ORIGINAL ARTICLE

A Randomized, Controlled Trial of an Aerosolized Vaccine against Measles

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The Global Vaccine Action Plan aims to eliminate measles from at least five World Health Organization (WHO) regions by 2020.[1] A safe and effective injectable measles vaccine has been widely available since 1963,[2] and intensified efforts between 2000 and 2010 reduced measles-related deaths by 74%.[3] Nevertheless, major outbreaks continue, particularly in resource-poor countries that lack investment in health care systems and the health service infrastructure. In these countries, immunization coverage through routine services and mass campaigns remains low.[4]

New approaches to measles vaccination could contribute to reaching elimination goals, particularly if they increase coverage, can be administered by people without clinical training, and do not cause injection-associated infections.[5-7] Aerosolized vaccine against measles was developed in Mexico and has been used in more than 4 million children there since 1980.[8] Nebulization delivers vaccine to the site of natural infection and induces measles-specific antibodies and cell-mediated immunity.[9,10]

Data about the efficacy of this aerosolized vaccine against measles in children are inconsistent, however. Two comprehensive reviews concluded that it was as good as or better than vaccine delivered subcutaneously in children 9 months of age or older.[11,12] However, the two randomized, controlled trials comparing these routes of administration in children 8 to 13 months of age were small, associated with a risk of bias, and inconsistent.[9,10] A subsequent systematic review pooled data about each route of administration from randomized, controlled trials and observational studies. Among children 10 to 35 months of age, the pooled seroconversion rate in five studies among those who received aerosolized vaccine against measles was 93.5% (95% confidence interval [CI], 89.4 to 97.7), and the pooled seroconversion rate in two studies among those who received the vaccine subcutaneously was 97.1% (95% CI, 92.4 to 100).[13] After subcutaneous vaccination, approximately 92% (interquartile range, 84 to 96) of children 9 to 10 months of age and 99% (interquartile range, 93 to 100) of children 11 to 12 months of age underwent seroconversion.[7]

Given the established record of injectable measles vaccine, alternative delivery methods should show noninferiority. A phase 1 trial in India of aerosolized vaccine against measles showed evidence of safety, immunogenicity, and feasibility in children older than 4 years of age and in adults.[14] In this individually randomized, open-label noninferiority trial involving children in India, we aimed to compare the immunogenicity and safety of a primary dose of aerosolized vaccine against measles with that of a primary dose of vaccine delivered subcutaneously.

METHODS

Study Design and Oversight

The WHO Initiative for Vaccine Research coordinated the Measles Aerosol Vaccine Project, and the Centers for Disease Control and Prevention and the American Red Cross were partners in the project. An independent data and safety monitoring board had access to unblinded data to assess serious adverse events. A product development group (see the Supplementary Appendix, available with the full text of this article at NEJM.org) reviewed progress. Ethics committees of the WHO, Christian Medical College (in Vellore, India), the National Institute of Virology, and King Edward Memorial Hospital Research Centre (in Pune, India) approved the protocol. The trial was designed

and conducted in accordance with Good Clinical Practice[15] and Good Laboratory Practice[16] guidelines.

The Serum Institute of India provided all vaccines free of charge, and Aerogen provided the delivery devices free of charge. Additional details about the trial design, conduct, and analysis are provided in the Supplementary Appendix and in the full protocol, including the statistical analysis plan, available at NEJM.org.

Study Participants and Clinical Setting

The trial was conducted in villages served by eight primary health centers in Pune. One study has shown that more than 90% of infants in Pune are breast-fed from birth, for a median of 4.7 months.[17] Children between 9.0 and 11.9 months of age were eligible to participate in the study if they were due to receive primary measles vaccination. Children were excluded from participation if they were ineligible to receive measles vaccine according to WHO criteria.[18]

Randomization and Vaccination

From December 20, 2009, through April 5, 2010, we randomly assigned children, in a 1:1 ratio, to receive measles vaccine by means of aerosol inhalation or by means of a subcutaneous injection. A detailed description of the randomization process is provided in the Supplementary Appendix. After obtaining written informed consent from the parents or guardians of the children, the study nurses telephoned a centralized Web-based service and recorded the study assignments. At the Vadu site, which is part of a demographic surveillance system,[19] two random subgroups of 100 children were selected to have blood drawn at either day 28 or day 364 for the monitoring of serologic responses.

We used a measles vaccine (Serum Institute of India), licensed by the WHO, that contained at least 1000 viral infective units of the live attenuated Edmonston–Zagreb strain of measles virus in each dose. The vaccine was delivered in 10-dose vials.

The study nurses reconstituted the 10-dose vials of measles vaccine and stored them until use at 2 to 8°C. They reconstituted the vaccine for aerosol delivery in 2-ml diluent and administered a single 0.2-ml dose, nebulized for 30 seconds through a single-use nonvented face mask, using a battery-operated Aeroneb vibrating mesh nebulizer (Aerogen). The nebulizer generated aerosol with a volume median diameter of 5.1 μm (geometric standard deviation, 2.1 μm) as determined by means of laser diffraction (Spraytec) (details are provided in the Supplementary Appendix).[14] The study nurses reconstituted the vaccine for subcutaneous delivery in 5-ml diluent and administered a single 0.5-ml dose into the left upper arm. The rooms for delivery of aerosolized vaccine and subcutaneous vaccine were separate so that children receiving subcutaneous vaccine were not exposed unintentionally to aerosolized vaccine. Reconstituted vaccine was discarded after 6 hours.

End Points

Immunogenicity

The prespecified primary end point was seropositivity for serum antibodies against measles 91 days after vaccination. We defined seropositivity as 0.1 or more optical-density units on an enzyme-linked immunosorbent assay (ELISA) (Enzygnost Anti-Measles Virus/IgG, Siemens) or, in samples containing less than 0.1 optical-density units, a measles antibody concentration of 120 mIU per milliliter or more as measured with the use of a plaque-reduction neutralization test (PRNT). The testing algorithm was based on a study that showed a positive predictive value of 99.4% for ELISA (cutoff value, 0.1 optical-density units) as compared with PRNT (cutoff value, 120 mIU per milliliter).[20]

All samples at baseline and day 91 were tested by means of ELISA. Specimens with less than 0.1 optical-density units and all samples from the Vadu site were tested by means of PRNT. Paired prevaccination and post-vaccination samples were tested in the same run. All specimens were tested at the Virus Reference Department, Public Health England (formerly the United Kingdom Health Protection Agency), United Kingdom, in March 2012. The specimens had been tested in Pune, but the results of a random 10% sample of ELISA and PRNT analyses did not meet the prespecified quality-assurance criteria, so all samples were shipped to the United Kingdom.

Prespecified secondary end points were seroconversion and geometric mean concentrations of antibodies. Seroconversion was defined as a change from seronegative at day 0 to seropositive at day 91. Secondary outcomes were the difference in rates of seroconversion (among participants who were seronegative at baseline), the ratio of geometric mean concentrations, and geometric mean concentrations at days 0, 28, 91, and 364 in children in Vadu.

Safety

The prespecified primary safety outcome was the frequency of all solicited and unsolicited reports of adverse events up to 91 days after vaccination on day 0.[21] Study nurses observed all children during and for 30 minutes after vaccination. Adverse events were then assessed according to the report of parents and guardians during home visits on days 3, 7, 10, 17, 21, 28, and 56 and by clinical examination on days 14 and 91 (Fig. S1 in the Supplementary Appendix). All children who were enrolled in Vadu were evaluated at day 364.

We collected information with the use of questionnaires that solicited information on 16 events (Table S1 in the Supplementary Appendix), by means of active surveillance both for events requiring treatment or hospitalization and for deaths, and through unsolicited reports of events from parents or guardians. We sent reports of all adverse events to the data and safety monitoring board, which had the authority to stop the trial if a single serious adverse event was judged to be attributable to the vaccine.

Follow-up and Blinding

We followed all participants until day 91 (from March through August 2010, depending on the date the patient underwent randomization). Case-based active surveillance with serologic confirmation of cases of fever and rash (Enzygnost Anti-Measles Virus IgM ELISA, Siemens) was in place in the entire trial area.[22] Parents or guardians, children, and study staff were aware of the route of vaccine administration.

To reduce bias, all outcome assessments were blinded. Field workers used follow-up case-report forms that did not record the vaccination assignment, laboratory staff conducted analyses of coded specimens, and statisticians conducted data checks and preliminary analyses of blinded data.

Statistical Analysis

We aimed to show that seropositivity after receipt of aerosolized vaccine against measles was no more than 5 percentage points lower than seropositivity after subcutaneous vaccination. This estimate was based on the 4 percentage-point difference in a previous systematic review of studies involving children 10 to 35 months of age[13]; in addition, with a bigger margin, aerosolized vaccine would not provide levels of protection required for herd immunity.[18]

We assumed that exactly 90% of the children in each group would be seropositive at day 91, and we allowed for lower immunogenicity in children younger than 10 months of age.[7] For noninferiority to be shown with the use of the confidence-interval approach, the lower limit of the two-sided 95% confidence interval for the difference (aerosol group minus subcutaneous group) in the proportion of seropositive children at day 91 had to be above −5 percentage points in the per-protocol population. If the upper confidence interval was below −5 percentage points, we would conclude inferiority, and if the lower interval was above zero, we would conclude superiority (Fig. S2 in the Supplementary Appendix). We estimated that with a sample of 800 children per group, the study would have 90% power to detect these differences. We planned to enroll 1000 children per group to allow for 20% who would not have results that could be evaluated at follow-up.

We calculated the difference between the proportion of children who were seropositive after receiving the aerosolized vaccine and the proportion who were seropositive after receiving the subcutaneous vaccine in the per-protocol population (which consisted of children who received the assigned vaccine, did not have any major protocol deviations, and had specimen results at day 91) and the full-analysis population (which consisted of all children who underwent randomization, excluding children for whom outcome data were missing). The full-analysis population was equivalent to a modified intention-to-treat population. We used the Wilson score method to estimate 95% confidence intervals.[23] Multiple imputation was used to predict seropositivity when outcome data were missing, and we repeated the analysis with inclusion of all participants (see the Supplementary Appendix).[24]

For the secondary end points, we used logistic regression to investigate the association of prespecified factors with lack of seroconversion after receipt of aerosolized vaccine. For safety outcomes, we calculated the percentages of children (with 95% confidence intervals) who had any solicited or unsolicited reports of an adverse event or serious adverse event up to day 91.

RESULTS

Study Participants

In total, 2004 children underwent randomization and 1996 received their assigned vaccine (Figure 1). The baseline characteristics of the two groups were balanced (Table 1, and Table S3 in the Supplementary Appendix). We followed 1956 of 2004 children (98%) until day 91. Specimens obtained from 331 participants (17%) thawed for a period during transport and were, therefore, excluded from the primary-outcome analyses; these specimens were distributed equally between the aerosol and subcutaneous groups (Fig. S3 and Tables S4 and S5 in the Supplementary Appendix).

FIGURE 1

Eligibility, Randomization, and Follow-up of Children in the Per-Protocol Population.

TABLE 1

The per-protocol population for the primary outcome included 77% of the children (775 of 1001 children) who were randomly assigned to aerosolized vaccine and 78% (785 of 1003 children) who were randomly assigned to subcutaneous vaccine (Figure 1). The full-analysis set included 79% (788 of 1001) of the children who were randomly assigned to aerosolized vaccine and 79% (796 of 1003) of the children who were randomly assigned to subcutaneous vaccine (Fig. S3 in the Supplementary Appendix). The case-based surveillance system in the trial villages identified 772 confirmed cases

of measles from November 1, 2009, through December 31, 2011.

Baseline Characteristics of the Participants.

Laboratory Assays

On the basis of both ELISA and PRNT results from day 28 samples obtained from children in Vadu, the positive predictive value of the ELISA cutoff value of 0.1 optical-density units, as compared with PRNT, was 96% (241 of 250 samples). The negative predictive value was 69% (34 of 49 samples); this confirmed the need to test samples that were negative on ELISA with the use of PRNT. All samples that were seronegative according to PRNT at baseline were also seronegative on ELISA.

Immunogenicity

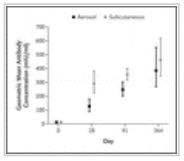
At day 91, a total of 662 of the 775 children in the per-protocol population who received aerosolized vaccine (85.4%; 95% CI, 82.5 to 88.0) and 743 of the 785 who received subcutaneous vaccine (94.6%; 95% CI, 92.7 to 96.1) were seropositive, a difference of −9.2 percentage points (95% CI, −12.2 to −6.3). The results, based on the confidence intervals, did not show noninferiority of aerosolized vaccine to subcutaneous vaccine at the 5 percentage-point margin. Aerosolized vaccine, as compared with subcutaneous vaccine, resulted in statistically inferior rates of seropositivity (Figure 2). After multiple imputation and with seroconversion as the outcome, results in the per-protocol and full-analysis data sets were similar (Table S6 in the Supplementary Appendix). In a sensitivity analysis in which the results of damaged specimens were classified as being either all seronegative or all seropositive, the differences between aerosolized and subcutaneous vaccine were smaller but still did not show noninferiority of the aerosolized vaccine. Among children who were seropositive at day 91, geometric mean concentrations were similar in the two groups (ratio of the concentration in the aerosol group to that in the subcutaneous group, 1.05; 95% CI, 0.99 to 1.11) (Table S6 in the Supplementary Appendix). None of the measured factors were very strongly associated with a lack of seroconversion after the receipt of aerosolized vaccine (Table S7 in the Supplementary Appendix).

FIGURE 2

Immunogenicity Outcomes at Day 91 in the Aerosolized and Subcutaneous Vaccine Groups.

Among children in Vadu, geometric mean concentrations increased at each time point up to 364 days after vaccination in both the aerosol and subcutaneous groups (Figure 3). Between-group differences in the proportion of children in Vadu who were seropositive (the percentage of children who were seropositive in the aerosol group minus the percentage of children who were seropositive in the subcutaneous group) were as follows: −0.5 percentage points (95% CI, −5.9 to 4.5) on day 0, −24.4 percentage points (95% CI, −36.3 to −11.8) on day 28, −11.2 percentage points (95% CI, −18.3 to −3.9) on day 91, and 1.5 percentage points (95% CI, −8.7 to 11.2) on day 364.

FIGURE 3



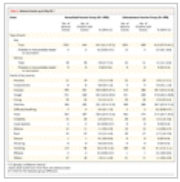
Geometric Mean Concentrations of Antibodies against Measles, According to Vaccine Group.

Safety

Serious Adverse Events

None of the children died during the trial or the follow-up period. By day 91, a total of 38 children who had received aerosolized vaccine and 31 who had received subcutaneous vaccine had had a serious adverse advent (Table 2, and Tables S8 and S9 in the Supplementary Appendix). The data and safety monitoring board did not judge any of the serious adverse events to be probably or most probably associated with vaccination (Table S8 in the Supplementary Appendix).

TABLE 2



Adverse Events up to Day 91.

Adverse Events

In total, 3776 adverse events from any cause (1952 in the aerosol group and 1824 in the subcutaneous group) were recorded up to 91 days after vaccination, mostly during three home visits in the first 14 days (Table 2, and Tables S9 and S10 in the Supplementary Appendix). Adverse-event profiles in the two groups were similar, but coryza was more common among children who received aerosolized vaccine (Table 2) (P=0.02). Five adverse effects (rash, coryza, cough, diarrhea, and fever) that were reported in 4 episodes in 2 children in the aerosol group and 13 episodes in 3 children in the subcutaneous group were judged as being probably or most probably related to the vaccination.

DISCUSSION

Aerosolized vaccine against measles, as compared with subcutaneously administered vaccine, resulted in statistically inferior levels of seropositivity at 91 days in children who were 9.0 to 11.9 months of age. Profiles of adverse events were similar in the two groups, and adverse events associated with vaccination were rare.

The difference of 9 to 10 percentage points in seropositivity between the aerosolized and subcutaneous vaccine was greater than the prespecified noninferiority margin of 5 percentage

points. The narrow noninferiority margin reflected the need to elicit a high level of seropositivity for antibodies against measles, given the established record of the licensed subcutaneous vaccine.[7] The main limitation of our trial was that we did not have measles antibody results for nearly 20% of the samples; although we followed almost all participants to day 91, a batch of specimens was damaged during transport. We do not believe that this biased our results, however, because these data were missing at random, sensitivity analysis with the use of multiple imputation showed that our findings were robust, and the sample size was adequate because the enrollment target allowed for 20% loss to follow-up.

The proportion of children who were seropositive 91 days after they received aerosolized vaccine against measles was 85% (95% CI, 83 to 88); this proportion was also lower than expected. Inhibitory maternal antibodies and immature immune systems could have reduced responses to the measles vaccine,[7] but only 2% of the children had measles antibodies at enrollment, and seropositivity was similar in older and younger children. Furthermore, seropositivity in children after receipt of the subcutaneous vaccine was in line with published data.[7]

The proportion of children who were protected against measles by aerosolized vaccine could be higher than observed because cell-mediated immunity is not captured by measurement of neutralizing antibodies. There is no consistent evidence, however, that cell-mediated immunity is relatively more important after aerosol vaccination than after subcutaneous vaccination.[10,25] Prolonging the duration of nebulization to increase the retained dose of aerosolized vaccine could increase levels of both neutralizing antibodies and cellular immune responses.[25] In the subgroup of children tested in Vadu, the geometric mean concentrations increased between day 91 and day 364 in children in both trial groups. Vaccine-induced antibody levels tend to decrease over time, but natural boosting from circulating measles virus can result in sustained or increasing antibody levels.[26] The case-based surveillance system showed that measles virus was circulating throughout the trial area,[22] so natural boosting of antibody levels in children in both trial groups might have attenuated the difference in seropositivity by day 364.

The results of this trial are relevant for the planning of future research to determine the ways in which aerosolized vaccine against measles could still contribute to further policies and goals for measles immunization worldwide.[1,18] First, aerosolized vaccine against measles might be effective in older children. In countries that have high levels of measles vaccine coverage or that are in the elimination phase, primary vaccination at 12 months of age is recommended. Second, a second dose of a measles-containing vaccine is now recommended to protect children who did not have a response to the first dose and to maintain the 95% level of population immunity required to eliminate measles.[27] By 2014, a total of 145 WHO member states had introduced a two-dose measles vaccination strategy.[4] Aerosolized vaccine against measles induced higher and more sustained levels of serologic protection than subcutaneous vaccine when administered as a second dose in school-age children in South Africa.[28,29] Third, if aerosolized vaccine increases the coverage of primary vaccination, this strategy could be more cost-effective than two-dose vaccination at lower levels of coverage.[30]

Data are lacking to evaluate the effectiveness and cost-effectiveness of aerosolized vaccine against measles as a primary dose in children older than 12 months of age and as a second dose in children younger than 5 years of age. Data are also lacking to evaluate the effectiveness and cost-effectiveness of aerosolized vaccine containing both measles and rubella virus. In this randomized, controlled trial, a primary dose of aerosolized vaccine against measles in children 9 months of age or older was immunogenic, but at the prespecified margin, the aerosolized vaccine was inferior to the subcutaneous vaccine with respect to the rate of seropositivity.

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Disclosure forms provided by the authors are available with the full text of this article at NEJM.org.

The views expressed in this article are those of the authors and do not necessarily represent the decisions, policies, or views of the WHO.

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SOURCE INFORMATION

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