood vessels resulting in elevated blood pressure ⁷. When a person is exposed to steady-state noise, adverse effects may only occur after a long-term exposure, unfortunately, with impulse noise, a single exposure can lead to irreversible damages ¹. The extent of this damage highly depends on personal factors such as susceptibility, gender, age, physical traits, and genetics, which cannot be easily predicted ⁸.

Evidently, the same hearing protection that has been used for ~30 years is not adequately protecting military personnel, especially the ones in the Air Force against noise damages as over half a million US veterans are currently receiving \$1 billion annually in Department of Veterans Affairs (VA) compensation for hearing loss ⁹. Furthermore, no technology exists to manufacture quieter fighter jet engines without losing in performance. Other challenges associated with noise exposures include the requirement to be close to the noise source, long duty hours and cumulative exposure time ¹⁰.

In addition, noisy environment may also affect the health and development of a pregnant aircrew and their fetuses. Before 1993, all aircrew were removed from duty when pregnant and would need to ask for a medical waiver to remain on the duty between 1 and 34 weeks of pregnancy. Also, pilots from dual-seat non-ejection aircrafts would have to apply for the medical waiver between 13 and 24th week of pregnancy if they wanted to continue their flying duties. In 1993, the United States Armed Forces began permitting women to serve in combat roles. In 2019, The Air Force updated its

policies governing the flight duties of pregnant aircrew. Currently, remotely piloted aircrew, missile duty crews and pilots allowed to do their jobs while pregnant, without asking for the medical waiver ¹¹.

Exposure to high level noise at low frequencies maybe hazardous to health. Indeed, it has been reported that low frequency (< 500 Hz) noise at high level (> 90 dB) can damage human cells and is able to destroy internal organs ^{12,13}. Thus, despite lifted restrictions, several scientific questions remain unanswered: 1) how exposure to high level noise at low frequencies affect the female body and fetus, 2) how much noise is enough to affect the health of the fetus and 3) what data and knowledge gaps exist to better safeguard health and development of mother and fetus in noisy environments.

2. Noise exposure

2.1. Aircraft noise

In the post-World War I commercial aviation, the constant noise exposure to over 120 dB was reported, which usually resulted in the hearing damage or even loss in pilots ¹⁴. However, the introduction of the gas turbine engine in the late 1940's significantly reduced the propeller and exhaust noise, in turn reducing the noise level in cockpits. Currently, loud noises above 115 dB in cockpits are usually associated with the flight tactics to avoid being detected by the radar, such as high speed flying at low altitudes.¹⁴ High cockpit noise is similar in military helicopters as well. For instance, in the modern Chinook helicopter noise >120dB is generated during flights¹⁵. Furthermore, as discussed in F-35 Lightning Joint Strike Fighter Program (United States Air Force),

modern fighter jets produce > 150 dB when using afterburners, which provide additional thrust for takeoff or high-speed pursuit. Also, the average noise level generated in service helicopters was found to be 97 dBA for 'Gazelle', 99.8 dBA for the 'Scout', 99.9 dBA for the 'Puma' and 100 dBA for the 'Lynx' helicopters. ¹⁶.

Aircraft noise is produced by two predominant sources, i.e. the external airflow around and the front of the aircraft, and the other one is internally produced by the air conditioning and cooling systems in the cockpit. The noise generated from the external sources highly depends on the speed and altitude of an aircraft. Importantly, noise levels decrease with increasing altitude due to the dynamic pressure being reduced due to decrease in air density at higher elevations ¹⁴. On the other hand, internal noise levels depend on cockpit conditioning/cooling intensities ^{14,17}.

Furthermore, many rotary wing aircraft have attached weapon systems (e.g. machine guns, missiles) with the uncovered noise source, thus making them very noisy. Also, fixed wing aircraft may also generate loud up to 122 dBA cockpit noise levels. The noise sources include engine and propeller noise and airflow noise that goes around the body of an aircraft ¹. Formation flying may significantly add to the combined noise levels as well ¹⁸.

The environmental noise at and around airports can be determined from the number and types of aircraft, their flight paths, cruising altitudes, take-offs and landings, and the atmospheric conditions.

2.2. Flight line noise

Flight lines also generate noises well above levels that could be safely attenuated using hearing protection ¹. According to Yankaskas and Komrower (2019), there is a limited number of personnel present close to the aircrafts when the engines start. However, there is always 150 – 200 people present on aircraft carriers during aircraft operations such as launch and recovery, fueling and refueling, maintenance, which are exposed to noises > 126 dBA. Also, the noise level can reach 148 dBA during tactical aircraft launches. ^{19,20} Unfortunately, effective noise management approaches are not developed yet that would minimize high level exposures to acceptable levels. ²¹

2.3. Pregnant military aircrew

Most military aircrew are exposed to loud noises during their career while training or deployed. Military weapon systems generate > 140 dB peak sound pressure level (dBP), which is considered the maximum allowed for a single safe unprotected exposure for impulse noise ²². Almost all the ground personnel and aircrew are exposed to steady-state noise higher than 85 dBA while on duty and stationed close to the noise source.

Pregnant military aircrew are exposed daily to loud noises, so the effect of noise exposure on pregnancy should be studied in great details because noise affects both, the fetus, and the mother herself. However, whether loud noise is detrimental to the developing fetus and requires pregnant mother to be removed from service is still unclear ²³. There is scientific evidence that women may have higher risk of cardiovascular changes when exposed to extreme noises ²⁴. Other studies suggest that the higher noise sensitivity of women is an independent risk factor and cardiovascular changes should not be attributed only to noise exposures ²⁵. However, these studies

have been performed on civilian pregnant women and, thus, the actual effects of extreme noise are uncertain in military personnel²⁶.

3. Noise health effects

3.1. Noise exposure mechanism

Noise is an external stressor that activates the endocrine and autonomous nervous system ²⁷. Dzhambov and co-workers (2014) found that the human body reacts to noise using a general stress response leading to neuroendocrine and cardiovascular modifications in the human body ²⁸. Noise activates the amygdala and hypothalamic centers ²⁹, thus affecting synaptic links, as well as emotional and cognitive pathways of perception through cortical and subcortical structures ³⁰. This, in turn, leads to stimulation of the sympathetic-adrenal axis ²⁸. Stress induce the release of maternal catecholamine, which may result in an increased blood pressure and uterine reactivity and thus lead to the decrease of placental integrity leading to hypoxia of the fetus ³¹. Also, cortisol from the mother can pass through placenta and interfere in the regulation of the fetal hypothalamic-pituitary-adrenal (HPA) axis ³². Furthermore, noise can also pass through the abdomen and membrane walls into the uterine environment and affect the development and health of fetus directly. ³³

3.1.1. Internal and external sounds to fetus

Inside the pregnant abdomen, fetus is continuously exposed to cardiovascular, respiratory, and intestinal sounds, which are considered as “background noise” (low frequency noise < 0.1 kHz and max of 90 dB). These background noises are always

complemented by additional external noises such as mother's speech, body sounds, and movements.³⁴ Importantly, vibrations from outside the maternal body (hand-arm or whole-body vibrations) can induce sounds inside the pregnant abdomen. Important parameters to consider when assessing the vibration induced sounds inside the uterus are the static and dynamic forces of the vibrating source and the distance from the source to the fetus.

3.1.2. Key frequencies in the pregnant abdomen

High frequency sounds (> 0.5 kHz) are attenuated by the uterine environment and almost inaudible to fetus, whereas low frequency sounds at about 300 Hz reach the fetus and may induce undesired changes in development and health. For instance, frequencies up to 4 kHz are attenuated by ~ 20 dB at a rate of 6 dB/octave.³⁵ Furthermore, exterior sounds of up to 70 dB (< 0.2 kHz) travel through tissues, uterine wall, and membranes to the fetus with a low attenuation of ~ 5 dB.³⁶ According to Gerhard and Abrams (2000), sound pressure inside the pregnant abdomen are enhanced by the characteristics of the uterine environment and can be significantly higher than outside the pregnant abdomen.³³

3.1.3. How does the fetus hear?

Development of the cochlea and hearing system is a complex process. There are tens of thousands of inner hair cells and receptors within the cochlea that react to specific frequencies³⁷. The main structure of the inner ear starts forming by the end of

15th week ³⁸, ability to respond to sounds coming through the amniotic fluid develops at about 20th week ³⁹, and cochlea as well as peripheral system develops by the 24th week of pregnancy. ^{40, 41}

The exact pathway by which noise is transferred to the fetus is not well documented. It has been hypothesized that predominantly low frequency sounds (< 300 Hz) pass through the amniotic fluid to the fetus by bone conduction. The sound pressure in the amniotic fluid induces skull vibrations which are transferred directly into the cranial cavity and then into the cochlear fluids. It is also possible that sounds are transferred to the fetus air or soft tissue conduction ^{39, 42, 43}

It is important to determine what sound conduction pathways are predominant to conduct sound to the fetus in pregnant females to accurately determine the noise exposures to fetus. There is a possibility that predominantly the soft tissue vibrations make fetus “hear” by inducing actual vibrations of skull bone (i.e., bone conduction-related mechanisms). ⁴⁴. However, there is a large difference between the acoustic impedances of the bone ($7.8 \times 10^6 \text{ kg/m}^2\text{sec}$); water and gel ($1.5 \times 10^6 \text{ kg/m}^2\text{sec}$); typical soft tissues ($1.6 \times 10^6 \text{ kg/m}^2\text{sec}$); air ($0.0004 \times 10^6 \text{ kg/m}^2\text{sec}$). ⁴⁵ It is reported that when there is a large acoustic impedance difference between two medias (air and skull bone is about 70 dB), sound is not transferred but reflected (i.e. attenuated) right at the boundary between these two media. ⁴⁶ For instance, when we have two medias: air and skull, sound vibration in air below 70 dB is not expected to induce bone conduction directly and sound is not anticipated to be transferred by a bone conduction mechanism.

To fully understand the health effect of noise to pregnant female and the fetus, it is important to know how much of the noise is attenuated, reflected, or enhanced as it

passes into the uterine environment. It is generally accepted that the walls of the uterus, fat, amniotic fluid, and muscles of the abdomen attenuate high frequency noises and thus, lower their volume before it could reach fetus ears ⁴⁷. Unfortunately, it is also reported that amniotic fluid amplifies low-frequency sounds, which may be detrimental to hearing development and overall health of the fetus ⁴³. Indeed, Richards et al. (1992) discovered that low-frequency sounds (0.125 kHz) generated outside the uterine environment and the pregnant abdomen were enhanced by about 3.7 dB. Also, internal sounds, such as the mother's voice were enhanced by an average of 5.2 dB, whereas external male and female voices were attenuated by 2.1 and 3.2 dB, respectively ⁴⁸.

3.2. Auditory and non-auditory health effects of noise

Noise-induced hearing damage or loss is usually due to the one-time or continuous exposure to intense impulse noises, such as jet engine, rocket launch or a gun shot or exposure to steady state noises at levels higher than 85 dB in industrial settings. As found by Basner and colleagues (2015), extreme noise permanently destroys sensory cells in the cochlea, thus inducing hearing loss.⁵ Subsequently, hearing loss leads to an inability to understand speech, affects cognitive performance and decreases attention to specific tasks ⁴⁹.

There is a disagreement in the scientific community, whether loud noise (especially in the lower frequency range) is detrimental to the development and overall health of the fetus and requires removal of the pregnant woman from exposure. The normal frequency range that humans hear is between 20 and 20,000 Hertz (Hz);

however, fetus up to 27 weeks of gestation predominantly hears lower frequencies (below 500 Hz) and probably cannot detect frequencies above 500 Hz until 29 weeks due to filtering by the maternal tissues⁵⁰. Also, high frequency sounds are attenuated by the pregnant abdomen environment.

The fetal environment differs from that of a sound environment in air. According to Gerhardt and Abrams (1988), the sound environment where fetus is present comprises of a number of internally generated noises, as well as sounds from the mother such as speaking and moving.⁵¹ There are number of factors that determine what and how fetus will hear the external sounds including but not limited to frequency, intensity of the “background” noise, attenuation, reflection, sensitivity of the hearing, age of the fetus and the position of the fetus in the uterus.

3.2.1. Auditory health effects

Noise-induced hearing loss in adults and children in air has been widely studied, and the permanent detrimental effects of extreme noise levels are well documented⁵².

For instance, The Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) suggested that pregnant women should avoid being in > 90 dB environments.⁵³

Unfortunately, evidence on fetal noise exposure and the effects on fetal health is still extremely limited. It is known that extreme noises (especially low frequency ones) can transfer through the tissues and amniotic fluid, and affect fetal inner ear through, for example, a bone conduction route.⁵⁴ Unfortunately, it is still unknown if all fetuses and at what point during gestation are affected by loud noises, and how exactly.

The fetus has a developmental advantage over the infant because the tissues of the abdomen and uterus muffle most of the high-frequency sounds and attenuate them by as much as 20 to 35 dB⁵⁰. However, there is a disagreement between the actual amount of dB that are potentially attenuated due to complicated procedures to assess it *in situ*. For example, the acceptable scientific procedure to assess fetal sound isolation during animal studies is to surgically remove the fetal head from the ewe, implant an electrode on the fetus, and return it to the uterus. A few days after surgery, a cochlear microphone (CM) response to different types of noises is recorded. Then, the fetus is delivered by cesarean section.³⁴ Unfortunately, as experiments cannot be performed on a human fetus for ethical and safety reasons and many questions cannot be answered directly from animal studies, there is a need to develop accurate predictive numerical modeling approaches and computer simulations.

Based on attenuation, some scientists suggest that pregnant women should avoid areas with noises above 115 dBA or peaks above 155 dBC, even if they are using hearing protection.⁵⁵ However, other evidence suggests that adverse fetal effects (e.g. hearing damage or loss, chromosomal anomalies, high cortisol levels, decreased lactogen levels, as well as ability to rest following sleep/wake cycle of 20 to 30 minutes)²⁸ might happen at much lower than 100 dB noise levels⁵⁶ and amniotic fluid may not sufficiently muffle external sounds. Also, some, especially low frequency sounds may even increase when they pass through the amniotic fluid. Therefore, scientific research and numerical modelling is highly warranted to seal these knowledge gaps.

3.2.2. Non-auditory health effects

According to the noise reaction model, constant low levels of noise may induce adverse non-auditory effects, like disturbances of physical activity and sleep, which can in turn trigger emotional responses, such as annoyance and stress ⁵⁷. Furthermore, chronic stress is linked to cardiovascular risks, such as increased blood pressure, increased blood viscosity and blood glucose, and activation of blood clotting factors ⁵. Continuous noise exposure also increases the risk of cardiometabolic diseases, like arterial hypertension, coronary artery disease, diabetes mellitus type 2, and stroke ⁵⁷.

Other noise effects that cause adverse health and/or developmental outcomes are the following. It was found that placental lactogen was significantly lower after 36 weeks of gestation in women living close to the airport and exposed to airport noise than women living in quiet areas ⁵⁸. Other studies indicated that high noise posed a risk of premature birth. Indeed, women exposed to 80 dB for an 8-hour shift were at higher risk for early birth (relative risk, 1.6; 95% confidence interval, 0.9 to 2.9) as well as the length of pregnancy to be inversely associated with noise exposure living close to an airport ($r = 20.49$; $P = 0.0008$) ⁵⁹. Decreased birth weight has also been associated with noise exposure⁶⁰. Knipschild et.al. (1984) observed that the birth weights of infants were significantly less (69 g, $P = 0.03$) if the mother lived in an area where the noise from aircrafts exceeded 60 to 65 dB ⁶¹.

Knowledge on other non-auditory health effects such as annoyance, increased stress, and dizziness as well as work accidents due to noise exposure is extremely scarce ⁶².

4. Conclusions

Military and more specifically aviation environments are full of high intensity, low and high frequency noises that are hazardous to health. The uterine environment and amniotic fluid may attenuate high frequency sounds, unfortunately, it may also enhance low frequency sounds that may be detrimental to the development and the overall health of fetus. The effects of high intensity sounds on the fetus are not completely known, but some evidence link a three-fold increase in infant hearing loss to occupational noise exposure during pregnancy as low as 90 decibels ⁶³.

Unborn humans are imminently innocent and worthy of protection in the occupational environment. These protections are included in federal and military specific statutes including but not limited to 29CFR1910, AFI 48-145, AFDP 48-1, DoDI 6055.05 and AFDP 90-8. We must understand that fetus is constantly exposed to hazardous noise levels in aviation without adequate protection that may be available to the mother. Unfortunately, the pathway and the level of exposure as well as outcomes are highly unknown. Direct and indirect physiological and psychological responses to noise may vary highly among individuals based on their physical well-being and genetics. This variability and inconsistency would significantly decrease comparability between results of different noise studies. Therefore, before making conclusions on the effects of noise on pregnant females and fetuses one must consider both extrinsic (noise duration, frequency, and intensity) and intrinsic (personal characteristics and physiological tolerance to noise) factors. So, a critical question remains to be answered by the scientific community: How much and what type of noise is enough to affect the health of the fetus or newborn? The answers to this question remain inconclusive.

Undeniably, there is an immediate need for more scientific evidence collected regarding temporary and permanent noise damage and exposures as well as the development of accurate, reliable and predictive modeling that would ensure health and safety of maternal aircrew and their unborn children.

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