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EVALUATION OF DIFFERENT SHIELDING MATERIALS FOR REDUCING ELECTROMAGNETIC INTERFERENCE OF THE PERSONAL DUST MONITOR 3700

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ABSTRACT

The personal dust monitor (PDM) (model PDM3700), as well as other electronic devices, can cause electromagnetic interference (EMI) which can disrupt the operation of some proximity detection systems (PDSs). A 15 cm (6 inch) minimum separation distance between the miner-wearable component (MWC) of the PDS and the electronic device usually avoids these disruptions, but due to the amount of equipment on a miner's belt and the method of wearing the PDM in some situations, this distance can be difficult to always reliably maintain. Another method of reducing EMI effects is utilizing magnetic field shielding. The shielding capability of several different materials was investigated by surrounding the PDM with the material and quantifying the EMI. A copper mesh pouch reduced the EMI from a PDM3700, allowing a minimum separation distance of 10 cm (4 inches) instead of 15 cm (6 inches) as shown in a previous study for an unshielded PDM. A MU-metal box had a better shielding effectiveness, as it further reduced the minimum separation distance to less than 7 cm (2.8 inches). Shielding reduced the EMI of the PDM with MU-metal providing better results than the copper mesh. These materials may be beneficial for shielding individual components of the PDM or for constructing a shielded pouch. However, before the advantages of a shielded pouch can be determined, the effects of just the shielding material (metal) on the PDS needs to be quantified.

INTRODUCTION

According to statistics from the Mine Safety and Health Administration (MSHA), 43 miners have been fatally struck or pinned by a continuous mining machine (CMM) since 1984. In an effort to prevent future striking and pinning fatalities from occurring, proximity detection systems (PDSs) have been developed and are required on all operating CMMs in underground coal mines, with the exception of full-face CMMs, by 2018 (MSHA, 2015).

PDSs are designed to alert miners and immediately stop machine motion in order to protect miners from being struck, pinned, or crushed by CMMs (Jobes, et al., 2012). Currently, MSHA-approved PDSs installed on CMMs are based on measurement of magnetic flux density (B-field) (Li, et al., 2012; Li, et al., 2011). The system generates a magnetic field around a CMM and determines the relative distance of a miner from the CMM based on a detected magnetic flux density. A MSHA approved PDS includes magnetic field generators, which are mounted on the machine, and magnetic field receivers, which are worn by the miners (the miner-wearable component (MWC)). A magnetic field generator utilizes a ferrite-cored coil antenna to generate a magnetic field that is proportional to the current running through the coil. A magnetic field receiver measures the field strength in terms of the magnetic flux density, which decreases in a predictable manner with increasing distance between the generator and the receiver. This measured field strength is then wirelessly transmitted between the receiver and the PDS controller, and the system uses the measurement to estimate the distance between the generator and the receiver. Based on the estimated distances, a determination is automatically made of whether the miner is located in an area susceptible to striking and pinning accidents. This information is used to determine when a miner wearing a MWC is in a warning zone or stop zone, which would trigger different alarms and actions, such as slowing the machine down or stopping it.

When implementing electronic devices like a PDS into a work environment, the electromagnetic compatibility (EMC) of the devices and electromagnetic interference (EMI) should be considered (Sevgi, 2009; Shechter, 2015). EMI is an unintentional electromagnetic interaction between two electronic devices or systems in which one of the devices experiences a degradation in its performance and functionality. This relates to an electronic device's inherent ability to emit levels of electromagnetic energy that may potentially interfere with the proper operation of another device (the victim) in its vicinity. EMC can be defined as the ability to control EMI so that two systems, in close proximity to each other, are able to operate as designed without any degradation in performance. The effects of EMC and EMI have, historically, been implicated in numerous incidents in which control systems failed, causing ships to run off course, aircraft to crash, and medical devices such as pacemakers and defibrillators to malfunction (Sterling, 2007; Paul, 2006; Hubing and Orlandi, 2005). These cases highlight the critical need to consider EMC/EMI in the design and integration of electronic devices for any given environment. Considerations to mitigate this phenomenon are critical in industries such as the military, medical fields, and mining, where faulty operation of equipment may result in costly repairs and even loss of life.

Over the years, several standards have been developed to achieve compatibility between different electronic devices and to prevent the degradation of performance of these devices (IEC, 1997; U.S. Department of Defense, 1999, Tuite 2010). Several administrative and engineering controls, including the filtering of radio frequencies, shielding of electronic components, and recommendations for separation distances of devices, have been developed to reduce the likelihood of EMI (Katrai and Arcus, 1998; Liu and Guo, 2002; Colaneri and Schacklette, 1992). With the promulgation of regulations mandating the use of electronic devices and sensors, the challenges of EMC and, by extension, EMI, are being brought to the forefront.

One case of EMI transpired soon after the personal dust monitor (PDM) 3700 was required to be used to determine respirable dust exposure (MSHA, 2016). The PDM 3700s are devices worn by a miner that continuously monitor and display the amount of respirable coal mine dust in the vicinity of the miner (Page, et al., 2008). The PDM has an internal motor which drives a pump to continuously draw in air from the miner's breathing zone through a tube. The air is drawn through with a cyclone which only permits respirable-size particles to collect on the filter, and the mass of the particles is determined by an oscillating microbalance. The results—the amount of dust in the vicinity of the miner—are displayed on a small screen on top of the instrument. After the implementation of PDMs in underground coal mines, MSHA confirmed reports that at times, the PDM 3700 was causing an interference to the PDS (MSHA 2016).

Internally, the PDM contains the electrical and electronic circuits to operate and control its motor, oscillating microbalance, display, and other units. Those components can generate and emit electromagnetic

(EM) energy. The emitted EM energy can cause a radiation interference with circuitry within a victim device, such as a proximity MWC, causing degradation in the PDS's performance.

One method of mitigating the influence of the PDM 3700 on the PDS is to keep a separation distance of at least 15 cm (6 inches) between the MWC and the PDM (Noll, et al., 2017). However, this is not always practical. Miners have to wear a number of components on their belt, and while performing their tasks, components can be shifted along the belt which can make it difficult to ensure that the MWC and PDM are 6 inches apart. In addition, especially in low coal, some miners prefer to have the PDM in a bag with a strap which can be moved out of the way when performing different tasks in mining. When moving the PDM it can be difficult to ensure that the PDM is 6 inches from the MWC. Another way of reducing the effects of the EMI is to mitigate it with different types of shielding. Conductive materials are used for shielding by redistributing or altering the path of the electromagnetic field lines, preventing the stronger field lines from reaching the victim device. For shielding low frequencies (< 100 kHz), material with high permeability is recommended (Emrich, 2010; Chung, 2000). The high permeability material redirects the magnetic field through the shielding material and away from the victim.

The frequency of concern with the PDS is between 70-100 kHz. Two commonly used shielding materials are copper and MU-metal (Emrich, 2010; Chung, 2000). Copper is highly conductive, which is good for high frequencies, and it can reduce EMI at frequencies near 100 kHz. MU-metal is a high permeability material and is better suited for the lower frequencies (<100 kHz). In this study, the PDM 3700 was surrounded by a copper mesh and different thicknesses of MU-metal to determine what types of materials would work best for reducing EMI from the PDM.

METHODS

Measuring EMI from PDM 3700 enclosed with different shielding materials:

Traditionally, the RE101 military standard has been used to characterize the EMI from different electronic devices (DoD, 1999)). In this study, it was used to characterize the effectiveness of different shielding materials. A series of RE101 experiments, using the set-up shown in Figure 1, were conducted to measure emissions from a PDM 3700 enclosed in different shielding materials. The RE101 tests (DoD, 1999) were completed in a Panashield radio frequency (RF) shielded enclosure that prevents any outside signals from traveling through the walls. The RE101 measurements were recorded with a Tektronix RSA5103A Real Time Signal Analyzer connected to a receiving loop antenna.

RE101 requires the electronic device to be 7 cm (2.8 inches) away from the antenna. In this test, an HP11966K magnetic field coil antenna was used to measure the EM emission radiated from the PDM 3700, and a Tektronix RSA5103A signal analyzer was used to store the measured emissions and perform the spectrum analysis. The emissions from the PDM 3700 were measured for different orientations (body, cyclone, front, and TEOM) as shown in Figure 2 and described below. The body position is the side that is against the body if worn on a belt. The cyclone position is where the dust enters the instrument through a cyclone (size selector). Lastly, the front is the side facing away from the body. The TEOM side is where the mass transducer was measured using the tapered element oscillating microbalance (TEOM).

First, the RE101 test was performed for the PDM 3700 without any shielding. Next, the same test was performed with the PDM enclosed in a shielding material. A PDM was completely shielded with a pouch or box made of different materials. A commercial copper mesh PDM 3700 shielding pouch was used to evaluate the copper mesh. Three MU-metal boxes with thicknesses of 0.05, 0.15, and 0.25 mm (0.002", 0.006", and 0.01") were constructed. Figure 3 shows the pouch with copper mesh, the 0.25 mm (0.01"), 0.15 mm (0.006"), and the 0.05 mm (0.002") MU-metal boxes..

If the PDM 3700 enclosed in the shielded pouch or box at 7 cm (2.8 inches) from the antenna still resulted in PDS interfering EMI, the same RE101 test was performed at distances of 10 cm (4 inches) and 15 cm (6 inches) between the enclosed PDM 3700 and the antenna. This procedure quantifies the EMI levels at different separation distances between the MWC and PDM 3700. It will also determine if the shielded pouch allows the PDM 3700 to be closer to the MWC, without causing a malfunction in the PDS, than an unshielded PDM 3700.

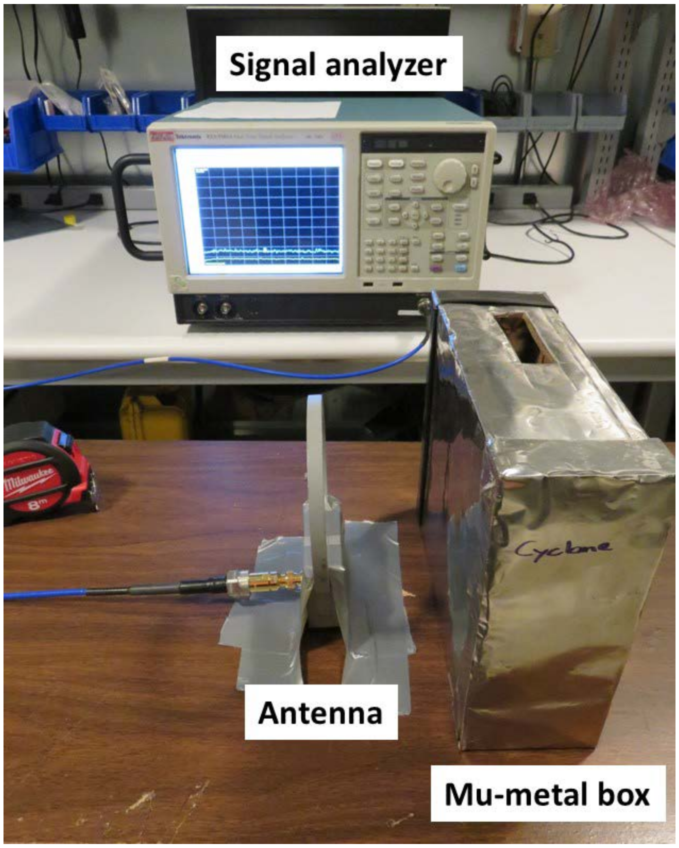

Figure 1. RE101 setup with electronic device (e.g. PDM 3700 in MU-metal box), antenna, and signal analyzer. This was performed in a RF shielded enclosure which is not shown in the picture.

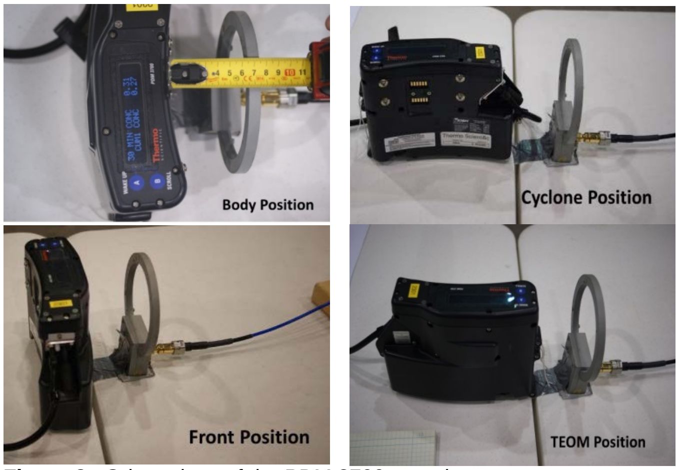

Figure 2. Orientations of the PDM 3700 tested.

Method of quantifying EM emission from individual components:

In addition to shielding the whole PDM 3700, another common way that shielding materials are used is to shield the main sources of EM emissions (individual internal components of the PDM 3700) (Valuc 2015, Lee et al. 2016). Therefore, this could potentially reduce the overall EMI from the PDM 3700. To identify the main sources of EMI, measurements of EM emission levels from different areas of the

PDM 3700 were collected. Figure 4 illustrates the experimental setup for the method. As seen in Figure 4, the probe of the Narda ELT-400 Tesla meter was placed to touch a point on the PDM 3700 and measure the magnetic flux density. The probe was moved to each point and the measurement was repeated. In this case, a total of 170 points were taken, covering all of the 6 surfaces of the PDM. Figure 5 gives an example of the space between each measurement horizontally. All areas of the PDM 3700 were quantified by the measurements. A tight series of measurements was required to correlate a high EM emission reading to individual internal components of the PDM 3700. Vertical measurements along the PDM 3700 surfaces were also collected in a close array.

Figure 3. Pouch with copper mesh (top left), a box with MU-metal 0.25 mm (0.01") thickness (top right), and boxes with MU-metal 0.05 mm (0.002") and 0.15 mm (0.006") thickness (bottom).

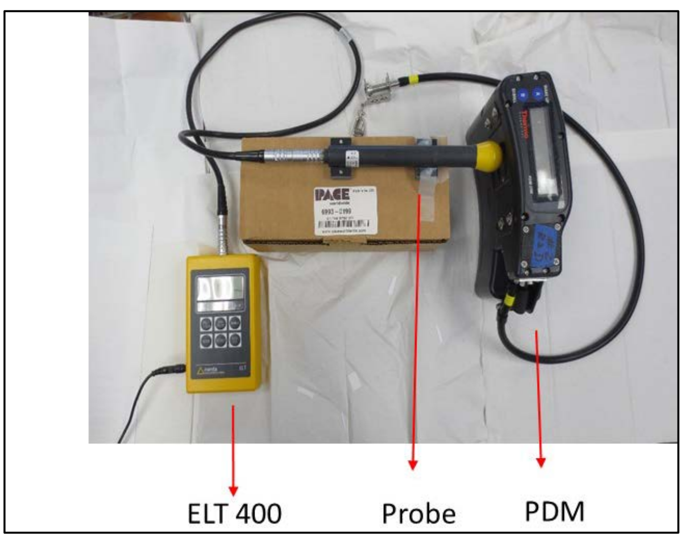

Figure 4. Schematic of probe from a Narda ELT-400 Tesla meter being used to capture measurement of one location of a PDM 3700.

RESULTS AND DISCUSSION

EMI from PDM enclosed in shielding materials

In order to determine how the EM emissions from the PDM with the different shielding materials would affect the PDS, the EM emitted from the PDM 3700 without shielding and with the different types of shielding were compared to the susceptibility curve (further described below) of the PDS determined in a previous study (Noll, et al., 2017). The susceptibility curve shows the EM emission level above which EMI could occur and interfere with the function of the PDS. Therefore, if the EM emission from an electronic device is less than the value of the susceptibility curve, then the EM emitted from the device should not interfere with the PDS. The RE101 results from the position (body, cyclone, front, and TEOM) which produced the highest or worst case EM emissions was used to compare to the susceptibility curve.

Figure 5. Examples of how each of the measurements was collected.

Test results in Figure 6 showed that the copper mesh and the MU-metal both reduced the EM emission from the PDM 3700. The reduction was better with the MU-metal of 0.05 mm (0.002 inch) thickness than with the copper mesh, and further reductions in EMI from the PDM 3700 was observed as the thickness in MU-metal increased. As shown in Figure 7 when copper shielding was used in a pouch which surrounded the PDM 3700, the emissions from the PDM 3700 were below the susceptibility curve at 10 cm (4 inches) from the antenna. The emissions from the PDM with the copper mesh was below the susceptibility curve in the front position when 7 cm (2.8 inches) from antenna. However, at times, the emissions from the PDM 3700 with copper mesh shielding were above the susceptibility curve when the PDM was 7 cm (2.8 inches) from the antenna and in the body (as seen in Figure 6), cyclone, and TEOM positions.

As also seen in Figure 6, the emission from the PDM 3700 enclosed with MU-metal was below the susceptibility curve with all three thicknesses. At the 73.35 kHz frequency which was the frequency most susceptible to EMI, the 0.05 mm (0.002") thickness was at 53.5 dBpT which was just below the value of the susceptibility curve (53.8 dBpT). The emissions from the 0.15 mm (0.006") thickness was better with a value of 51.28 dBpT at the 73.35 kHz, and 0.25 mm (0.01") thick MU-metal provided the best shielding of the materials tested with the emissions of 42.36 dBpT.

Some mines are using pouches to reduce EMI from the PDM 3700. Both the copper mesh and MU-metal demonstrated benefits as materials for these pouches, but the MU-metal demonstrated more reduction in EMI and potentially allowing the PDM to be closer to the MWC than the copper mesh. The PDM 3700 with the copper mesh was within 10 cm (4 inches) from the antenna when the emissions were below the susceptibility curve in all cases tested. The emissions of the PDM 3700 enclosed with MU-metal were below the susceptibility curve even when within 7 cm (2.8 inches) of the antenna for all tests.

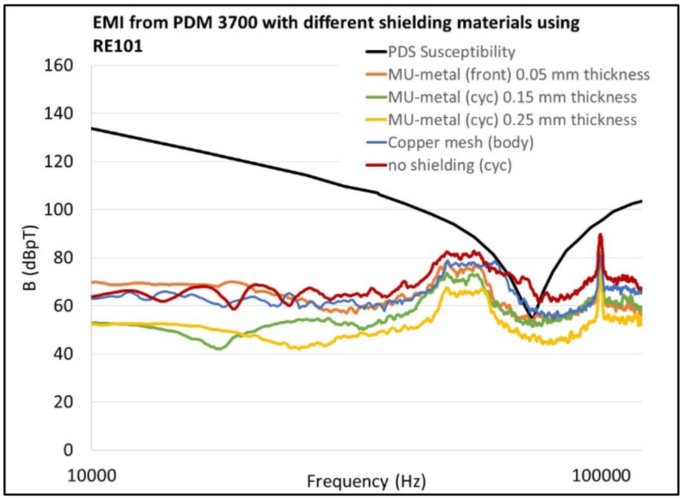

Figure 6. Graph of electromagnetic emissions from the PDM 3700 with no shielding and enclosed in copper mesh, and in 0.05, 0.15, and 0.25 mm (0.002", 0.006", and 0.01") MU-metal.

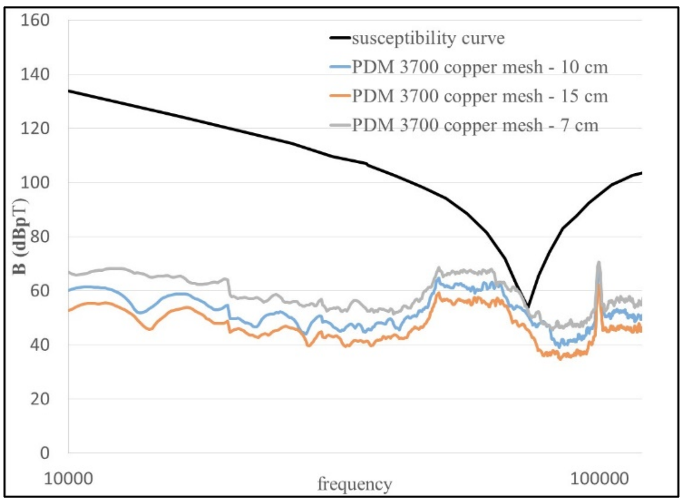

Figure 7. Graph of electromagnetic emissions from the PDM 3700 enclosed with copper mesh at different distances from the antenna.

However, this does not necessarily mean that if a PDM 3700 is enclosed with MU-metal that it can be within 7 cm (2.8 inches) of the MWC and not influence the PDS. The shielding material will reduce the EM emission from the PDM, but the metal itself may interfere with the PDS. The effect of the shielding material itself on the PDS needs to be quantified before it is known how these pouches and boxes may be beneficial.

EM emissions from individual components

Besides a complete enclosure, these shielding materials could be used to encase certain components to reduce the effects of the EM emission as stated before. Therefore, the EM emission was quantified around the PDM 3700 to find the large radiation sources from it. After collecting measurements around the case of the PDM 3700, a comparison was made among these measurements to identify the areas of radiation. Figure 8 shows an emission map of the front of the PDM 3700. Most of the measurements were below 1 µT. Measurements above this baseline or above most EM values around the PDM indicated areas of higher emissions. There were some locations on other sides of the PDM, which showed higher emissions as seen in Figure 9.

The high emission areas shown in Figure 9 indicate that the mass transducer, PWM motor control, and battery pack were much higher in emissions and may be components where shielding may help reduce the EMI effects of the PDM 3700.

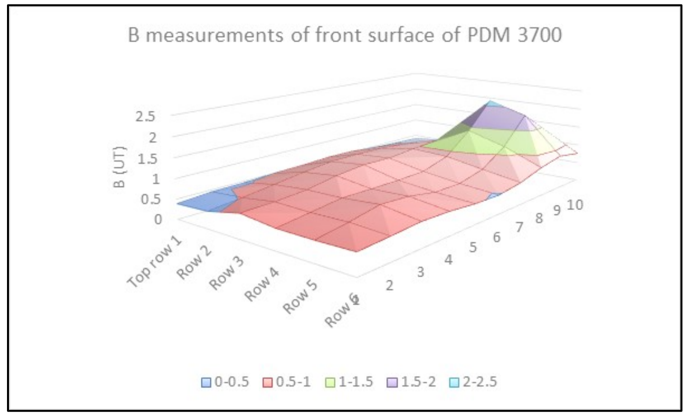

Figure 8. Mapping of the emission level for different positions on the front of the PDM 3700. The height of each square area represents a magnetic flux density measurement at the area measured.

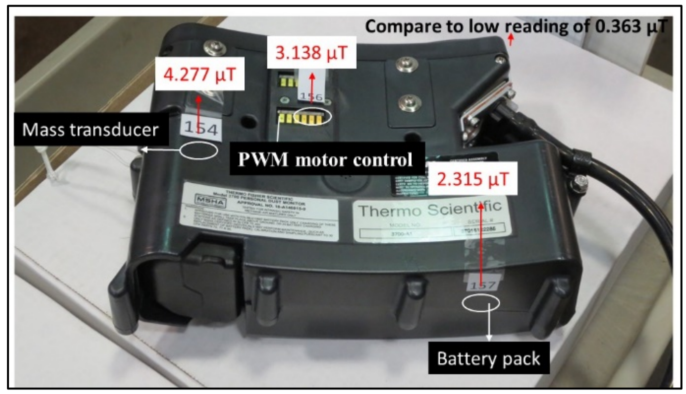

Figure 9. Illustration showing areas of the PDM 3700 that demonstrate higher EM emissions.

CONCLUSION

This paper presents the test results of some shielding materials and the measurement results of the EM emission of the PDM. A copper mesh pouch reduced the EMI from a PDM 3700, but the MU-metal boxes were found to reduce the EMI more effectively than the copper mesh. These shielding materials may also be used to surround individual components that are inside of the PDM 3700 to provide an overall reduction in EMI. The tests showed that the components of the mass transducer, PWM motor control, and battery pack are locations of the higher sources of EMI. From this, a shielding strategy could be developed to reduce the overall EM emission of the PDM by shielding these components. This will reduce the effects of EMI on the PDS enhancing its capability of protecting miners from striking and pinning accidents.

LIMITATIONS

Before the overall benefit of using a completely shielded enclosure on a PDM is recommended, the effects of just the shielding materials themselves on the PDS need to be quantified. The shielding material itself may influence the operation of the PDS. In addition, how these materials could be constructed into a pouch was not discussed in this paper. The effectiveness of the exact pouch design would need quantified.

DISCLAIMER

Mention of a company name or product does not constitute an endorsement by the National Institute for Occupational Safety and Health. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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