Digital radiological surveillance of silicosis and related tuberculosis in the South African mining industry: practical and technical considerations

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ABSTRACT

The switch from analogue to digital radiography formats for surveillance for silicosis and tuberculosis in the South African mining industry raised the question of equivalence of formats for this purpose. As a result, the South African Mine Health and Safety Council (MHSC) sponsored a study, recently published, on the equivalence of digital and analogue radiography in this setting. This commentary aims to provide a summary of the study findings, accompanied by an overview of the practical considerations that arise in the use of digital radiographic surveillance in the South African mining industry. Through a clear understanding of the objectives of surveillance, use of quality and reference standards for hardware and software, and interpretation of digital images, avoidance of common pitfalls, and use of all the clinical and occupational health information on each miner, the contribution of surveillance to identification and control of silicosis and tuberculosis in the mining industry can be maximised.

Keywords: **radiology, surveillance, mining, silicosis, tuberculosis**

INTRODUCTION

This paper is directed at medical practitioners and other professionals with responsibility for, or an interest in, mass radiography in the mining industry and, more generally, in silica dust generating industries in South Africa and elsewhere. Given the widespread changeover from analogue to digital radiography in recent years, we draw attention to a recent study comparing analogue and digital radiography in the detection of silicosis and pulmonary tuberculosis.[1] The publication of this study provides an opportunity to consider, in more detail, a number of technical and practical issues in radiographic surveillance of miners in the South African mining industry, and to make recommendations to enhance the efficiency and effectiveness of the system.

Radiological medical surveillance

The main target conditions of mass radiography in the South African mining industry are silicosis and pulmonary tuberculosis. Both occur at high rates as a result of exposure to respirable silica with its known association with tuberculosis,[2] as well as high tuberculosis infection rates in congregate settings and high prevalences of HIV infection.[3,4]

The Witwatersrand gold mining industry was one of the first to introduce mass radiography at the beginning of the 20th century.[6] Mass miniature radiography (MMR), which became widely used in the 1960s, was originally developed for the South African mining industry.[7] However, racially-based practice pervaded the system: white miners were examined with full size films, while MMR was restricted to miners in job groups four to eight (mainly black miners) (Paulette Brink, personal communication, 5 March 2018). This persisted until the early 2000s, when full size analogue radiography was introduced for all miners.[6]

Underground miners subject to radiological surveillance undergo two such examinations annually. With approximately 366 000 miners employed in the gold, coal and platinum sectors in 2016,[8] and even given that not all would be required to undergo radiographic examination, the implied volume of radiography is enormous. The cost of any inefficiency or ineffectiveness inherent in practice would be high.

To be able to evaluate this system, it is necessary to understand its purpose and the fact that radiological medical surveillance fulfils two functions, more precisely characterised as active screening and disease surveillance.

Medical surveillance is the general term used in occupational health to describe the regular examination of workers for pre-clinical or clinical abnormalities. Active screening is directed at the individual worker. Its aim is to detect disease – in this case, silicosis or pulmonary tuberculosis – at a stage prior to that at which the individual would present for care as a result of symptoms or ill-health. The rationale for screening is that early clinical action, such as treatment, or occupational management, such as risk counselling, job change or compensation, will limit the impact of the disease on that individual.

Disease surveillance is directed at the population. Its aim is to measure the number of cases of the disease in the target population, which can be expressed as prevalence or annual incidence. The rationale for surveillance is that such information is needed for disease prevention and control, and for health programme planning. Both of these functions are important in the mining industry.

Legal background

Both the Mine Health and Safety Act (MHSA) of 1996 as amended and its related guidance notes, and the Occupational Diseases in Mines and Works Act (ODMWA) of 1973 as amended, mandate medical surveillance of miners.[9,10] The MHSA imposes duties on the Inspectorate of Mine Health and Safety, Department of Mineral Resources, as well as on the manager of each mine and the occupational medical practitioner employed by the mining company, to ensure that medical surveillance occurs. In terms of the ODMWA, the Director of the Medical Bureau for Occupational Diseases (MBOD) is empowered to inspect the equipment and outcomes of any medical examinations. Where a medical practitioner considers or suspects that a miner or ex-miner is suffering from a compensable disease, he or she is required to report the findings to the Director.

Clinico-radiological features of silicosis and pulmonary tuberculosis

Practitioners with responsibility for mining radiology need to be familiar with the common radiologic presentation of silicosis. In particular, it is essential to distinguish the early radiological features of silicosis from those of a normal chest, or of tuberculosis, and the signs of active tuberculosis from those of 'healed' disease.[11,12] This task is made considerably easier by high-quality imaging and the use of reference standards (both discussed later in this paper), and the converse holds for a poor-quality imaging which might make the distinction impossible.

The most common form of silicosis seen today in the mining industry is chronic uncomplicated silicosis, characterised by bilateral, more or less symmetrical, rounded nodulation with upper lobe predominance. When extensive, the whole lung may be affected, a pattern which needs to be distinguished from miliary tuberculosis, especially if the nodules are small. Complicated silicosis may also be characterised by regular or irregular masses exceeding 1 cm in the long axis, most commonly, and originating in the upper zones – labelled progressive massive fibrosis. In such cases, the association with surrounding nodules may be apparent, or lung destruction with surrounding emphysema may incorporate and obscure the nodules in the adjacent lung. Eggshell calcification of hilar or mediastinal nodes, while not pathognomonic, is an uncommon but distinctive marker of longstanding silicosis.

Pulmonary tuberculosis has a wider range of appearances than silicosis and may be due to previous 'healed' tuberculosis or to active tuberculosis requiring immediate action. Appearances include cavitation, adenopathy, masses, asymmetrical nodules, often clumped and heterogeneous in size, linear fibrosis, fibrocystic disease, bronchiectasis, pleural thickening or effusion, hilar distortion with 'compensatory' emphysema, or lung collapse. Symmetrical bronchopneumonic or miliary patterns may also occur.

ANALOGUE VS DIGITAL RADIOGRAPHY – THE STUDY

Background

The most widely used system for categorising the abnormalities seen on chest radiographs due to the inhalation of fibrogenic dusts is the International Labour Organization (ILO) classification.[13] While the ILO system was developed using analogue film radiographs, in recent years a number of validation studies have shown that interpretations of soft copy digital radiographs (i.e. digital radiographic images displayed on a radiology-quality high resolution computer workstation) are equivalent to those for film radiographs (analogue) for classifying parenchymal and pleural abnormalities due to pneumoconiosis.[14-19]

Largely on the basis of these reports, the ILO and the United States National Institute for Occupational Safety and Health (NIOSH) have promulgated guidelines for use of digital radiographs for such purposes.[13, 22] However, all the validation studies were conducted in the United States, western Europe or Japan, regions in which the incidence of pulmonary tuberculosis is low. Because there were few, if any, subjects with tuberculosis in these studies, it was not possible to assess whether digital radiographs were equivalent to film radiographs for identifying radiographic changes suspected to be related to tuberculosis, or combined silicosis and tuberculosis.

Digital radiographic equipment was installed in the health services of the larger mines in South Africa in the early 2000s. Although analogue film chest radiography continues to be used in the health facilities in remote rural areas of South Africa and surrounding countries where the majority of migrant ex-miners live, there is increasing adoption of digital radiographic technology in some of these areas in South Africa and Lesotho. In 2007 the South African Mine Health and Safety Council (MHSC), composed of representatives from labour, management and government, requested evidence on the equivalence of the two formats in the detection of silicosis and tuberculosis.

Methods

A sample of 132 active gold miners with a range of radiographic findings of both silicosis and tuberculosis, from 'normal' to 'severe' for each outcome, and combinations of the two, were recruited. Previously-taken periodic surveillance radiographs were reviewed to identify potential study subjects from among active workers at a single mine, who were then invited to participate. Each miner completed a questionnaire and underwent a digital chest radiograph as part of routine periodic health screening at the mine. The digital image was then printed as a hard copy. In addition, a film chest radiograph was obtained for study purposes on the same day.

The main objective of the study was to measure the intra-reader agreement (reliability) between the three formats – soft copy digital, hard copy digital, and traditional film images – for silicosis and/or tuberculosis, as well as the prevalences obtained with each of the three formats. Measurement of agreement between readers (inter-reader agreement) was a secondary objective.

For each image format, the radiographic and printing protocol was that in effect at the mine at the time (2012). Owing to circumstances outside the researchers' control, hard copy images were printed at two thirds of the size of the other two formats, a size that is common practice in hard-copy digital printing and deemed acceptable in the ILO guidelines.

De-identified images were interpreted independently and in random order by four expert readers, two from South Africa and two from the United States. Readers classified images according to the 2011 revision of the ILO classification system and NIOSH guidelines.[13, 22] Criteria for marking the symbol 'tb' were based on the instructional language in the ILO guidelines, viz. "The symbol *tb* should be used for either suspect active or suspect inactive tuberculosis. The symbol '*tb*' should not be used for the calcified granuloma of tuberculosis or other granulomatous process, e.g. histoplasmosis. Such appearance should be recorded as *cg*."

The primary focus of the study was to assess intra-reader agreement (same reader, same miner, different image formats) among pair-wise comparisons of the three radiographic formats. For each pair of formats, the kappa statistic was calculated as a measure of intra-rater agreement.[23] The kappa statistic is used to measure agreement between two raters on an outcome after adjusting for the proportion of agreement due to chance. Kappa values can range from -1 (perfect disagreement) to +1 (perfect agreement), with kappa = 0 representing no agreement beyond chance. Values of kappa

>0.75 are considered to indicate ‘excellent’ agreement, values 0.40 to 0.75, ‘fair to good’, and values < 0.40, ‘poor’.[24]

The kappas were pooled across the four readers. We considered only the dichotomous outcomes, e.g. silicosis read as profusion >=1/0 vs <1/0, or tuberculosis as present vs absent, using the ILO system. Assessment of inter-reader agreement (different readers, same miner, same image and format) was a secondary goal of the study. Full methods are described in Franzblau et al., 2018.[1]

Main findings of the research

Digital soft copy and traditional film images showed consistent prevalence of findings for tuberculosis and silicosis. By contrast, digital hard copy (printed) images yielded higher prevalences.

Intra-reader agreement of film versus digital soft copy was *fair to good* for the detection of tuberculosis, while three of the four readers showed *fair to good* agreement for parenchymal abnormalities consistent with silicosis.

Inter-reader agreement for film and digital soft copy readings was *fair to good* for tuberculosis. Agreement on parenchymal abnormalities (silicosis) was *fair to good* for film, but *poor* for digital soft copy. This latter finding was due to one reader reporting parenchymal abnormalities much more frequently than the other readers.

Previous studies of equivalence, whether intra- or inter-reader, have found agreement in the fair to good ranges of kappa.[14-19] Using this standard, we concluded that the study demonstrated reasonable equivalence of soft copy digital chest images in comparison to traditional film for conducting radiological surveillance in working populations that might be exposed to both silica dust and tuberculosis. We concluded that use of hard copy digital should be discouraged because this method might overstate prevalence.

RECOMMENDATIONS ON DIGITAL SURVEILLANCE FOR SILICOSIS AND TUBERCULOSIS

In this section we set out the standards that we believe should be followed in digital radiographic surveillance, with special reference to internationally recommended standards.

Radiographic process and quality standards

While only qualified radiographers are legally permitted to carry out radiography, the Health Professions Council of South Africa (HPCSA) does allow supplementary diagnostic radiographers to operate under the supervision of a radiographer to carry out chest radiography on the mines.

The recommended technique for performing chest radiography has been well-described by the American College of Radiology (ACR).[25] A high kilovoltage peak (kVp) technique (100-120 kVp) is recommended for chest radiography to reduce contrast between bone and soft tissue, making ‘grey’ lung parenchyma more visible. Increasing the mAs (tube current) does not improve the quality of the image while increasing patient dose.

Digital postero-anterior chest radiographs should conform to the same positioning standards as analogue positioning, ensuring that the entire lungs and pleural reflections are visible. The dynamic range of digital chest radiography is considerably larger than that of film-screen images, permitting a wider range of diagnostically acceptable exposures. An overall advantage of digital radiography is the ability to produce lower dose diagnostically acceptable images. However, it is also possible to produce images at low exposure settings with acceptable contrast but excessive quantum noise, which might simulate small opacities.

The converse is also true: exposures can be progressively increased, resulting in very low noise and high-quality images, but at the expense of excessive patient dose. This is possible because the brightness and contrast of the image are uncoupled from the exposure. When this occurs systematically, it is known as ‘dose drift’ or ‘dose creep’. Vendor-specific exposure indicators have been developed to allow each facility to monitor exposure factors by the technologist and mitigate dose drift.[26]

Monitors, workstations and use of screen software

The desired reading environment is described in the 2011 ILO booklet.[13] The room should be evenly lit with low ambient light, no direct sunlight, no glare, and clean viewing surfaces, and be clean, quiet and free from distractions.

The NIOSH and ILO guidelines also provide standards for monitors.[13,22] The technical specifications should be adhered to but, where the mega-pixel number is higher than five and the pixel pitch (the dark space between two pixels) is <0.2 mm, the other specifications will usually also be met. A quality control system is recommended to evaluate monitors and to ensure they continue to perform adequately. For this purpose, quality control software is available that ensures daily testing of monitors for reading fidelity.

The digital acquisition of an image involves the conversion of photons to an electronic signal, using a detector. The image is preprocessed with vendor-specific algorithms, producing an image histogram. Post-processing algorithms can then be applied by the technologist to the image for the purpose of creating an image that most efficiently displays the anatomic information of the radiograph, both contrast and spatial resolution. Post-processing spatial frequency algorithms that create edge enhancement should be specifically avoided as they can artificially accentuate normal parenchymal markings and simulate small opacities. Grid suppression or anti-aliasing software should be activated; failure to do so may result in artefactual parallel lines on the image.

Finally, if a very high-energy technique is used, the digital equivalent of overexposure, known as detector saturation, occurs. The over-exposed region registers as black on the monitor, and no window-and-level adjustment will display anatomic information. Detector saturation could suppress or obscure small, or even large, opacities of pneumoconiosis.

Viewing image with ILO reference standards

Historically, the ILO has provided a set of 22 standard (film) radiographic images for side-by-side comparison and classification of film chest radiographs for findings related to inhalation of pneumoconiotic dusts.[21] In 2011, the ILO produced a set of digitised standard radiographic images for side-by-side comparison and classification of soft-copy digital chest radiographs, for findings related to inhalation of pneumoconiotic dusts.[21] NIOSH has also issued a guideline document that builds on that of the ILO and is intended to provide ‘technical and operational guidance for radiographic facilities and physician readers who obtain digital chest radiographs for the evaluation of pneumoconiosis’.[22]

A key element of application of the ILO system for interpretation of radiographic images is the requirement for side-by-side comparison of a patient’s image with the ILO standard images. Historically, when using traditional film images, this was not difficult since both images could be displayed on adjacent viewing boxes. However, the clinical Picture Archiving and Communication System (PACS) is designed not to permit display of the images of two different patients side-by-side, to avoid inadvertent interpretation of the incorrect patient radiograph. While this failsafe is important in clinical radiology, it is problematic when interpreting radiographs for pneumoconiosis where the specified expectation is that the examinee images will be compared with the ILO standard radiographs in the same image format.

Fortunately, several solutions are available. Configuring a dedicated PACS workstation with appropriate high-resolution monitors is the initial step. The facility must develop a method to receive transmitted images via virtual private network (VPN) or upload chest radiograph images, for example, on CD, to a database for viewing. Once the ILO digital standards and the examinee images are available in the same database, simultaneous viewing is required. Free BViewer software is available through the NIOSH site[20] but requires a set-up which is not easy to execute. Other free DICOM (Digital Imaging and Communications in Medicine) viewers which perform satisfactorily are more easily employed and, depending on the local setup, allow a parallel display of the examinee and standard images. In all cases, however, one has to purchase the standard image digitised set from the ILO. There is also purchasable vendor software (for example, OsiriX FDA-approved version for Mac) which allows two images to open side-by-side for comparative viewing. Alternatively, side-by-side workstations could be employed; however, this adds the expense of a second workstation solely for comparison with the standards.

Training and materials

To promote reliability in the interpretation of reading radiographs of the pneumoconiosis, the NIOSH 'B reader program' was created in 1974. It is restricted to medical graduates. (An 'A reader' was a candidate who had completed a NIOSH-approved training course without an examination; however, such certification has been discontinued.) Initially focused on coal workers' lung disease, the content of the programme was expanded to include pneumoconiosis related to asbestos and silica. The B reader examination is offered a number of times a year at the NIOSH facilities in Morgantown, West Virginia,[27] as well as from time to time in other countries. To achieve B reader certification, a candidate must pass a timed exam consisting of 125 radiographs and consistently apply the ILO system in four major areas: technical quality, parenchymal abnormalities, pleural abnormalities, and other abnormalities. Certification must be renewed every four years. The training course offered by the ACR in previous years has been discontinued.

Information and training in the use of the ILO system is available from a number of sources. The guideline/booklet already cited[13] and digital standard images can be ordered from the ILO.[21] A NIOSH self-study syllabus (including a CD or hard-copy images) is offered by the NIOSH via its website.[20]

In the near future, a set of consensus-read images will be available via the Safety in Mines Research Advisory Committee (SIMRAC) and the MHSC. These are images that were acquired in the study described above, and which achieved a high degree of consensus among the expert readings.

The importance of the archive and information system

The availability of prior radiological, occupational and clinical information provides the time dimension and is one the great advantages of serial surveillance. This advantage is lost if images are read as one-off investigations, with the risk of both missing diagnoses and duplicating previous investigations at unnecessary cost. This is particularly the case in a population with a high prevalence of silicosis, and both previous and active tuberculosis. Comparison of the most recent chest image with previous images is necessary to identify new appearance or progression of silicosis, and changes which might suggest active tuberculosis, particularly against a background of old tuberculosis.[11,12]

For both diseases, the diagnosis is clinical. Apart from a chest image showing changes consistent with silicosis, the diagnosis of silicosis requires a history of sufficient exposure to inhaled silica, typically in the order of 10-20 years, depending on the intensity of silica exposure. Time since first exposure (latency), independently of the number of years exposed, may add further risk. Ideally, the occupational database should contain cumulative dust information for each miner but, lacking this, a full job history can serve as a proxy for likely relative intensity of exposure.

Similarly, knowledge of the miner's previous history of tuberculosis and other chest conditions and HIV status will assist in interpretation of an abnormal image. Such correlative information requires a PACS or equivalent, and a clinical and occupational database accessible by the practitioner responsible for radiographic surveillance. A paperless system is ideal.

The importance of using all clinical and occupational information available on each miner, to maximise the efficiency and effectiveness of the examination of the individual miner, cannot be overemphasised. Since the site may be physically remote, a mechanism needs to be in place for contacting responsible parties if an abnormality requiring immediate action is required. In the current context, this will most often be suspicion of active tuberculosis. The archival system needs to provide for backing up and confidentiality of medical information, as required by South African law, and security against physical events, such as fire or flooding, and human agency, such as cyber incursion.

Hard copies, the MBOD, and digitisation

The printing of digital chest radiographic images onto hard-copy and their submission to the MBOD for compensation purposes is still in current practice. However, the study reported in this paper and previous work[14] have clearly shown that soft-copy readings are recommended above hard-copy readings. This is because hard-copy readings overestimate the prevalence of pneumoconioses. We therefore do not recommend the use of hard-copy images. In this regard, the current wording 'X-ray photograph' used in the current amended version of the ODMW Act is ambiguous and should be replaced by the words 'radiographic image'.

The MBOD is in the process of setting up a digital radiography and reading system which enables it to receive and read digital images, submitted with claims for compensation under the ODMW Act. This will require substantial investment but is a necessary goal given the statutory requirement for radiographic medical surveillance in the South African mining industry. Such a system will need to be logistically meshed with the archive of the individual miner's history and analogue films held by the MBOD, and will need to include a PACS system to manage the flow of radiographic images, as well as viewing software and suitable hardware to read the images.

CONCLUSION

Radiological surveillance for silicosis and tuberculosis in the South African mining industry has an important role to play in the prevention and management of both diseases, to the benefit of miners and their families and mine management and owners.

To fulfil this role, radiological surveillance needs to be undertaken with a clear understanding of its goals, and ability to achieve these goals should be subject to evaluation from time to time. Such programmes require training of readers, irrespective of their backgrounds. Meticulous attention needs to be paid to choice and quality control of software and hardware, including workstation environment, use of standard images, and archiving of images and information. Finally, closure of the loop from reading to reporting and action, must be assured.

DECLARATIONS

RE has written expert reports for plaintiffs' lawyers in silicosis litigation. AF has written reports on behalf of defendants in silicosis and asbestos litigation. JtWN has worked for lawyers setting up compensation funds for asbestos, silicosis and tuberculosis-affected miners. CAM has worked as a B reader in several large studies supported by the National Industrial Sand Association, and has provided medical expert testimony in coal workers' pneumoconiosis litigation.

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LESSONS LEARNED

- Digital soft copy (on screen) has been shown to be equivalent to traditional film images in the reading of silicosis and tuberculosis. Digital hard copy is not recommended.
- For reading soft copy, the reading environment, hardware and software systems should comply with recommended standards for pneumoconiosis, where available, and be equipped with the digitised International Labour Organization (ILO) chest radiograph set.
- Training of readers of pneumoconiosis and tuberculosis is essential, making use of established programmes and/or materials developed by projects such as the consensus-read image set described in this paper.
- Efficient and effective surveillance for silicosis and tuberculosis in the mining industry requires that prior occupational, clinical and radiological information be available as well as a rapid referral mechanism for abnormal findings.

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