Mathematical modelling of lead assimilation by printing press operators in a poor indoor air quality environment

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Abstract: Most printing presses in developing countries are located in buildings with inadequate natural and mechanical ventilation such that the press operators work for major hours in poor indoor air quality buildings, which expose them to a wide range of health hazards such as lead poisoning. Understanding how poor air quality affects the operator's body system is studied using a methodology involving the principle of diffusion and the law of mass action. A hypothetical press in Nigeria is used as a case study to illustrate the workability of the model, which may be of value to health inspectors to printing presses.

Keywords: lead; assimilation; nose printing press; operators.

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1 Introduction

Several mishaps such as hearing losses, loss of fingers, hands, legs and other vital parts of the body and high level of occupational risks ranging from exposure to dangerous moving parts of machines to contacts with harmful substances have been reported as severe occupational hazards faced by printing press workers (Sinha et al., 1993; Cherry et al., 2001; Steinberg, 1961). They have also been found to have some deficiencies in the body system (such as iron) and a number of gastrointestinal problems such as constipation, vomiting, poor appetite, weight loss, kidney problem, and reproductive malfunctioning. In printing press environments, lead has been reported to significantly affect operators through the use of ink or toner, which is poisonous to the human body (Blaskette and Boxal, 2001; CDCP, 2006; NHMRC, 2006). Lead absorption among printing press workers has, therefore, become a major research interest on a worldwide scale since enormous loss of lives of workers is experienced owing to lead poisoning, and an increasing legal liability results owing to litigation charges.

Documentation on lead exposure in occupational settings has been recorded on battery manufacturing units (Krishna-Murthy et al., 1988), printing press workers (Murthy et al., 1990; Twyman, 1970; WHO, 2006), and among traffic personnel (Krishna-Murthy et al., 1992). Successful investigations have been carried out across countries such as India (Krishna-Murthy et al., 1988, 1992; Murthy et al., 1990). In two investigations, Rajah and Ahuja (1995, 1996) studied lead exposure among printing press workers. The first study evaluated the genetoxicity of a combination of lead and smoking exposure in printing press workers (Rajah and Ahuja, 1995). The approach relies on the interaction between lead and smoking exposure as two common agents. It was reported that lead-exposed individuals had a significant increase in frequency of sister chromatid changes and that double exposure to smoking and lead inhibits mitosis. The second study by Rajah and Ahuja (1996) evaluated the genetoxicity of a double-exposure to alcohol and lead in subjects from the printing industry, and the possible interaction between these two agents. It was found out that alcohol consumers had a significant increase in frequency of Sister Chromatid Exchanges (SCEs) when compared with the controls. Though there was an increase in the frequency of chromosome aberrations and SCEs in individuals exposed to lead, it was not significant. Statistical analysis did not reveal an interaction between alcohol and lead in either assay. In sum, Rajah and Ahuja (1995,

1996) related three variables in their two studies: lead exposure, smoking and alcohol. The studies reviewed here are experimental but limited since it could not be generalised in all situations. This gap should be bridged by theoretical modelling, which is pursued in the current work.

Murthy et al. (1990) reported a morbidity survey relating to lead toxicity among workers engaged in letter press printing work by clinical examination of workers and estimation of blood lead and urine lead in their blood and urine samples. It was observed that higher blood and urine lead levels existed among the study groups when compared with the age and experience of the matched control group. While this study provides adequate information for further studies, results obtained may vary depending on the environment where the measurements are made and other set parameters. However, incorporating this into mathematical model may provide adequate insights on obtaining a robust model that would be useful in many work environments. This important gap is pursued in the current work.

In Nigeria, the printing enterprises share similar characteristics with those in other developing countries in Africa, Asia and the rest of the world. Usually, many printing businesses occur on a small scale, and are geographically scattered, and located across major cities. For example, in Lagos, Nigeria, a large concentration of these small-scale printing businesses are located in the areas of Somolu, Agege and Mushin. These locations are of short distances to the concentration of multinationals and local industries, which have their headquarters in Lagos. Such companies that require printing services include advertisement and product packaging. Thus, printing is a lucrative business in many of these commercial nerve centres of Nigeria. Unfortunately, a large number of Small Scale Enterprises (SMEs) still engage in the traditional processing activities in building enclosures that are poorly ventilated. Of particular concern is the improper usage and handling of poisonous substances and materials such as lead, which are used for printing purposes. In these SMEs, operators usually inhale some of these substances in quantities that may be hazardous to health. In other situations, operators swallow these substances through food intakes.

Despite the seriousness of these problems, it appears that little documentation exists on lead exposure research; in particular, quantifying the amount of lead absorbed into the body by operators in printing presses is missing. Since lead is emitted in a gradual process and gets to a threshold in the operator's blood that its effect is noticed to determine the quantity of lead assimilation at that threshold, there is a strong requirement to mathematically model the relationship among variables involved in the assimilation process and determine the time it will reach that harmful level. This goal is pursued in the current work. The structure of the paper is as follows: the introduction presents the problem, the motivation for carrying out the study. Section 2 discusses the methodology utilised to solve the problem. Section 3 presents the case study that discusses the practicality of the proposed model through a verifiable practical case. Section 4 concludes the study with remarks.

2 Methodology

2.1 Assumptions

The following assumptions are made to make the model valid:

- The amount of particles inhaled by the operator varies directly as the level of activities the operator is engaged in. For example, within the same enclosure and condition of work, an operator who spends a maximum of 5 hours per day on lead-related activities would not inhale as much lead particles as one who spends overtime (above 8 hours of work).
- The amount of lead particles inhaled depends on the ventilation provided in the enclosure that the worker operates. It also depends on the size of enclosure. Thus, in highly ventilated environments, lead particles are blown away from the operator. Also, for small enclosures, the operator is much restricted in movement and hence trapped in lead particles.
- The amount of lead deposits in the blood of operation is directly proportional to the rate of working.

2.2 *Mathematical derivations*

From the understanding of the concept of lead assimilation, it seems that the principle of diffusion is applicable to the problem at hand. Fick's law of diffusion has recently dominated the research arena with a number of contributions made during the last decade to model transport problems (Gomez et al., 2007; Keer and Kacur, 1998; Steel and Nieber, 1994; Lai et al., 2004; Prabhugouda et al., 2005). Gomez et al. (2007) modelled pure-diffusive transport problems by substituting the classical time-dependent constitutive equation by Fick. Keer and Kacur (1998) model the kinetics of some diffusion-limited phase transformation using Fick's laws. Lai et al. (2004) modelled the inertialess particle deposition onto smooth surfaces under the influence of electrostatic force using a modified Fick's law equation accounting for Brownian and turbulent diffusion, spatially independent external force based on the simplified three-layer model. Prabhugouda et al. (2005) combined the application of Fick's law of diffusion and Beer-Lambert law for light absorption to determine the diffusion coefficient and aniline in benzene. Steel and Nieber (1994) adapted a cubic sphere and tube network model of porous media from petroleum engineering using Fick's law and the principle of conservation of mass to simulate one-dimensional, steady-state, isothermal, isobaric, molecular diffusion of a dilute binary gas in a nonadsorbing porous medium containing a single nonwetting fluid (air) and a single wetting fluid (water). From the above review, there are evidence that Fick's law is applicable to lead assimilation in a poor indoor air quality environment as treated in this work. This is a strong justification for the mathematical derivations that follow.

The starting point in modelling lead assimilation is to apply the law of conservation of matter. It is known that:

$$Y = X + Z. \tag{1}$$

However, lead particles deposited in printing press, those inhaled, and the amount not inhaled all varies with respect to time. Thus, we could express equation (1) as a function of time, t, as follows:

$$Y(t) = X(t) + Z(t). \tag{2}$$

If we consider rate of change of X, Y and Z with respect to time as differentials, we have:

$$\frac{dY}{dt} = \frac{dX}{dt} + \frac{dZ}{dt}. \tag{3}$$

It is now required to find out substitute equations for the variables in equations (2) and (3). Now, consider the analysis on the amount of lead particles inhaled by the operator. Since these particles have diffusive characteristics in the environment, Fick's law of diffusion may be helpful in understanding how to analyse this situation. In an applied form, Fick's law of diffusion relates to the time rate of the movement of the lead into the operator through the nose. This is proportional to the area of the nose and the difference in concentrations of the lead on the inside and outside parts of the nose of the operator. Usually, the research period is to short that growth of the human body could be negligible. Consequently, the area of nose is held constant. The concentration of the lead on the outer side is kept fixed since the main action part, which permits much concentrated lead, is the inside part through which lead enters the lungs as deposits. Hence, concentration of the lead at the centre side of the nose is 'd'. Note that, concentration of the lead on the other side initially is $U_o = d$. Then, Fick's law gives:

$$\frac{dd}{dt} = k(d - U) \tag{4}$$

k is a constant.

However,

$$U_{(o)} = U_o. \tag{5}$$

By integrating the re-expressed form of equation (4) with equation (5),

$$d - U_{(t)} = (d - U_{(o)})\,e^{-kt}. \tag{6}$$

Note that as $t \to \infty$, $U(t) \to d$, whatever be the value of $U(o)$. It should be known that $U(t)$ is actually $X(t)$. To find $Y(t)$, we can apply the law of mass action since the lead particle is combined with the air in the printing press environment. First, let us consider the two chemical substances 'air' and 'lead' to be combined in the ratio of say, $e:f$ to form a third substance, J.

However, the proportions of air and lead present in third substance J are $eJ_{(t)}/(e+f)$ and $fJ_{(t)}/(e+f)$, respectively. Now, considering the initial amounts of air and lead in the environment (say E and F, respectively, and applying Fick's law of diffusion,

$$\frac{dJ}{dt} = k\left(E - \frac{eJ}{(e+f)}\right)\cdot\left(F - \frac{fJ}{(e+f)}\right). \tag{7}$$

Equation (6) obtained is a non-linear differential equation for a second-order reaction. Similarly, for an nth order reaction, we obtain the non-linear equation:

$$\frac{dJ}{dt} = k\,(E_1 - e_1J), (E_2 - e_2J), \ldots, (E_n - e_nJ) \tag{8}$$

where $e_1 + e_2 + e_3 + \ldots + e_n = 1$.

Note that a condition exists in which $E \equiv E^*$, and $F \equiv F^*$. Thus, dJ/dt actually refers to $Y_{(t)}$. If E^* is the amount of air in the printing press environment. Also, F^* is the amount of lead deposited into the printing press environment. It must be noted that dJ/dt is actually $Y_{(t)}$.

We do not look at the aspect in which the mixed reaction of air and lead dust now travel through the nose of the operation into the body of the operator. If the lead enters the nose at a constant rate R and after filling the nose with the mixture concentration $e_{(t)}$. If it also enters the lungs of the operators at the same rate R, so the volume of the solution in the nose remains M. Analysing all the variables, we apply the principle of continuity, we get:

$$M\left[e(t+\Delta t) - e_{(t)}\right] = RN_{N} - \mathrm{Re}_{(t)N} + O_{(N)} \tag{9}$$

reducing, we have:

$$M\frac{de}{dt} + \mathrm{Re} = RN. \tag{10}$$

Integrating, we have,

$$e_{(t)} = e_{(o)}\exp\left(-\frac{R}{m}t\right) + N\left[1 - \exp\left(-\frac{R}{m}t\right)\right]. \tag{11}$$

As $t \to \infty$, $e(t) \to N$, so that ultimately the nose has the same concentration as the printing press environment.

Since,

$$e_{(t)} = N - (N - e_o)\exp\left(-\frac{R}{m}t\right). \tag{12}$$

If $N > e_o$, the concentration in the nose increases to N; on the other hand, if $N < e_o$, the concentration in the nose decreases to N. This can be seen in Figure 1. If the rate R' at which the solution leaves the nose is less than R, the equations of continuity give:

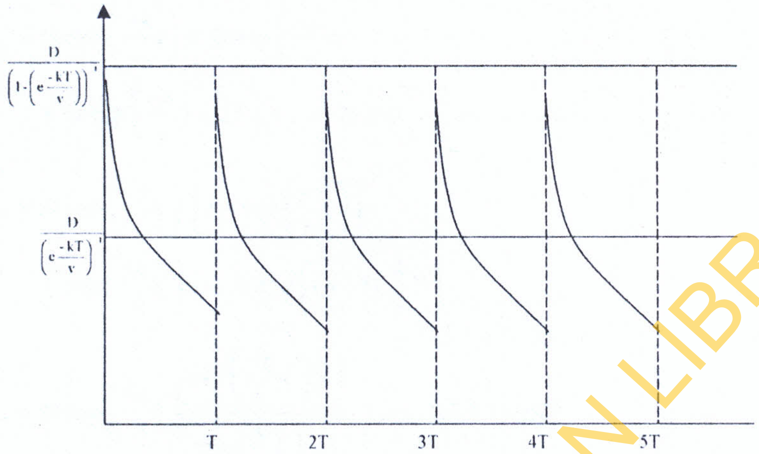
$$\frac{d}{dt}\left[(M_o + (R - R')t)e_{(t)}\right] = RN - R'_{(et)} \tag{13}$$

where M is the initial volume of the solution in the vessel. This is also a linear differential equation of the first order. Let us now take a look at the dissolution that takes place in the human body. Let $g_{(t)}$ be the amount of undissolved lead in the blood of the operator at the time t and let h_o be the maximum concentration or saturation concentration, i.e., the maximum amount of the lead that can be dissolved in a unit volume of the solvent. Let V be the volume of the blood. It is found that the rate at which the lead is dissolved is proportional to the amount of undissolved lead and to the difference between the concentration of the lead at time t and the maximum possible concentration, so that we get:

$$\frac{dg}{dt} = kg_{(t)}\left(\frac{g_{(o)} - g_{(t)}}{V} - h_o\right) \tag{14}$$

$$\frac{dg}{dt} = \frac{kg_{(t)}}{V}(g_o - h_oV - g_{(t)}). \tag{15}$$

Figure 1 Concentration levels of lead in the body



Now, to analyse the mixing rate, so that the effect can eventually ascertain, let the volume of blood in the human body be V and let the initial concentration of lead in the blood stream be $c_{(o)}$. Let lead be introduced in the blood stream at a constant rate, I. Lead is also removed from the blood stream owing to the immune guards of the human body at a rate proportional to $c_{(t)}$, so that the continuity principle gives:

$$V\frac{dc}{dt} = I - kc \tag{16}$$

which is similar to equation (2).

Now, let an amount of lead dust D be inhaled into an operator at regular intervals of duration T each. The lead also disappears from the system at a rate proportional to $c(t)$, the concentration of the lead in the blood stream, then the differential equation given by the continuity principle is:

$$V\frac{dc}{dt} = kc. \tag{17}$$

Integrating,

$$c_{(t)} = D\exp\left(\frac{-k}{v}t\right), \quad 0 \le t < T. \tag{18}$$

At time T, the residue of the first lead intake $D\exp((-k/v)\,t)$ and now another intake D is given, so that we have:

$$\begin{aligned} c_{(t)} &= \left(D\exp\left(\frac{-k}{v}t\right) + D \right)\exp\left(\frac{-k}{v}(t-T)\right) \\ &= D\exp\left(\frac{-k}{v}t\right) + D\exp\left(\frac{-k}{v}(t-T)\right) \quad T \le t < 2T. \end{aligned} \tag{19}$$

The first term gives the residual of the first intake and the second term gives the residual of the second intake.

By proceeding in the same way, we get after n intake have been given:

$$c_{(t)} = D\exp\left(\frac{-k}{v}t\right) + D\exp\left(\frac{-k}{v}(t-T)\right)$$
$$+ D\exp\left(\frac{-k}{v}t - 2T\right) + \ldots + D\exp\left(\frac{-k}{v}(t-(n-1)T)\right) \tag{20}$$

$$c_{(t)} = D\exp\left(\frac{-k}{v}t\right)\left(1 + \exp\left(\frac{k}{v}T\right)\right)$$
$$+ \exp\left(\frac{2k}{v}T\right) + \ldots + \exp\left((n-1).\frac{k}{v}T\right) \tag{21}$$

$$c_{(t)} = D\exp\left(\frac{-k}{v}t\right)\frac{\exp\left(\frac{-k}{v}T\right)-1}{\exp\left(\frac{k}{v}T\right)-1}, \quad (n-1)T \le t < nT \tag{22}$$

$$c\,(nT-0)D = \frac{1-\exp\left(\frac{-k}{v}nT\right)}{\exp\left(\frac{k}{v}T\right)-1} \tag{23}$$

$$c\,(nT+0) = D\frac{\exp\left(\frac{k}{v}T\right) - \exp\left(\frac{-k}{v}nT\right)}{\exp\left(\frac{k}{v}T\right)-1}. \tag{24}$$

Thus, the concentration never exceeds $D/(1 - \exp(-kT/v))$. The graph of $c(t)$ is shown in Figure 1.

To finally consider the rate at which this lead poisoning can be spread, we use this model:

Let $S_{(t)}$ and $I_{(t)}$ be the number of lead infected operators and non-infected operators. Initially, let there be n non-infected and one infected person in the printing press environment so that:

$$S_{(t)} + I_{(t)} = n + 1, \quad S_{(o)} = n, \quad I_{(o)} = 1. \tag{25}$$

The number of infected persons grows at a rate proportional to the product of non-infected operators and infected persons and the number of non-infected persons decreases at the same rate so that we get the system of differential equations.

$$\frac{dS}{dt} = -\beta SI; \quad \frac{dI}{dt} = \beta SI \tag{26}$$

so that

$$\frac{dS}{dt} + \frac{dI}{dt} = 0, \quad S(t) + I(t) = \text{constant} = n + 1 \tag{27}$$

and

$$\left.\begin{aligned}\frac{dS}{dt} &= -\beta S\,(n+1-S)\\ \frac{dI}{dt} &= -\beta I\,(n+1-I)\end{aligned}\right\}. \tag{28}$$

Integrating,

$$S_{(t)} = \frac{n(n+1)}{n + e^{(n+1)\beta t}}, \quad I_{(t)} = \frac{(n+1)e^{(n+1)\beta t}}{n + e^{(n+1)\beta t}} \tag{29}$$

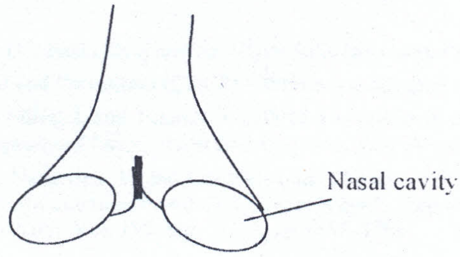
so that

$$\underset{t\to\infty}{\mathrm{Lt}}\ S_{(t)} = 0; \quad \underset{t\to\infty}{\mathrm{Lt}}\ I_{(t)} = n+1. \tag{30}$$

3 Case study

The case examined here relates to a hypothetical business enterprise located at the commercial nerve centre of Lagos. This business, Wemimo printing press is a medium-scale organisation sited at Onipanu. The business occupies two large spaces in a two-storey building, which includes houses, the administrative offices and store on the first storey and the production floor at the ground floor. The spaces being used by Wemimo enterprises was originally designed for a living accommodation without provision for natural ventilation since air-conditional slots are provided on the walls. However, because of the small size of the business enterprise, air conditioners cannot be afforded as mechanical ventilation devices. As such, only two small fans can the business provide. These fans are insufficient for the cutting and Kord machines, which generate a lot of heat. Besides, the poor ventilation of the building makes workers uncomfortable during production activities. The production staff consists of ten workers (seven males and three females), which are spread across various workstations of machines, sorting and collation of printed materials. The products by the business include different kinds of cards, calendars, and books. It should be noted that the ink used for making impression on papers is lead. This material is supposed to be used with gloves worn on the hands. Sadly, the workers do not utilise these protective gloves, and the management has not enforced them. Majorly, the source of inhalation of lead is through the nose. As such, finding the area of the nose is of importance to us (Figure 2).

Figure 2 The nose through which lead is assimilated in the human body



Let 0.02% (w/v) be the amount of lead particles deposited or found in the printing press. Also, let 0.008% (w/v) be the amount of lead particle inhaled by the operator. Then, 0.012% (w/v) will be the amount of lead particle not inhaled. Thus,

$$0.02\%\,(\text{w/v}) = 0.008\%\,(\text{w/v}) + 0.012\%\,(\text{w/v}). \tag{31}$$

This equation is similar to equation (1). We consider the above equation in respect to time and have:

$$0.02\%\,(\text{w/v})(t) = (0.008(t) + 0.012(t))\%\,(\text{w/v}) \tag{32}$$

differentiating:

$$\frac{0.02(t)}{dt} = \frac{d(0.008)(t)}{dt} + \frac{d(0.021)(t)}{dt}. \tag{33}$$

If the area of the nose is constant and the concentration of the lead on one side is kept fixed at say 0.01% (w/m^2) and the concentration on the otherside is 0.008% (w/m^2), then

$$\frac{d0.01}{dt} = k(0.01 - 0.008). \tag{34}$$

This means $0.008\%(\text{w/m}^2)_{(0)} = 0.008\%(\text{w/m}^2)_1$. So $0.01 - 0.008(t) = (0.01 - 0.008_{(0)})e^{kt}$ and $0.008\,(t) \to d$ as $t \to \infty$.

It must be known that 0.08(t) is actually 0.008(t). To find 0.02(t), we can use the law of mass action since the lead particle is combined with the air already in the printing press environment.

First, let us consider the two chemical substances. 'Lead' and 'Air' combine in the ratio of say 2 : 98 to form a third substance 1%(w/v).

If 1%(t) is the amount of the third substance at time t, then, a proportion $(2 \times 1)_t/100$ of it consists of the first substances, which is air and a proportion $(98 \times 1)_{(t)}/100$ of it consists of the second substance.

4 Conclusion

This paper has presented a model to predict the effect of lead assimilation by operators in printing press. A case examination of Wemimo printing press at Shomolu Lagos is given. Figures 1 and 2 are illustrative of the process. It was observed that long exposure to lead could affect the kidneys and liver, and large quantity exposure could result in death.

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Nomenclature

Y	Amount of lead particles deposited in the printing press
X	Amount of lead particles inhaled by the operator
Z	Amount of lead particles not inhaled
M	Volume of air of concentration $e_{(t)}$ in the nose at time t
N	Constant concentration of the solution of air and lead in the press environment
R	Rate at which lead enters the nose
$g_{(t)}$	Amount of undissolved lead in the blood of the operator at the time t
h_o	Maximum concentration or saturation concentration
V	Volume of the blood in the body of the operator
$J_{(t)}$	Amount of the third substance at time, t

E	Initial amounts of air in the environment
F	Initial amounts of lead in the environment
*E**	Amount *f* air in the printing press environment
*F**	Amount of lead deposited into the press environment