Use of a colorimetric assay to measure differences in cytotoxicity of *Mycobacterium tuberculosis* strains

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INTRODUCTION

*Mycobacterium tuberculosis* is a bacterial pathogen that produces a detrimental effect on mammalian cell cultures. This effect can be due to the induction of cell apoptosis or necrosis leading to cell death. The phenotype is reported as a cytotoxic or cytopathic effect (Castro-Garza et al., 2002; Danelishvili et al., 2003; Dobos et al., 2000; McDonough & Kress, 1995) and it can be roughly quantified by analysing the altered cell morphology (cell rounding and loss of monolayer integrity) (Daniel et al., 2004; Fischer et al., 1996), setting up a scale to estimate the percentage of rounded or detached cells (Read et al., 1974) or counting the amount of degraded cells by electron microscopy (McDonough & Kress, 1995). A more precise quantitative assay, such as measuring lactate dehydrogenase (LDH) release by using a colorimetric kit, has also been reported (Danelishvili et al., 2003; Dobos et al., 2000). However, most of the above experimental procedures are only semi-quantitative or are time-consuming.

There are other methods to quantify cytotoxicity; however, they are not practical for use with *M. tuberculosis* infection systems: exclusion or inclusion of vital dyes requires direct handling of samples, the release of radiolabelled substances increases the biosafety level, and the reduction of coloured compounds such as 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl-2H-tetrazolium bromide (MTT), 4-[3-(4-i(podophenyl)-2-(4-nitrophenyl)-2H-5-tetrazolio]-1,3-benzene disulfonate (WST-1) and other tetrazolium salts by bacteria (Franzblau et al., 1998; Gomez-Flores et al., 1995) as well as macrophages (Ferrari et al., 1990) in *in vitro* infection models would produce a high background and the results obtained would not be accurate.

Crystal violet (CV) is a triphenylmethane dye also known as gentian violet. The most commonly used application for this dye is as the primary stain in the Gram-staining procedure. Gillies et al. (1986) used CV to quantify the cell number in monolayer cultures as a function of the absorbance of the dye taken up by the cells. This method has been used with modifications for a wide number of applications, most of them to determine cytotoxicity or cell death produced by chemicals, drugs, or toxins from pathogens (Harhaji et al., 2004; Shaik et al., 2004; Abbreviations: CV, crystal violet; CVA, crystal violet assay; PLC, phospholipase C; WST-1, 4-[3-(4-i(podophenyl)-2-(4-nitrophenyl)-2H-5-tetrazolio]-1,3-benzene disulfonate.
Rothman, 1986), and to determine cell viability (Thomas et al., 2004) or cell proliferation (Zivadinovic et al., 2005) under different conditions.

A unique characteristic of *M. tuberculosis* bacilli is their outer lipid bilayer, which is the thickest biological membrane known. Because of its hydrophobic nature, the bacterial wall is not accessible to hydrophilic substances such as CV, and *M. tuberculosis* cannot be stained with the regular Gram-staining reagents, resulting in a remarkable Gram-neutral (neither positive nor negative) or Gram-ghost appearance of mycobacteria (Trifiro et al., 1990). Therefore, the CV assay (CVA) becomes a very attractive method to quantify mycobacterial cytotoxicity, because CV will not react or be absorbed by the mycobacteria and any change in absorbance reading is due solely to the difference in the number of mammalian cells in a culture.

**METHODS**

**Mycobacterial strains, culture and growth conditions.** *M. tuberculosis* clinical isolates DR-689, DR-448 and DR-1289 lacking the plcA-plcB-plcC phospholipase C (PLC) locus were used for the present study. The extension of the deletions and the description of the changes in the locus are described in a previous paper (Vera-Cabrera et al., 2007). *M. tuberculosis* H37Rv was included as a positive control for cytotoxicity. Stock cultures of mycobacterial strains were prepared in Middlebrook 7H9 broth supplemented with oleic acid/albumin/dextrose/catalase (OADC), grown to mid-logarithmic phase.

**Cell cultures.** Human monocyte cell line THP-1 was maintained in RPMI 1640 medium (Gibco-BRL) supplemented with 10 % fetal bovine serum (FBS; Gibco-BRL) and 1 mM sodium pyruvate (Sigma). In order to transform the cells into macrophages, the cells were subcultured four times without sodium pyruvate and then seeded into 24-well microplates (Costar Corning) at a concentration of 6.25 ng ml\(^{-1}\) of 5\(^{6}\) cells per well in complete RPMI 1640 supplemented with phorbol-12-myristate-13-acetate (PMA; Calbiochem Biosciences) at a concentration of 6.25 ng ml\(^{-1}\). Cell cultures were washed twice with RPMI 1640 every 48 h for no longer than 4 days.

**CV.** Control and infected cell cultures were fixed at the time points indicated for each experiment in 10 % buffered formalin for 24 h at 4 °C. In all cases, the volume added to each well of the different solutions was 500 μl. Fixative solution was discarded and a 0.1 % aqueous CV solution was added to each well. The samples were incubated at room temperature for 30 min with gentle shaking.

**Mycobacterial cytotoxicity assay.** Before the beginning of the experiment, bacteria were thawed at 37 °C, mixed vigorously using a vortex, and diluted in tissue-culture medium to obtain the desired density to infect the cells with an m.o.i. of 1 : 10 (bacilli : cells). Bacterial c.f.u. from infected cultures was determined at the beginning and end of each experiment in 7H10 medium supplemented with OADC.

Macrophase (THP-1 cell line) monolayers were infected in triplicate with the *M. tuberculosis* strains tested. Infected cultures were incubated at 37 °C and 5 % CO\(_2\) for up to 72 h. Every 24 h, the culture media from three wells from each strain and controls was discarded and the cells fixed in 10 % buffered formalin for at least 24 h at 4 °C. A different microplate was used for each time point, to avoid the effect of formaldehyde vapour on the rest of the cell culture. The cytotoxic phenotype was observed qualitatively as disruption of the confluent monolayers over time using a phase-contrast light inverted microscope Axiovert 25 (Carl Zeiss).

The quantitative analysis of cytotoxicity on the stained cultures infected with *M. tuberculosis* was based on the percentage of dead cells, employing the following equation:

\[
\text{Percentage dead cells} = \frac{(\text{control } A_{600} - \text{ sample } A_{600})}{\text{control } A_{600}} \times 100
\]

All experiments were repeated three times in triplicate.

**RESULTS AND DISCUSSION**

* A\(_{600}\) readings were proportional to the number of cells per well. Regression and correlation analysis of data (1.5 × 10\(^4\)–5 × 10\(^5\) cells per well) showed a slope value of 0.2019 with an \(r\(^2\)\) value of 0.9465 (Fig. 1). This result confirms the utility of CVA to determine viability or cell culture density, as reported previously (Gillies et al., 1986).

In order to test a cytotoxic agent, we used Triton X-100, which is an anionic detergent that dissolves the cell membrane leading to cell death, and the effect depends on the concentration used. Triton X-100 produces a clear

![Fig. 1. CVA in the THP-1 cell line. Bars show mean ± SD of three independent experiments done in triplicate. A row of an experimental microtitre plate is shown in which the wells correspond to the numbers of cells.](image-url)
In order to compare the cytotoxicity of different M. tuberculosis clinical isolates DR-689, DR-448 and DR-1289 strains using the CVA, THP-1 cell monolayers M. tuberculosis were infected with produced exclusively by in absorbance readings in infected monolayers would be produced by the mycobacteria. Accordingly, any change quantifying mycobacterial cytotoxicity, since no background differences were found by an ANOVA one-way analysis bacterial densities were very similar and no significant (all of them lacking the PLC locus). M. tuberculosis H37Rv produced a cytotoxic effect on THP-1 cell monolayers that was observed microscopically 24 h post-infection. After 72 h, it could be visually estimated that around 50 % of the cell monolayer was destroyed (Fig. 3). On the other hand, M. tuberculosis DR-689 and DR-1289 did not disrupt the cell monolayer 72 h post-infection. Strain DR-448 produced cytotoxicity at 72 h as determined by CVA. The CVA values obtained from these experiments are shown in Table 1. All the strains infected the cell cultures, as shown by the c.f.u. values for each strain determined at the end of the experiment, which were: DR-689, 3.5 x 10^4; DR-448, 2.3 x 10^4; DR-1289, 2.2 x 10^4; and H37Rv, 3.7 x 10^3. The strain DR-689, with a yield of 3.5 x 10^5 c.f.u., produced no effect on cell cultures, while H37Rv, with a similar yield, had the highest cytotoxic effect. This result shows that the cytotoxicity is not only due to the intracellular growth but also the strain producing the activity. We have previously reported similar results with M. tuberculosis strains Erdman and CDC-1551, and Mycobacterium bovis BCG (Castro-Garza et al., 1997). Although the clinical isolates used in this work lacked the PLC locus, they still had residual PLC activity (data not shown). There is a fourth phospholipase gene (plcD) in a different region of the genome. In H37Rv, the plcD gene is truncated and interrupted by a copy of the IS6110 insertion sequence. Raynaud et al. (2002) have demonstrated the importance of phospholipases in virulence by inactivating either each individual ORF or all of them concurrently and testing for virulence to mice; however, phospholipases are not the only mycobacterial product able to produce cytotoxicity.

Recently, Takii et al. (2005) have reported the use of CV to test the pyrazinamide susceptibility of M. tuberculosis in a fibroblast-based assay, in which the host-cell viability is reflected by the state of the bacilli inside the host cells. In this study, we demonstrated that the CVA can quantify the cytotoxicity produced by M. tuberculosis in a THP-1 cell monolayer. The ability of the CVA to measure this effect with other mycobacterial species remains to be tested, although a biofilm produced by Mycobacterium avium can be stained with CV (Carter et al., 2003). Mycobacteria other than M. tuberculosis, such as Mycobacterium ulcerans and Mycobacterium marinum, are natural pathogens of poikilothermic organisms (Trucksis et al., 2005), but produce only localized skin infections in humans (Ranger et al., 2006), while Mycobacterium abscessus is commonly associated with contaminated traumatic skin wounds and

and increasing cytotoxic effect starting at a concentration of 0.05 % and reaching a maximum at 0.1 %, as measured with the CVA (Fig. 2). Regression and correlation analysis of data (three experiments each in triplicate) between 0.02 and 0.1 % Triton X-100 gave a slope value of 2821.5 and an r^2 value of 0.9865.

To test the ability of the method to quantify the cytotoxicity produced by M. tuberculosis, it was necessary that no background was caused by staining of the bacteria. As mentioned above, M. tuberculosis is not stained by CV and we found this feature very useful for this model. THP-1 cell monolayers were infected with a variable number of mycobacteria with an m.o.i. up to 10 : 1 (bacteria : cell), incubated for 6 h to allow the internalization of bacteria into the cells, and then immediately subjected to the CVA before any effect was produced by M. tuberculosis on the monolayers. Absorbance readings for all the different bacterial densities were very similar and no significant differences were found by an ANOVA one-way analysis (P<0.05). This result supports the use of the CVA to quantify mycobacterial cytotoxicity, since no background was produced by the mycobacteria. Accordingly, any change in absorbance readings in infected monolayers would be produced exclusively by M. tuberculosis cytotoxicity.

In order to compare the cytotoxicity of different M. tuberculosis strains using the CVA, THP-1 cell monolayers were infected with M. tuberculosis H37Rv strain and M. tuberculosis clinical isolates DR-689, DR-448 and DR-1289 (all of them lacking the PLC locus). M. tuberculosis H37Rv produced a cytotoxic effect on THP-1 cell monolayers that was observed microscopically 24 h post-infection. After 72 h, it could be visually estimated that around 50 % of the cell monolayer was destroyed (Fig. 3). On the other hand, M. tuberculosis DR-689 and DR-1289 did not disrupt the cell monolayer 72 h post-infection. Strain DR-448 produced cytotoxicity at 72 h as determined by CVA. The CVA values obtained from these experiments are shown in Table 1. All the strains infected the cell cultures, as shown by the c.f.u. values for each strain determined at the end of the experiment, which were: DR-689, 3.5 x 10^4; DR-448, 2.3 x 10^4; DR-1289, 2.2 x 10^4; and H37Rv, 3.7 x 10^3. The strain DR-689, with a yield of 3.5 x 10^5 c.f.u., produced no effect on cell cultures, while H37Rv, with a similar yield, had the highest cytotoxic effect. This result shows that the cytotoxicity is not only due to the intracellular growth but also the strain producing the activity. We have previously reported similar results with M. tuberculosis strains Erdman and CDC-1551, and Mycobacterium bovis BCG (Castro-Garza et al., 1997). Although the clinical isolates used in this work lacked the PLC locus, they still had residual PLC activity (data not shown). There is a fourth phospholipase gene (plcD) in a different region of the genome. In H37Rv, the plcD gene is truncated and interrupted by a copy of the IS6110 insertion sequence. Raynaud et al. (2002) have demonstrated the importance of phospholipases in virulence by inactivating either each individual ORF or all of them concurrently and testing for virulence to mice; however, phospholipases are not the only mycobacterial product able to produce cytotoxicity.

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![Fig. 2. Cytotoxic effect of Triton X-100 on the THP-1 cell line.](http://jmm.sgmjournals.org)

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**Quantification of M. tuberculosis cytotoxicity**

![Fig. 3. Cytotoxicity of M. tuberculosis towards THP-1 cells. Cell monolayers 72 h post-infection are shown (×250). (a) Uninfected cells, (b) M. tuberculosis H37Rv infected cells, (c) M. tuberculosis DR-689 infected cells. Bar, 200 μm.](http://jmm.sgmjournals.org)
with post-surgical soft-tissue infections (Petriti, 2006). These mycobacterial species exhibit cytotoxicity towards cell cultures or have a necrotic effect in their pathologies (Torrado et al., 2007; Ranger et al., 2006). It would be very interesting to apply the CVA to measure and compare their activities, either between species or among mutant strains of a single species, such as the M. ulcerans mutant lacking the mycolactone toxin, which has only been analysed by altered cell morphology (Daniel et al., 2004).

The results of this work support the use of the CVA as a rapid, sensitive and reliable quantitative assay to measure the cytotoxicity of M. tuberculosis and to compare differences in activity between strains that could potentially be related to virulence.

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REFERENCES


Table 1. Cytotoxicity of M. tuberculosis strains

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<tr>
<th>Incubation time</th>
<th>M. tuberculosis strains</th>
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<tr>
<td></td>
<td>DR-689</td>
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<tr>
<td>24 h</td>
<td>0</td>
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<tr>
<td>72 h</td>
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Values show the percentage of dead cells, and represent the mean ± SD of three independent experiments done in triplicate.


Quantification of *M. tuberculosis* cytotoxicity