ABSTRACT
Objectives: Suboptimal medication adherence for infectious diseases such as tuberculosis (TB) results in poor clinical outcomes and ongoing infectivity. Directly observed therapy (DOT) is now standard of care for TB treatment monitoring but has a number of limitations. We aimed to develop and evaluate a smartphone-based system to facilitate remotely observed therapy via transmission of videos rather than in-person observation.

Design: We developed an integrated smartphone and web-based system (Mobile Interactive Supervised Therapy, MiST) to provide regular medication reminders and facilitate video recording of pill ingestion at predetermined timings each day, for upload and later review by a healthcare worker. We evaluated the system in a single arm, prospective study of adherence to a dietary supplement. Healthy volunteers were recruited through an online portal. Entry criteria included age ≥21 and owning an iOS or Android-based device. Participants took a dietary supplement pill once, twice or three-times a day for 2 months. We instructed them to video each pill taking episode using the system.

Outcome: Adherence as measured by the smartphone system and by pill count.

Results: 42 eligible participants were recruited (median age 24; 86% students). Videos were classified as received—confirmed pill intake (3475, 82.7% of the 4200 videos expected), received—uncertain pill intake (16, <1%), received—fake pill intake (31, <1%), not received—technical issues (223, 5.3%) or not received—assumed non-adherence (455, 10.8%). Overall median estimated participant adherence by MiST was 90.0%, similar to that obtained by pill count (93.8%). There was a good relationship between participant adherence as measured by MiST and by pill count (Spearmans ρ, 0.66, p<0.001).

Conclusions: We have demonstrated the feasibility, acceptability and accuracy of a smartphone-based adherence support and monitoring system. The system has the potential to supplement and support the provision of DOT for TB and also to improve adherence in other conditions such as HIV and hepatitis C.

Strengths and limitations of this study

- Our system is novel and was developed to be simple to use and relevant to patients with TB requiring directly observed treatment.
- We tested the system for monitoring adherence at a range of pill frequencies (up to three times daily).
- We tested for robustness against deliberate deception.
- Initial technical problems with the system which reduced observed adherence in some individuals.
- We tested the system in a predominantly young and technologically literate cohort, which, while ideal for identifying and reporting initial problems during the pilot stage, is not representative of a patient cohort.

BACKGROUND
Non-adherence to medications is one of the main causes of suboptimal patient outcomes.1 For treatment of infectious diseases such as tuberculosis (TB), HIV and hepatitis C, non-adherence to medication reduces the patients’ chances of recovery but also increases the risk of the development of drug resistance and the spread of disease in the community. These public health risks are considered to justify a more invasive approach to supporting and monitoring adherence, in contrast to other conditions where non-adherence poses risks that are mainly limited to the individual.

To address the issue of poor adherence for TB, the WHO developed directly observed treatment (DOT).2 This initiative primarily involves direct observation of adherence, which usually requires a patient to travel to a clinic daily. Limitations of this approach include the heavy burden it places on already overstretched health systems, the time and inconvenience for patients that can
lead to employment challenges, loss of earnings and mental health problems; and frequent journeys on public transport which potentially expose other commuters to TB. Similar approaches to observed therapy have been suggested for HIV-infected individuals who have adherence challenges—in the past this has not been framed in terms of public health risk to the community, but as the benefits of virological suppression on HIV disease transmission have become more clearly established (and indeed now form the cornerstone of HIV public health policy), systematic programme-based adherence support approaches may also become more relevant for HIV.

Since the introduction of DOT more than 20 years ago, mobile phone ownership has increased from 34 million subscriptions globally to more than 7 billion. The most rapid growth in the first quarter of 2016 was seen in India, Myanmar and Indonesia. Globally, smartphones now account for 50% of all mobile phone subscriptions and 80% of all new subscriptions. In middle-income countries such as Peru, Kenya, Philippines and Russia, one to two out of every four people own a smartphone. These figures are increasing rapidly. Smartphone subscriptions in Africa are predicted to increase by more than 200% by 2021. Smartphones are capable of recording and transmitting high-quality video to distant healthcare facilities, with potential benefits for public health that have not yet been fully exploited.

We aimed to develop and evaluate a smartphone-based system to facilitate remote directly observed therapy via transmission of videos rather than in-person observation.

METHODS
Design and development of the system
The system, which we called ‘Mobile Interactive Supervised Therapy’ (MIST), comprises integrated web and smartphone-based components (figure 1). The web component of the system allows the administrator to set the required time(s) of pill-taking each day, selected according to the frequency of therapy and patient preferences. Although a common time is usually set for all days of the week, the system allows this to be set to different times each day (eg, different on weekdays and weekends) and could be adjusted if the patient’s preference changes during the course of treatment. Once set, the system sends pill reminder notifications (via SMS or push service) to the patient’s mobile phone 30 min prior to each scheduled pill time, with repeated reminders every 15 min continuing until the patient uses their smartphone to transmit a video of themselves taking the pill or 1 hour has passed since the planned time of ingestion. The system stores uploaded videos with a time and date stamp on a secure cloud server linked only to a subject number. Following successful upload videos are automatically deleted from the phone. The

![Figure 1: Schematic representation of the components of MIST system. MIST, Mobile Interactive Supervised Therapy.](http://bmjopen.bmj.com/ on July 7, 2021 by guest. Protected by copyright.)
The MIST application was installed onto the participant’s smartphone, and they were given a demonstration on how to use the system to submit videos. They were asked to submit videos for all scheduled pill taking episodes. To test the ability of the system to detect deliberate deceit, all participants were also asked to try to circumvent the system once or twice during the 2-month study, at a time and in a manner of their choosing, by uploading a video where they appeared to take a pill but did not actually swallow their prescribed pill. They were given contact details of an independent researcher and asked to inform them when they had sent a sham video. The independent researcher kept a list and provided this to the study team at the completion of the study.

A research nurse accessed the MIST web portal at approximately the same time each day to review all videos submitted within the preceding 24-hour period. Videos submitted over a weekend were reviewed on the subsequent working day. If videos were found to be missing for three consecutive timeslots, the research nurse telephoned the participant to determine the cause. Participants were also given the contact number of the research nurse and asked to report any problems experienced with the system. After discussion with the participant, reasons for missing videos were categorised as either a technical problem or non-adherence. When participant non-adherence was detected, participants were counselled and a change in scheduled pill time was offered where this might address the underlying problem. Reported technical problems were rectified as quickly as possible, but the study was not interrupted.

At the final study visit, participants were asked to return their pill bottle and a pill count was performed. Participants were asked to evaluate whether they felt the system helped them adhere to their course of pills, using a seven point Likert scale (1: 'strongly disagree' to 7: ‘strongly agree’).
recording or uploading the video, we counted this as an episode of adherence (because they were instructed to take the pill in the event they could not record the video, and they would have taken the pill prior to attempting to upload). Correlation was assessed using Spearman rank coefficient. A one-way ANOVA was performed to assess differences in adherence at increasing pill frequencies. All analyses were carried out using SPSS V.21.

RESULTS
We assessed 48 healthy volunteers for participation, of which 42 met criteria and were recruited (median age 24 (range 22–40); 17 (45%) male; 36 (86%) students). Three were taking multivitamin supplements regularly prior to the study (changed to study multivitamins for the duration of the trial), and none were on any other medications. Eleven had taken medication courses previously, with a high self-reported adherence score (median 6 out of a scale of 7; range 4–7). Participants also reported high technical skill level with computers (median 6, range 5–7) on the same scale. The main device used for accessing MIST was Apple iPhone in 11, Android-based smartphone in 26 and a personal computer with webcam in 5. Twenty-three received a once a day regimen, 10 twice a day and 9 three times a day. Twenty-eight received resveratrol, and the remainder received a combination of resveratrol and multivitamins.

Videos were classified into one of five categories (see Table 1): received—confirmed pill intake (3475, 82.7% of the 4200 videos expected), received—uncertain pill intake (16/4200, <1%), received—fake pill intake (31/4200, <1%), not received—technical issues (223/4200, 5.3%) or not received—assumed non-adherence (455/4200, 10.8%). Reasons for non-adherence were often related to illness or overseas travel (participants could still take the pill and use the system overseas but often chose not to do so because of increased data charges). Participants reported sending 40 videos mimicking deliberate non-adherence, of which 28 were accurately identified by the observer, 12 were missed and 3 normal videos were incorrectly identified as showing deliberate non-adherence. The reported techniques for faking pill intake that were not detected included using an opaque cup into which the participant spat the pill while taking a sip of water and holding the pill under the tongue.

Overall the median estimated participant adherence by MIST was 90.0% (range 48.3–100%), similar to that obtained by pill count (93.8%, range 46.7–100.0%). There was a good relationship between participant adherence as measured by MIST and adherence by pill count (Spearman correlation coefficient ρ 0.66, p<0.001, see figure 2). Overall adherence by MIST was classified as ≥90% in 22 (52%) participants; 80–90% in 11 (26%) and <80% in 9 (21%); similar to the proportions obtained by pill count for these three categories (28 (66.7%), 7 (16.7%) and 7 (16.7%), respectively). There was no significant difference observed in adherence between once, twice or three times a day pill intake, measured by MIST (p=0.134), or pill count (p=0.414) (one-way ANOVA). Thirty per cent of technical problems were attributable to four individuals.

The system was perceived to be beneficial by the participants (a median score of 6 (range 4–7) of 7, when asked whether the system helped them to adhere to the course of medication).

DISCUSSION
We developed and tested a smartphone-based system to facilitate remote video observation of pill intake, which can provide real-time information about patient adherence and act to support and enhance adherence. We found that the system was well accepted by participants who all continued the study to the end, and most felt it contributed to their ability to adhere to a 2-month course of pills. It provided images of sufficient quality to allow reliable assessment of pill ingestion by a remote observer and the majority of attempts at cheating the system were detected—those that were not detected could likely be prevented by changes in procedures (such as the use of a transparent drinking cup, or by requiring participants to raise their tongue to show the sublingual area after swallowing). The system also appeared to give accurate estimates of overall adherence in comparison to pill counts. Thus, we have demonstrated

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Overall numbers of expected videos received or not received (left column) and median proportion per patient (right column)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Videos expected (n=4200)</strong></td>
<td><strong>Video outcomes</strong></td>
</tr>
<tr>
<td></td>
<td>Total number in each category</td>
</tr>
<tr>
<td>Video received (n=3522)</td>
<td>Confirmed pill ingestion</td>
</tr>
<tr>
<td></td>
<td>Uncertain pill ingestion</td>
</tr>
<tr>
<td></td>
<td>Fake ingestion</td>
</tr>
<tr>
<td>Video not received (n=678)</td>
<td>Assumed non-ingestion</td>
</tr>
<tr>
<td></td>
<td>Technical issue reported</td>
</tr>
</tbody>
</table>
feasibility of the system, based on participant acceptability, ease of implementation and accuracy.

The strengths of our study are that we have developed and described a novel system, and one that is relatively simple and easy to replicate. This study demonstrates the principle of the approach which is likely generalisable beyond the specific system we tested. Furthermore, we have tested the system over a substantial period of pill-taking (2 months) and using a range of pill frequencies (from once to three-times daily) that is representative of many clinical scenarios. A small proportion of participants were already taking pills at study entry, but this would be typical of a patient population starting TB treatment and does not affect the validity of the feasibility assessment. The limitations of the study are that we evaluated the system in parallel with continued system development—thus there were some initial technical problems that prevented transmission of videos in a small proportion of occasions, a substantial number of which were attributable to four individuals, likely due to specific phone compatibility issues. We made some assumptions about adherence during these episodes. As the majority of these technical issues occurred at the video upload stage, it was assumed that the pill had already been ingested. Technical issues only accounted for 5% of missed videos, and so alternative assumptions would not substantively alter our conclusions. In spite of initial temporary challenges, participants still maintained their commitment to using the system. Any such system reliant on smartphone connectivity is also likely to have intermittent challenges in patient populations, and it is important to think of this as just one way of adherence support. In some instances, this may need to be supplemented by verbal report, text messages or reversion to standard in-person observation. The study population was mainly young and well educated and technologically aware, which may not be generalisable to the target population in which directly observed therapy is most often used—patients with TB who tend to be from lower socioeconomic strata with fewer years of education.12 As a pilot study, the intervention was limited to a 2-month course of dietary supplements. TB treatment would last at least 6 months and have a higher chance of side effects, both factors which might adversely affect adherence.

This study adds to the limited published literature supporting telemedicine-based approaches to adherence support and monitoring. A number of studies assessed SMS or phone call medication reminders for TB13 14 and HIV.15–20 However, such systems can function as a reminder only and cannot provide a real-time assessment of adherence. Skype and videophones have been tested, but these were limited because a healthcare worker also had to be connected at the allotted time, which is resource heavy, and limits the ability of the patient to choose user friendly pill times.21–23 Multimedia Messaging Service (MMS) has also been tested, but the technology is limited by the poor video resolution.24 Our system allows patients to submit high resolution videos, at a time of their choosing, and grants the healthcare worker the flexibility to review all the days’ videos in a single session at a time that is convenient. One other published study has been carried out that used a system of smartphone transmission of images and text reminders similar to ours.25 This was shown to be feasible and acceptable in a small group of patients with TB in USA and Mexico, the majority of whom were also comfortable at baseline with various aspects of the technology and so were likely somewhat selected. Taken together, these two studies demonstrate strongly the feasibility of this potential approach to supporting and monitoring adherence. Upscaling such systems will not
be without challenges. The network demands of the system are well within those of many countries, even those with limited resources, but the security of such systems must also be taken into consideration. While the videos uploaded to the server are de-identified, there will always exist a small risk that an individual’s privacy could be compromised due to malicious activity. This is a challenge that any healthcare system provider must be alert to, and such systems should be appropriately encrypted.

There are several potential advantages of using a system such as MIST for TB compared to standard DOT. It should be noted that DOT is itself lacking in a strong evidence base. Studies from India and Ghana have shown adherence rates with DOT ranging from 63% to 93%,26–28 and a meta-analysis did not identify any significant difference in treatment completion rates between DOT and self-administered treatment.29 A more patient-friendly alternative such as MIST may in itself motivate adherence. Adherent patients could take their pills from their own home or office at a time of their choosing, resulting in less time off work and lost earnings. Second, in some settings MIST has the potential for enhancing adherence compared to standard DOT. MIST has the potential for more frequent monitoring than most DOT programmes, which do not monitor adherence at weekends or more than once a day. In low or middle income countries that are unable to provide in person DOT, video DOT could be deployed at minimal cost, by taking advantage of a resource that an increasing proportion of video DOT could be deployed at minimal cost, by taking countries that are unable to provide in person DOT, potential for more frequent monitoring than most DOT adherence compared to standard DOT. MIST has the resulting in less time off work and lost earnings. Second, their own home or of adherence. Adherent patients could take their pills from friendly alternative such as MIST may in itself motivate

References


