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RESEARCH ARTICLE

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Comparison of digital and film chest radiography for detection and medical surveillance of silicosis in a setting with a high burden of tuberculosis

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Background: Continuing use of analog film and digital chest radiography for screening and surveillance for pneumoconiosis and tuberculosis in lower and middle income countries raises questions of equivalence of disease detection. This study compared analog to digital images for intra-rater agreement across formats and prevalence of changes related to silicosis and tuberculosis among South African gold miners using the International Labour Organization classification system.

Methods: Miners with diverse radiological presentations of silicosis and tuberculosis were recruited. Digital and film chest images on each subject were classified by four expert readers.

Results: Readings of film and soft copy digital images showed no significant differences in prevalence of tuberculosis or silicosis, and intra-rater agreement across formats was fair to good. Hard copy images yielded higher prevalences.

Conclusion: Film and digital soft copy images show consistent prevalence of findings, and generally fair to good intra-rater agreement for findings related to silicosis and tuberculosis.

KEYWORDS
digital radiographs, pneumoconiosis, silicosis, surveillance, tuberculosis

1 | INTRODUCTION

The most widely used system for categorizing the abnormalities seen on chest radiographs due to the inhalation of pneumoconiotic dusts is the International Labour Organization (ILO) classification.[1–3] While the ILO system originally was developed using analog film radiographs, in recent years a number of validation studies have shown that interpretations of soft copy digital radiographs (ie, digital radiographic images displayed on a radiology-quality high resolution computer workstation) are equivalent to those for film radiographs

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for classifying parenchymal and pleural abnormalities due to pneumoconiosis.[4–10] Largely on the basis of these reports, the ILO and the National Institute for Occupational Safety and Health (NIOSH) have promulgated guidelines for use of digital radiographs for such purposes.[1,11] However, all of these validation studies were conducted in the United States, Western Europe, or Japan, regions in which the incidence of pulmonary tuberculosis is low (eg, 9.9 cases per 100 000 in the United States in 2014).[12] Because there were few, if any subjects with tuberculosis in these studies, they were, by design, not capable of assessing whether digital radiographs were equivalent to film radiographs for identifying radiographic changes suspected to be related to tuberculosis or combined silicosis and tuberculosis.

In 2014, South Africa had the highest general population incidence rate of tuberculosis in the world (834 cases per 100 000 population).[12] Rates of tuberculosis among gold miners in South Africa are even higher, up to 2950 cases per 100 000,[13] which is attributable to high rates of infection with the human immunodeficiency virus (HIV), silica exposure among miners, and exposure in congregate settings on the mines.[14,15] In addition to South Africa, a number of other countries with large extractive industries, such as Brazil, India, and China, also have high rates of tuberculosis.[12] For these reasons, workplace radiological surveillance programs among miners in South Africa and other developing countries may need to serve the dual purpose of surveillance for silicosis and tuberculosis.[16] Historically, such surveillance programs utilized traditional analog film chest radiographs. Since 2004, digital radiographic equipment began to be installed in the South African mining industry, at least in the health services of the larger mines.[17] However, analog 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 and on which they are dependent for the continuing surveillance that is required by South African mining law. In 2007, the South African Mine Health and Safety Council, which is composed of representatives from labor, management and the government, requested evidence on the equivalence of the two formats in the detection of silicosis and tuberculosis.

This issue is not limited to Southern Africa. In middle income countries with large mining, quarrying and/or stone working sectors and related pneumoconiosis and tuberculosis burdens, such as Brazil, India and China, plain film radiography continues to be widely used in screening for pneumoconiosis and tuberculosis among workers (Dr. E. Algranti [Brazil], Dr. J. Patel [India], and Dr. W. Chen [China], personal communications).

The primary goal of the present study was to compare traditional film and digital radiography for the prevalence of findings and intra-rater agreement across formats (based on the kappa statistic) for changes related to silicosis and tuberculosis among South African gold miners. Examination of inter-reader agreement for the presence of silicosis and tuberculosis, given their co-occurrence in this context, was a secondary goal.

2 | MATERIALS AND METHODS

2.1 | Subject recruitment

The original goal was to recruit 220 subjects from among workers at a single, large South African gold mine who displayed a range of radiological presentations of silicosis and tuberculosis. For statistical reasons, the goal was not to recruit a representative sample of the worker population, but rather to create a study group that would provide sufficient power for the analyses comparing prevalence, and intra-rater and inter-rater agreement using the kappa statistic (see section 2.6).

For silicosis, there were three broad target categories for the final study population: (1) no abnormalities (~50%); (2) "mild" abnormalities (ie, ILO major category "1" for silicosis—~30%); (3) and "severe" abnormalities (ie, ILO major category "2" or greater—~20%). For tuberculosis, there were also three target categories for the study population: (1) no tuberculosis (~40%); (2) "mild" tuberculosis (ie, involving only 1-2 lung zones, as defined by the ILO system—~40%); 3) and "severe" tuberculosis (ie, involving three or more lung zones —~20%). The goal was to identify potential study subjects who fitted into a 3 × 3 matrix with these marginal prevalences of abnormalities.

With the cooperation of the mine management, two investigators (JtW and RIE) reviewed digital radiographs from an archive of previously taken radiographs to identify potential study subjects based on the criteria outlined above. Eligible candidates who fitted into the pre-defined categories were selected. As recruitment of candidate study subjects was slower than expected, part way through the study statistical power requirements were re-calculated, determining that only ~104 subjects were needed. By this time 132 subjects had already been recruited, and further recruitment was stopped.

Direct subject recruitment was performed by a research staff nurse accompanied by one of the occupational health nurses. There was no financial incentive offered to subjects. Once an approach was made and the identified worker expressed interest, the nurse explained the study and obtained written informed consent in one of three locally used languages, being Zulu, Sotho, and English. All study forms explaining the project were available in these languages as well as in Afrikaans. Ethics approval was granted by the Human Research Ethics Committee of the Faculty of Health Sciences, University of Cape Town (HREC reference number 385/2011) and the University of Michigan Institutional Review Board (IRB number HUM00055022).

2.2 | Data collection

Each subject completed a research questionnaire and underwent a digital chest radiograph as part of routine periodic health screening at the mine. The latter was reviewed clinically by the mine's medical staff, for abnormalities needing immediate attention. In addition, a film chest radiograph was taken for study purposes (see section 2.3 below for details on radiographic methods). The questionnaire elicited demographic information (age, gender, height, weight), work history, smoking history, self-reported HIV status, and a limited respiratory health history including history of tuberculosis. Participants were asked whether they had ever been diagnosed with tuberculosis, and if so, the year(s) of diagnosis and treatment.

2.3 | Imaging methods and quality control

After obtaining the digital radiograph at field radiography facilities, each miner was transported on the same day to the mine medical center for the film radiograph. Film and digital radiographic techniques, which did not change over the course of the study, were those in effect at the respective sites at the time of the fieldwork (February to June, 2012), and are described below.

The protocol for capturing film images was as follows. Radiography unit make and model: Philips Optimus 50 (Philips Healthcare, Hamburg, Germany). Technique: 125 kVp, 2-3.8 mAs (AEC-side chamber), 180 cm source-to-image distance, with a grid of 36 LP/cm, RATIO 12:1 of focal length 140 cm; Agfa CP-GC chest film, Agfa CURIX regular 400 speed screen cassette (Agfa Healthcare—NV, Mortsel, Belgium). Exposed film was developed in an Agfa EOS Classic processor with Agfa G138i developer and Agfa G334i fixer (Agfa Healthcare).

The protocol for capturing digital images was as follows. Digital images were captured using a Swissray ddR Modulaire TM chest system with a dOd-HD-16™ Detector (Swissray Medical—AG, Hochdorf, Switzerland). Technique: 125 kVp, 2-3.8 mAs (AEC-side chamber), 150 cm source-to-image distance, with a grid of 80 LP/cm, ratio 10:1 of fixed focal length of 150 cm. The pixel size of the detector was 168 micrometres, and the image array size was 2046 × 2560 pixels (14 × 17 inches). Digital images were stored as DICOM lossless images. Although a 150 cm source-to-image distance is non-standard, this distance is used commonly in South Africa for digital images.

Hard copy digital images were printed on an AGFA DRYSTAR 5302 laser printer using AGFA DRY LASER FILM DT2B film (Agfa Gevaert—NV, Mortsel, Belgium). They were printed using the standard look-up table recommended by AGFA. Hard copy images were printed at 80% scale along the x-axis and y-axis; the images were thus 0.8 × 0.8 = 0.64 or 64% of full-size. Since earlier validation studies have shown that hard copy digital images are inferior to soft copy and film images,[4] the primary focus of this article is comparison of film and soft copy results. The full results, that is, those comparing film, soft copy and hard copy are available in the on-line Supplemental Tables.

2.4 | Reading and scoring of images

Four readers, three radiologists and one pulmonologist experienced in reading radiographs for pneumoconiosis, independently interpreted all film and digital images. Two of the readers were from South Africa and two were from the United States. The South African readers both have expertise in respiratory imaging of miners—one has been reading for the statutory pneumoconiosis bureau since 1998 and the other has been an academic radiologist for the past 20 years. All readers had extensive experience in reading digital radiographic images. The readers from the United States were NIOSH-certified B readers for 13 and 32 years, respectively, at the time of the study, and had participated as readers in previous validation studies.[4,7]

Interpretation of film, soft-copy digital images, and hard-copy digital images were performed in random order. All images were stripped of personal identifiers and labeled with a study ID number; the study ID numbers differed by image format and images were presented in random order for each image format. The total number of potential image interpretations was: 132 subjects × 4 readers × 3 formats = 1584. However, due to one missing image and one additional missed reading, the final total number of readings was 1579 (one subject was missing a digital image, and one reader neglected to read the digital image for one additional subject, for a total of five missing readings). The final number of readings varied slightly for analyses for different outcomes due to a small number of images that the readers interpreted as being "unreadable" for ILO purposes.

Readers classified images according to the 2011 revision of the ILO classification system and NIOSH guidelines with one modification: if readers checked the symbol "tb," they were asked to mark which of six lung zones were involved (upper, middle and lower; left and right sides) in a fashion similar to section 2 of the ILO form.[1,11] Criteria for checking the symbol "tb" were based on the instructional language in the ILO guidelines ("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 processes, for example, histoplasmosis. Such appearances should be recorded as **cg**.").[1] Tuberculosis was read without reference to disease activity. As the participants were selected based on previous radiographs, it was expected that most if not all of the changes attributable to tuberculosis would reflect previous rather than active disease. In order to ensure similar interpretation and scoring of tuberculosis, a training workshop including 30 control radiographs was held in Cape Town for all four readers on the day prior to the first readings.

In order to avoid the risk of loss during shipment, interpretation of film images was performed independently by all readers in South Africa. Otherwise, readers interpreted hard copy and soft copy digital images at their respective home facilities. Other than the use of high-resolution workstations for interpretation of digital images, it was not feasible to standardize radiology work stations across facilities for this study. Readers were allowed to use various features of digital display at their own discretion, as would occur in everyday practice, and similar to procedures employed in previous studies.[4,5,7]

2.5 | Standard ILO images

Each of the four readers used their own set of the 22 hard-copy standard ILO radiographs when they read film and hard-copy digital images, in accordance with the ILO guidelines.[1] In order to perform side-by-side readings of soft copy digital images with digital versions of the ILO standard images (with permission from the ILO), the American readers used the same digital versions of the ILO standard films that had been created and used previously.[4] For technical reasons, the South African readers were unable to utilize the digital standards. Accordingly, they used the traditional hard-copy standard ILO radiographs when interpreting digital images.

2.6 | Statistical methods

Summary statistics were calculated describing the demographic characteristics, smoking status, mining experience, as well as self-reported history of tuberculosis and infection with HIV for the sample under study.

For each pair of formats within each reader, Cohen's kappa statistic was calculated as a measure of intra-rater agreement.[18] For this project, we considered only the dichotomous outcomes, for example, silicosis read as profusion >1/0 versus <1/0, or tuberculosis as present versus absent using the ILO system.

For each image format and each outcome with four different readers, there are six possible pairwise comparisons among readers. Since between-reader comparison is not of primary interest, we decided to pool inter-rater agreement across all readers. An overall agreement measure among readers was computed for each image format using the multiple rater version of the kappa statistic.[19] This version is applicable to outcomes with dichotomous as well as multiple ordinal categories. In the case of dichotomous outcomes, kappa has an attractive interpretation as an intra-class correlation coefficient. Fleiss has offered language for describing kappa results: values greater than 0.75 are "excellent"; values between 0.40 and 0.75 are "fair to good"; and values less than 0.40 show "poor" agreement.[19]

Mixed effects logistic regression models were used to evaluate rating differences across image formats with and without controlling for subject characteristics. In the unadjusted models image format was used as a fixed effect, while subject and reader were used as random effects. Adjusted versions of the models had the additional covariates of age, body mass index (BMI), and smoking status (current or former vs never). An additional sensitivity analysis was carried out using self-reported HIV status as a controlling variable.

The contribution to variability of image format and reader in explaining the variation in the data was assessed in the following way. In the first stage, a "null" model with only a random subject effect was fitted. Subsequently two separate models were fitted, one including an image format effect in addition to the subject effect, and the other with a reader and a subject effect. The percentage increase in pseudo log likelihood between the second and the first stage models, indicating the degree of improvement in goodness of fit, was used as an assessment of the additional contribution to explaining variation.

Statistical analysis was carried out in SAS® version 9.4.[20] Generalized linear mixed models were implemented using proc glimmix. The SAS macro "MAGREE" was used to compute the overall multi-rater kappa value and its standard error (SE) with 95% confidence intervals computed using ±1.96 × SE.

3 | RESULTS

The characteristics of the study participants are summarized in Table 1. A total of 132 male gold mine workers participated in this study. The mean age of the sample was 47.6 years with a standard deviation (sd) of 6.6 years. The study participants were primarily of normal weight or overweight with a mean body mass index (BMI) of 24.1 kg/m^2 (sd 3.9) for the sample. Subjects had a mean of 23.3 years of gold mining experience (sd 8.4), reflecting a long service sample. About three quarters of the subjects were currently non-smokers. Only 10% of the sample reported to have been previously diagnosed with tuberculosis while 31% reported having tested positive for HIV.

A total of 1579 radiographic readings were completed for the study, with a varying number of readings available for different outcomes due to a small number of missing images or images that were scored as "unreadable" (see section 2). Table 2 reports the distributions of the ILO classification outcomes for traditional film and soft copy images. The marginal distributions of ILO findings for the two formats show no significant differences for any outcomes, with the exception of image quality. By design, the prevalence of findings of parenchymal abnormalities and findings suggestive of tuberculosis in the study group were high, 66% and 38%, respectively. The comparisons shown in Table 2 do not adjust for the clustering within readings made on the same subject using different image formats (see Table 5). Full results, including those for hard copy digital images, are available in Supplemental Tables S1-S7.

Although the overall prevalence of radiographic findings of tuberculosis (38%—see Supplemental Table S1) was much greater than the self-reported history of tuberculosis (10%—see Table 1), these

TABLE 1 Subject characteristics

N = 132	Sub-categories within each variable	Frequency	%
Age (years) Mean standard deviation (SD) = 47.6 (6.6)	45 or younger 46 to 50 Over 50	36 52 44	27 39 33
Body mass index (kg/m^2) Mean (SD) = 24.1 (3.9)	Less than 25 25 to 30 Equal to or more than 30	85 33 11	66 26 9
Years of gold mining Mean (SD) = 23.3 (8.4)	15 or fewer 16 to 20 21 to 25 26 to 30 More than 30	19 17 39 27 25	15 13 31 21 20
Smoking status	Never Former Current	95 7 27	74 5 21
Self-reported history of tuberculosis (TB)	Yes No	13 119	10 90
Self-reported HIV positive	Yes No	36 82	31 69

TABLE 2 Results of ILO classifications using film and soft copy, with χ^2 tests for differences

	Overall		Film		Soft copy		X^2
	n	%	*n*	%	*n*	%	*P*
Image quality (*n* = 1051)							
1	537	51	223	42	314	60	<0.001
2	470	45	265	50	205	39	
3	39	4	35	7	4	1	
4 (unreadable)	5	<1	5	1	0	0	
Any parenchymal abnormalities (*n* = 1051)							
No	373	36	191	37	182	35	0.561
Yes	673	64	332	63	341	65	
Shape/size of primary small opacities (*n* = 673)							
Round (p, q, r)	633	94	311	94	322	94	0.679
Irregular (s, t, u)	40	6	21	6	19	6	
Small opacity profusion (*n* = 1045)							
Major category 0	418	40	213	41	205	39	0.953
Major category 1	363	35	179	34	184	35	
Major category 2	222	21	110	21	112	21	
Major category 3	42	4	20	4	22	4	
Tuberculosis (*n* = 1046)							
No	664	63	326	62	338	65	0.441
Yes	382	37	197	38	185	35	
# of zones with TB (*n* = 1046)							
0	664	63	326	62	338	65	0.719
1	195	19	97	19	98	19	
2	151	14	82	16	69	13	
≥3	36	3	18	3	18	3	
Large opacities (*n* = 1045)							
O	975	93	485	93	490	94	0.875
A	59	6	31	6	28	5	
B	11	1	6	1	5	1	
C	0	0	0	0	0	0	
Large opacities (*n* = 1045)							
No (O)	975	93	485	93	490	94	0.615
Yes (A, B, or C)	70	7	37	7	33	6	
Coalescence of small opacities (ax) (*n* = 1046)							
No	946	90	464	89	482	92	0.058
Yes	100	10	59	11	41	8	
Large opacities or ax (*n* = 1045)							
No (O)	903	86	443	85	460	88	0.145
Yes (A, B, C, or ax)	142	14	79	15	63	12	
Pleural abnormalities (*n* = 1046)							
No	973	93	493	94	480	92	0.115
Yes	73	7	30	6	43	8	
Costophrenic angle obliteration (CAO) (*n* = 1046)							
No	1000	96	504	96	496	95	0.228

(Continues)

TABLE 2 (Continued)

	Overall		Film		Soft copy		X^2
	n	%	*n*	%	*n*	%	*P*
Yes (right and/or left)	46	4	19	4	27	5	
CAO or pleural effusion (*n* = 1046)							
No	992	95	502	96	490	94	0.094
Yes (right and/or left)	54	5	21	4	33	6	
Diffuse pleural thickening (*n* = 1046)							
No	1023	98	513	98	510	98	0.527
Yes (right and/or left)	23	2	10	2	13	2	

two outcomes were significantly associated (data not shown). In two previous cross-sectional studies of ex-miners self-reported tuberculosis was more common than radiographic evidence of tuberculosis,[21] while in a study of active miners, the radiographic prevalence was similar to or greater than the prevalence based on history.[22] The reasons for these discrepancies are unknown. The self-reported prevalence of HIV infection is very high at 31% but is of the same order as that reported in other surveys of working miners, such as the 27% found by Corbett et al,[23] and would be expected to be high, in part, because of the enrichment of this sample with cases of past tuberculosis.

Not surprisingly, since the subjects for this study were gold miners with silica exposure, not asbestos exposure, the prevalence of pleural abnormalities attributable to pneumoconiosis was relatively low (8.3% overall—see Supplemental Table S1). While pleural scarring and thickening can result from tuberculosis,[24] there was no association between findings of pleural abnormalities and self-reported tuberculosis nor findings of pleural abnormalities and radiologically recorded tuberculosis (data not shown).

The intra-rater agreement values for film versus soft copy are reported in Table 3 for each reader and all major dichotomous outcomes. The agreement is consistently fair to good for the detection of tuberculosis, and three of the four readers had fair to good results for parenchymal abnormalities. The other outcomes show considerable variation of intra-rater agreement across formats (eg, large opacities, coalescence of small opacities, pleural abnormalities, costophrenic angle obliteration, diffuse pleural thickening). Such variation is not surprising since the prevalences of these findings were generally low (less than 10% in most instances), and it is well known that kappa is less stable and approaches zero when the underlying prevalence of the condition approaches zero or 100%.[25]

Inter-rater agreement, using multi-rater kappa, for film and soft copy readings are displayed in Table 4. Agreement for tuberculosis was fair to good for both film and soft copy. Agreement on parenchymal abnormalities was fair to good for film, but was poor for soft copy (the latter likely due to one reader [reader 4] reporting parenchymal abnormalities much more frequently relative to the others—see Supplemental Table S2). Re-calculation of results shown in Table 4 without reader 4 showed increased multi-rater kappas for parenchymal abnormalities, but essentially no change for kappas for tuberculosis—see Supplemental Table S10.

Kappas for several of the other inter-rater outcomes indicate poor agreement, likely for the same reasons noted above—that the prevalence of the underlying condition was low.[25] Most important for the purposes of this study, there is little difference between the

TABLE 3 Intra-rater Kappa values for agreement between traditional film and digital soft copy

	Film versus soft			
	Reader 1	Reader 2	Reader 3	Reader 4
Parenchymal abnormalities (yes/no)	0.67	0.69	0.59	0.35
Tuberculosis (yes/no)	0.48	0.60	0.58	0.60
Large opacities (yes/no)	0.53	0.25	0.66	0.07
Coalescence of small opacities (ax) (yes/no)	0.36	0.45	0.80	−.03
Large opacities or ax (yes/no)	0.56	0.49	0.79	0.10
Pleural abnormalities (yes/no)	0.10	0.52	–	0.43
Costophrenic angle obliteration (yes/no)	0.23	0.67	–	0.37
CAO or pleural effusion (yes/no)	0.30	0.63	−.01	0.37
Diffuse pleural thickening (yes/no)	−.02	0.79	–	0.74

– Indicates kappa cannot be calculated; there were no findings of this type for this reader and certain image formats.

TABLE 4 Multi-rater kappas with 95% confidence intervals, showing agreement across readers within each image format, for dichotomous radiographic findings (present vs absent)

Finding	Film	95%CI	Soft	95%CI
Parenchymal abnormalities	0.59	(0.52, 0.66)	0.37	(0.30, 0.44)
Tuberculosis	0.43	(0.36, 0.50)	0.44	(0.37, 0.51)
Large opacities	0.16	(0.09, 0.23)	0.28	(0.21, 0.35)
Coalescence of small opacities (ax)	0.21	(0.14, 0.28)	0.13	(0.06, 0.20)
Large opacities or ax	0.29	(0.22, 0.36)	0.27	(0.20, 0.34)
Pleural abnormalities	0.2	(0.13, 0.27)	0.29	(0.22, 0.36)
Costophrenic angle obliteration	0.33	(0.26, 0.40)	0.34	(0.27, 0.41)
CAO or pleural effusion	0.42	(0.35, 0.49)	0.43	(0.36, 0.50)
Diffuse pleural thickening	0.32	(0.25, 0.39)	0.29	(0.22, 0.36)

inter-rater kappas for film and soft copy across the outcomes for findings with low prevalence.

Table 5 exhibits the odds ratios of film versus soft copy in finding an abnormal outcome using a model-based approach, as opposed to comparison of simple prevalence as in Table 2. As the results in the table indicate, there are no significant differences between formats with the exception of coalescence of small opacities (symbol "ax"). For this outcome film format has about a 1.7 times higher odds than the soft copy format of identifying this abnormality (OR: 1.69, 95%CI: 1.05, 2.74). Interestingly, in Table 2 this outcome approached statistical significance. Overall, the results in Table 5 appear to be quite robust to subject level adjustments (ie, age, BMI, and smoking).

Table 6 displays the degree of improvement in pseudo log likelihood of logistic models fit for image format and for reader for each of the major ILO outcomes. For all outcomes the variation due to the readers dwarfs the variability attributable to image format. The increase in pseudo log likelihood due to reader is between 7- and 120-fold of that due to image format.

4 | DISCUSSION

Of the 22 "high-burden countries" which account for 83% of the global burden of tuberculosis,[12] a number have large and/or growing extractive industries, notably South Africa, Brazil, and China. The prevalence of tuberculosis needs to be taken into account in reading for silicosis in silica exposed workforces for epidemiological, screening and/or clinical purposes. This is particularly notable in the South African context of very high tuberculosis incidence rates. Radiographic images among individuals with a history of tuberculosis present patterns that overlap with silicosis.[26] Specifically, when tuberculosis heals with scarring it may leave a nodular pattern or large opacities which need to be distinguished from silicosis. Alternatively, tuberculosis may heal with linear fibrosis or loss of lung volume, obscuring an underlying silicotic pattern. Tuberculosis can also result in effusions and ultimately scarring of the pleura. Active tuberculosis may also be confused with silicosis, particularly when miliary.

The relative performance of digital versus analog radiography in such a setting has not previously been studied. The continued use of both formats in industrializing lower and middle income countries for the foreseeable future thus makes this a relevant question for occupational health practitioners and compensation administrators involved with pneumoconiosis in these countries.

Our results demonstrate that, despite the co-occurrence of tuberculosis in the sample, among experienced readers interpretation of soft copy digital chest images and traditional film chest radiographs show a similar prevalence of parenchymal abnormalities consistent

TABLE 5 Odds ratios for findings of abnormalities, traditional film versus soft copy, with and without adjustment for subject characteristics

Odds ratios (95% confidence interval)	Film vs soft copy	Film vs soft copy, adjusted[a]
Parenchymal abnormalities	0.88 (0.61, 1.27)	0.88 (0.60, 1.29)
Tuberculosis	1.18 (0.84, 1.65)	1.17 (0.83, 1.65)
Large opacities	1.15 (0.68, 1.95)	1.07 (0.63, 1.84)
Coalescence of small opacities (ax)	1.73 (1.06, 2.81)	1.75 (1.06, 2.86)
Large opacities or ax	1.46 (0.95, 2.23)	1.41 (0.91, 2.18)
Pleural abnormalities	0.62 (0.36, 1.07)	0.70 (0.40, 1.22)
Costophrenic angle obliteration (CAO)	0.58 (0.28, 1.21)	0.69 (0.32, 1.47)
CAO or pleural effusion	0.50 (0.25, 0.99)	0.57 (0.28, 1.15)
Diffuse pleural thickening	–[b]	–[b]

[a]Adjusted for age, BMI, ever/never smoked.
[b]Model did not converge due to very few readings with diffuse pleural thickening.

TABLE 6 Percentage increase in (pseudo) log-likelihood with the addition of either image format or reader to a baseline model of subject only; ratio of reader to image format contribution

% improvement in pseudo log-likelihood	Image format (%)	Reader (%)	Ratio
Parenchymal abnormalities	0.08	9.67	121.4
Tuberculosis	0.07	4.90	73.5
Large opacities	0.01	1.38	99.5
Coalescences of small opacities (ax)	0.46	10.40	22.5
Large opacities or ax	0.20	6.75	33.4
Pleural abnormalities	0.46	6.98	15.2
Costophrenic angle obliteration (CAO)	0.41	12.71	31.1
CAO or pleural effusion	0.76	5.45	7.2
Diffuse pleural thickening	–[a]	–[a]	

[a]Model did not converge due to very few readings with diffuse pleural thickening.

with silicosis, and generally fair to good intra-rater agreement between these image formats. More specifically Table 5 shows no odds ratios significantly different from the null for parenchymal abnormalities while Table 3 shows "fair to good" agreement across formats for three out of four intra-rater kappa values. More generally, Tables 2 and 5 show no significant differences across these formats for the prevalence of findings for all major outcomes (except image quality in Table 2).

The range of kappa values for intra-rater agreement for parenchymal abnormalities found among the four readers in the present study (kappa = 0.35 to kappa = 0.69—see Table 3) is similar to what has been reported previously. Laney et al, using seven readers, found the intra-reader kappa values for small pneumoconiotic opacities comparing interpretations of film and soft-copy digital images ranging from kappa = 0.39 to kappa = 0.72.[6] As noted previously, the relatively poor inter-rater agreement for parenchymal abnormalities for soft copy is likely due to the outlier influence of one reader (see Tables 4, S2, and S10). In another study involving eight readers, Laney et al reported inter-rater agreement for parenchymal abnormalities based on using the ILO classification system as applied to film and soft copy images: for film, kappa = 0.39 (95%CI: 0.28-0.49); and for soft copy, kappa = 0.42 (95%CI: 0.31-0.53).[5] While the results are similar to ours, it is important to note that direct comparisons of kappa statistics between studies are hampered by differences in study design and the exact method used for calculating kappa (eg, weighted versus unweighted).[8]

As this is the first study to our knowledge to examine inter-rater and intra-rater agreement on the reading of tuberculosis using digital chest radiography in a silica exposed population, there are no prior studies for comparison of kappa values. Efficacy of screening for pulmonary tuberculosis using digital chest radiography has been demonstrated among various high-risk populations, including homeless persons, drug addicts, alcohol users, and prisoners.[27] That was a validation study, and did not address reliability of radiographic methods. In our study, despite the co-occurrence of silicosis as a potential radiological confounder, intra-rater agreement on abnormalities assigned to tuberculosis across film and soft copy images was fair to good for all four readers while inter-rater agreement, as represented by multi-rater kappas, did not differ by format.

Although the interpretations of hard copy images showed similar results for intra-rater agreement for parenchymal abnormalities and tuberculosis with film and soft copy (see Supplemental Table SVI), there were significant differences between hard copy digital and traditional film and soft copy digital for the odds of finding these two outcomes (see Supplemental Tables S4 and S5), which is consistent with previous findings for parenchymal abnormalities.[4] A limitation in making this comparison is that the hard copy digital images used in this study were about two thirds the size of the film and soft copy images. While it has been common for hard copy digital images to be printed in reduced format,[28] it has been shown that reduction of image size can contribute to loss of detection accuracy.[29]

Overall, the results of the present study support the use of soft copy digital imaging for surveillance of silicosis and tuberculosis among miners in South Africa and elsewhere, as providing continuity with the use of analog imaging. Use of hard copy digital, however, may result in some degree of overestimation of these two key outcomes relative to either film or soft copy digital; overall, we recommend that hard copy digital images should be avoided if possible, and if used, done so at full size and with due recognition of their limitations.

Readings for many outcomes showed considerable variation among readers and within readers. However, as shown in Table 5, subject characteristics (ie, age, BMI, and smoking history) made little or no contribution to differences in readings between image formats. And, as demonstrated in Table 6, readers are a far greater source of variation for all outcomes than image format. The finding that even experienced readers are a more important source of variation than image format is consistent with previous results.[4] Training of readers, whether radiologists, mine medical officers, or other types of clinicians, in a standardized approach to reading images as part of such surveillance programs is thus essential.

In conclusion, the present study demonstrates reasonable equivalence of soft copy digital chest images in comparison to traditional film for conducting radiological surveillance in working populations that may have exposures to both pneumoconiotic dusts and tuberculosis. Use of hard copy digital images is discouraged.

AUTHORS' CONTRIBUTIONS

This study was designed by Drs Franzblau, Ehrlich, teWaterNaude, and Sen. Dr teWaterNaude was the principal investigator and with Dr Ehrlich oversaw the data collection; data analyses were overseen and/or performed by Drs Sen and Franzblau, and Ms d'Arcy. Radiographic interpretations were performed by Drs. Smilg, Mashao, Meyer, and Lockey. The manuscript was prepared by Drs Franzblau, teWater-Naude, Ehrlich, and Ms d'Arcy. All authors have reviewed and are accountable for the final manuscript.

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ETHICS APPROVAL AND INFORMED CONSENT

Ethics approval was granted by the Human Research Ethics Committee of the Faculty of Health Sciences, University of Cape Town (HREC reference number 385/2011) and the University of Michigan Institutional Review Board (IRB number HUM00055022). Written informed consent was obtained from each study participant.

DISCLOSURE (AUTHORS)

AF has written reports on behalf of defendants in silicosis and asbestos litigation. RIE has written expert reports for plaintiffs' lawyers in silicosis litigation. JtW has worked for lawyers setting up compensation funds for silicosis and tuberculosis-affected miners. JEL and CAM have written reports on behalf of defendants in coal workers pneumoconiosis litigation. The authors have no other conflicts to declare.

DISCLOSURE BY AJIM EDITOR OF RECORD

Steven B. Markowitz declares that he has no competing or conflicts of interest in the review and publication decision regarding this article.

DISCLAIMER

The contents of this publication are the sole responsibility of the authors, and do not necessarily reflect the views, opinions or policies of the Mine Health and Safety Council of South Africa, the International Labour Organization, AngloGold Ashanti, or the National Union of Mine Workers. Mention of commercial products is not an endorsement by the authors, the MHSC, the ILO, AngloGold Ashanti, or the National Union of Mine Workers.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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