Kinematic Study of the Temporomandibular Joint in Normal Subjects and Patients Following Unilateral Temporomandibular Joint Arthrotomy With Metal Fossa-Eminence Partial Joint Replacement

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Purpose: The primary purpose of this study is to quantify the kinematics of the temporomandibular joint (TMJ) in patients following unilateral TMJ arthrotomy with metal fossa-eminence partial joint replacement and compare them with TMJ kinematics of healthy individuals.

Materials and Methods: Fourteen healthy volunteers and 13 female surgical patients (minimum 4 years postoperative) participated in this study. An electromagnetic tracking device was used to record the kinematics of the mandible relative to temporal bone during opening-closing, protrusive, and lateral movements. The mean linear distance (LD) traveled by condyles was compared between operated and normal subjects.

Results: Patients responded with statistically significant improvement in pain and jaw function questions. Mean satisfaction with the surgical result was 25.7 on a scale of 1 to 30. The LD measured for condyles during all 4 movements showed similar measurements. However, operated and unoperated condyles showed statistically significant motion values during opening and protrusive motion from each other and from normal subjects. In addition, contralateral condyles during lateral motion showed statistically significant values in operated, unoperated, and normal condyles.

Conclusion: The results of this study suggest that the surgical reconstruction of the TMJ with partial joint replacement provided highly significant clinical improvement. Moreover, condyle and incisor kinematics were preserved to a significant amount as compared with the normal group. The difference in kinematic measurements between the operated and unoperated condyle was significant and secondary to previous joint disease and previous surgical intervention. These results should be evaluated by prospective studies in pre- and postsurgical patients.

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In most temporomandibular joint (TMJ) patients, the symptoms are mild and cyclic with varying degrees of pain and restricted movement. These patients can often be managed medically with nonsteroidal anti-inflammatory drugs, physiotherapy, and other forms of nonsurgical therapy. In patients with progressive disease, the meniscus and interpositional soft tissues within the TMJ can be displaced or perforated, allowing for bone on bone contact between the mandibular condyle and glenoid fossa. Functional loading leads to degeneration of the osseous articular surfaces, subarticular bone erosion, and sclerosis of the underlying cancellous bone. This condition is classified as degenerative joint disease or osteoarthritis. Further progression can lead to fibrous/osseous ankylosis. These patients often require surgical intervention and fall into the hands of oral and maxillofacial surgeons.\(^1\)

The indications for TMJ surgery are rigorous and historically thought of as the "last resort," with only 1% or less of all patients referred with a diagnosis of temporomandibular disorder requiring surgery. Widmark\(^2\) concluded that unsuccessful conservative treatment should not exceed 3 to 6 months, and patients with fibro or bony ankylosis should be treated surgically without delay. We believe a high percentage of osteoarthritic patients with bone on bone contact and persistent pain should also be treated surgically without delay. Many techniques for the reconstruction of the osseous structure (fossa, eminence, and condyle) and/or disc of TMJ have been described and include both autogenous, alloplastic, and partial/total joint materials and systems.\(^1,3\)

There is controversy on the indications and techniques for reconstruction of the TMJ. Before 1980, alloplastic joint replacement (hemiarthroplasty/partial joint replacement) was performed mainly after ablative surgery and in cases of bony ankylosis, trauma, or severe degenerative joint disease. In the mid to late 1980s, as many patients began to fail initial medical and surgical treatment, partial or total TMJ prosthetic reconstruction was performed as salvage therapy.\(^4\) Recently, Woldorf et al\(^5\) described selection criteria for prosthetic TMJ reconstruction as: 1) multiply operated, 2) previous failed alloplastic implants, 3) osteoarthritis, 4) inflammatory or resorptive arthritis, 5) connective tissue or autoimmune disease, 6) ankylosis, and 7) absent or deformed structures.

Mercuri\(^6\,7\) reported the advantages of alloplastic TMJ reconstruction as: 1) physical therapy can begin immediately, 2) no need for a secondary donor site, 3) decreased surgery time, and 4) ability to mimic normal anatomy. The stated disadvantages were: 1) cost of the prosthetic device, 2) alloplastic material wear and failure, 3) long-term stability, and 4) lack of adjustment in a growing patient.

We have used the Co-Cr-Mo metal fossa-eminence prosthesis (partial joint replacement system; TMJ Implant, Inc, Golden, CO) since 1988 and recently reported on an 8-year retrospective pilot study on the surgical management of advanced degenerative arthritis of TMJ with metal fossa-eminence hemi-joint replacement prosthesis.\(^3\) We concluded "the surgical placement of the partial joint replacement provided significant focal preauricular pain relief and reduced TMJ dysfunction secondary to advanced degenerative arthritis."

The purposes of the current study are to quantify the kinematics of TMJ function in healthy individuals and to determine the kinematics of TMJ function in patients following unilateral TMJ arthrotomy with metal fossa-eminence partial joint replacement.

### Materials and Methods

#### SUBJECTS

Fourteen healthy volunteers (11 women, 3 men; mean age, 31.4 years) participated in the study. All participants were at least 18 years of age. All subjects had complete dentitions except third molars and angle Class 1 occlusion without obvious abnormalities such as a cross bite or an excessive overbite (>5 mm). Volunteers were checked for signs or symptoms for TMJ disorders; history of pain or noise in the TMJ, pain and/or fatigue of the masticatory muscles, impaired jaw mobility, facial pain, headache, and odontalgia. No signs or symptoms were present at the time of study testing. Also, none of the normal subjects had undergone major dental treatment within the last 3 years (such as orthodontics, orthognathic surgery, or extensive restorative therapy).

Thirteen female patients (mean age, 45 years; range, 31 to 61 years) who had undergone unilateral surgical reconstruction of advanced degenerative TMJ arthritis participated in this study. All patients had unilateral TMJ arthroplasty with metal fossa-eminence partial joint replacement (Christensen TMJ implant system; TMJ Implant Inc, Golden, CO). Surgical selection criteria at our institution are previously published.\(^3\) The minimum postoperative follow-up was 4 years. To insure consistent surgical technique and treatment protocol, patients of 1 surgeon were studied. The aim and protocol of this study was explained to all participants before starting the kinematic recordings. All subjects provided written informed consent to participate. This study was approved by the authors' Institutional Review Board.

#### DATA COLLECTION

**Subjective Data**

Information regarding the surgical patient's previous nonsurgical/surgical TMJ treatments and symptoms was obtained from the institutional records of
Table 1. PATIENT QUESTIONNAIRE: PRESURGICAL AND CURRENT, VAS (1-30)

1. Pain intensity (0 = no pain, 30 = severe, intense, incapacitating pain)
2. Chewing ability (0 = no problem, 30 = impossible to chew)
3. Jaw opening (0 = no opening problem, 30 = no opening)
4. Joint noise (0 = no noise, 30 = severe annoying noise)
5. Satisfaction with surgical result (0 = no satisfaction, 30 = complete satisfaction)
6. Pain experience (presurgical and current, 1-6)
   0 = no pain
   1 = some pain, which you easily can disregard
   2 = some pain, which you cannot disregard but does not make your usual activities more difficult
   3 = pain that makes concentration on more demanding task more difficult
   4 = pain that makes most things you do more difficult except the most basic
   5 = pain that is so severe that you have to rest
   6 = pain that is so severe you cannot stand it

Mayo Clinic, Rochester, MN, and confirmed by the first author before the experimental study.

Subjective presurgical and current data regarding pain intensity, chewing ability, jaw opening, joint noise, and overall satisfaction with surgical treatment were collected using a visual analog scale of 30 mm in length. Pain experience was collected using a 1 to 6 rating system (Table 1). Patients were asked to complete questionnaires according to their presurgical and postsurgical experiences, retrospectively.

Objective Data

Mandibular incisor and condylar motion were collected using a method developed by the authors (details of this method can be found in a previous article). An electromagnetic tracking device (3Space Fastrak System; Polhemus, Colchester, VT) (static accuracy of 0.8 mm RMS for translation, 0.15° RMS for orientation) and accompanying software (The Motion-Monitor; Innovative Sports Training, Inc, Chicago, IL) were used to record the 3-dimensional kinematics of the mandible relative to the temporal bone. This was achieved by attaching 1 electromagnetic sensor to the upper and 1 to the lower plastic dental brackets (Fig 1). The magnetic source was placed posterior to the patient’s shoulder just inferior to the height of the sensors using a Plexiglas mounting bracket (Fig 2). A custom, calibrated Plexiglas digitizing probe was used to locate anatomic points for defining the anatomic coordinate systems and for defining landmarks of interest. In addition, 4 anatomic landmarks, the mid-superior edge of the upper central incisors, and the lateral pole of the right and left TMJ condyles were digitized to be tracked in 3-dimensional space (Fig 3). The positions of the anatomic condylar points were determined by palpating the deepest point of condylar fossa curvature during opening and closing movements of the mouth and digitizing reference points 5 mm inferior from the palpated points.

Three trials of protrusive-retrusive movements, opening-closing, and lateral (right and left) movements were performed at a rhythm of approximately 1 complete excursive movement every 2 seconds. Subjects were instructed to perform each movement maximally, symmetrically, and as smoothly as possible. Each movement started and ended in the maximum intercuspal position. Before each recording, participants were given the opportunity to practice the required task. Position and rotation of the mandible were obtained dynamically...
NORMAL VERSUS POSTSURGICAL TMJ KINEMATICS

in the anatomic coordinate system during the movements. After jaw motion was recorded, the plastic dental brackets were removed with an orthodontic debonding instrument. Any residual adhesive on the teeth was removed with hand or rotary instrumentation. A final prophylaxis of the involved teeth was performed.

Data Analysis

Pain and functional capability were analyzed by mean values and t-test \((P < .05)\) to compare the preoperative status with current status. t-tests were also used to detect the differences in TMJ kinematics between the healthy subject group and the surgical patient group. Only opening portions of the best 3 trials were selected from the time series data to represent the movement. Figure 4 depicts a representative sagittal and frontal view of the time series data for the condyles and incisor.

The linear distance (LD) in mm (ie, the LD between the start and end position) was calculated for the lower incisor landmark and both condyles during the opening and protrusive movements in the sagittal (X-Y) plane and during the lateral movements in the frontal (X-Z) plane. The total deviation of the lower incisor (ie, distance from greatest left deviation to greatest right deviation) and both condyles were calculated during the opening and protrusive movements in the frontal (X-Z) plane.

Results

QUESTIONNAIRES

In the surgical patient group, mean preoperative symptom duration was 70 months (range, 0 to 360 months). Mean follow-up period (years between surgery and data collection) was 90 months (range, 50 to 140 months). The average number of previous open surgical treatments in the patients who had previous TMJ surgery was 2 (range, 1 to 6). Two patients had not received prior open surgical treatment. All clinical outcomes improved significantly \((P < .05)\) and included: pain experience (76%), pain intensity (60.6%), chewing ability (53.0%), jaw opening (40.7%), and joint noise (53.6%). Mean satisfaction with the surgical result was 25.7 on a scale of 1 to 30 (Table 2).

KINEMATICS

Mean LDs (LD in mm) and standard deviations for mandibular incisor and condyles for both healthy subjects and surgical patients were calculated and summarized in Table 3. During all movements, LD measurements for right and left condyles of healthy patients were not significantly different; therefore, we combined the data from right and left to simplify the comparison analysis with surgical patients. Mandibular incisor measurements for normal subjects were not significantly different during right and left lateral movements so they were also combined to simplify the comparison analysis. Condyle motion was analyzed in 3 groups: normal subjects condyle (NC), operated condyle (OC), and unoperated condyle (UC).

OPENING MOVEMENTS

Mean LD of incisors during maximal mouth opening for the surgical patient group was 35.0 ± 6.9 mm and 18% less than the normal subjects (43.6 ± 5.6 mm; \(P < .01\); Fig 5). Mean LD for mandibular right and left condyles was symmetrical in the normal group (16.5 ± 5.7 and 16.5 ± 5.1 mm, respec-
Table 2. CLINICAL OUTCOME DATA (MEAN ± SD, VAS)

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Preoperative</th>
<th>Postoperative</th>
<th>Improvement Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain experience (0 to 6)*</td>
<td>4.7 ± 1.3</td>
<td>1.6 ± 1.4*</td>
<td>76%</td>
</tr>
<tr>
<td>Pain intensity (0 to 30)*</td>
<td>23.6 ± 5.3</td>
<td>9.3 ± 7.8*</td>
<td>60.6%</td>
</tr>
<tr>
<td>Chewing difficulty (0 to 30)*</td>
<td>183 ± 6.1</td>
<td>8.6 ± 7.2*</td>
<td>53%</td>
</tr>
<tr>
<td>Jaw opening difficulty (0 to 30)*</td>
<td>18.7 ± 8.8</td>
<td>11.1 ± 10.2*</td>
<td>40.7%</td>
</tr>
<tr>
<td>Joint noise (0 to 30)*</td>
<td>18.6 ± 10.1</td>
<td>7.9 ± 6.4*</td>
<td>53.6%</td>
</tr>
<tr>
<td>Satisfaction with surgical result (0 to 30)</td>
<td></td>
<td>25.7 ± 5.1</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviation: VAS, visual analog scale.
*Statistical significance at $P < .05$ (paired t test).


Table 3. KINEMATIC DATA: MANDIBULAR INCISOR AND CONDYLAR MOVEMENTS FOR NORMAL SUBJECT GROUP (N = 14) AND SURGICAL TEMPOROMANDIBULAR HEMI-JOINT ARTHROTOMY PATIENT GROUP (N = 13, MEAN ± SD, mm)

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Opening-Closing</th>
<th>Protrusive</th>
<th>Right Lateral</th>
<th>Left Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incisors of normal subjects</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ld</td>
<td>43.6 ± 5.6</td>
<td>9.0 ± 1.9</td>
<td>11.8 ± 2.9</td>
<td>12.1 ± 2.9</td>
</tr>
<tr>
<td>Dev</td>
<td>2.7 ± 2.2</td>
<td>1.9 ± 1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right condyle of normal subjects</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ld</td>
<td>16.5 ± 5.7</td>
<td>9.0 ± 2.1</td>
<td>2.7 ± 1.3</td>
<td>7.9 ± 3.0</td>
</tr>
<tr>
<td>Dev</td>
<td>2.3 ± 1.7</td>
<td>1.3 ± 1.1</td>
<td>(ipsilateral)</td>
<td>(contralateral)</td>
</tr>
<tr>
<td>Left condyle of normal subjects</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ld</td>
<td>16.5 ± 5.1</td>
<td>8.7 ± 2.1</td>
<td>7.1 ± 1.9</td>
<td>3.1 ± 1.4</td>
</tr>
<tr>
<td>Dev</td>
<td>2.2 ± 2.0</td>
<td>1.3 ± 1.0</td>
<td>(contralateral)</td>
<td>(ipsilateral)</td>
</tr>
<tr>
<td>Incisors of Patients</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ld</td>
<td>35.0 ± 6.9*</td>
<td>5.1 ± 1.7*</td>
<td>9.4 ± 2.5†</td>
<td>5.1 ± 3.0*</td>
</tr>
<tr>
<td>Dev</td>
<td>5.8 ± 2.7*</td>
<td>3.3 ± 1.7†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operated condyle of patients</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ld</td>
<td>7.1 ± 3.1†</td>
<td>3.4 ± 2.9†</td>
<td>3.1 ± 1.2</td>
<td>3.4 ± 2.1†</td>
</tr>
<tr>
<td>Dev</td>
<td>1.6 ± 0.8</td>
<td>1.2 ± 0.7</td>
<td>(ipsilateral)</td>
<td>(contralateral)</td>
</tr>
<tr>
<td>Nonoperated condyle of patients</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ld</td>
<td>12.2 ± 3.1†</td>
<td>6.9 ± 2.0*</td>
<td>6.4 ± 2.4</td>
<td>2.1 ± 1.3</td>
</tr>
<tr>
<td>Dev</td>
<td>2.1 ± 1.1</td>
<td>1.2 ± 0.8</td>
<td>(contralateral)</td>
<td>(ipsilateral)</td>
</tr>
</tbody>
</table>

Toward operated side: From operated side to normal side
Away from operated side: From normal side to operated side

Abbreviations: LD, linear distance; Dev, deviation.
*Statistical significance between normal vs surgical patient group at $P < .01$ (paired t test).
†Statistical significance between normal vs surgical patient group at $P < .01$ (paired t test).
‡Statistical significance between unoperated condyle vs operated condyle in surgical patient group at $P < .01$ (paired t test).

with condyles of normal subjects, which moved almost identically (Fig 6).

LATERAL MOVEMENTS

During the lateral movement, condyles follow different patterns from each other. To overcome this confusion, condyles during lateral motion were defined as ipsilateral and contralateral (Fig 4B). Mean LD measured for incisor and condyles during right and left lateral movements were not statistically different; therefore, they were combined to simplify the comparison analysis. The combined mean LD measured during lateral movements for incisors, contralateral condyle, and ipsilateral condyle of the normal group was 12.0 ± 3.0, 7.5 ± 2.5, and 2.9 ± 1.4 mm, respectively.

For the surgical patient group, the mean incisor LD away from the operated side (5.1 ± 3.0 mm; P < .01) and toward the operated side (9.4 ± 2.5 mm; P < .05) as compared with the normal group incisors (12.0 ± 3.0 mm) were reduced by 67% and 32%, respectively.

In the operated patients, LD measurements of the contralateral side on the operated condyle (3.4 ± 2.1 mm) showed significantly less motion (P < .01) than the other 2; 55% less than normal condyle (7.5 ± 2.5 mm) and 47% less than unoperated condyle (6.4 ± 2.4 mm). However, on the ipsilateral side, the unoperated condyle motion (2.1 ± 1.3 mm) was less than the others; 38% less than normal condyle (2.9 ± 1.4 mm) and 42% less than operated condyle (3.1 ± 1.2 mm) (Fig 7).

Discussion

After placement of a mandibular condylar, or total or hemi-temporomandibular joint prosthesis, loss of translational movements of the mandible on the operated side is often observed, especially in an anterior direction. Some investigators attribute this effect to loss of lateral pterygoid muscle function secondary to the condylectomy on the operated side. However, several other factors can be responsible for loss of mandibular translational movements following TMJ surgery. These include generalized scarring of the joint region itself and scarring of the associated muscles of mastication. These chronically impaired mandibular movements frequently remain long term, despite complete healing and replacement of the condylar and/or fossa eminence anatomy. It is reasonable to expect that patients who have undergone multiple TMJ surgeries will always have significant restricted jaw motion.

Robinson described a “false” stainless steel TMJ fossa prosthesis that was placed as a type of box against the temporal bone fossa and eminence. Although the patient had no functioning external pterygoid muscle, some anterior movement of the mandible was noticed. This motion was attributed to the forward angled force vector of the remaining masticatory muscles and the absence of the posterior slope of the articular eminence, which would theoretically block any forward movement.

Kiehn et al. used PMMA cement to fit and fix a total joint prosthesis; and a lack of lateral motion of
the jaw was observed, "possibly due to the absence of the function of the lateral pterygoid muscle, which cannot be preserved." Sonnenburg and Sonnenburg\textsuperscript{12} reported that lateral jaw movements were limited to 1 mm (right or left) following prosthetic condyle replacement. In addition, protrusive movements were no longer possible, which was attributed to loss of attachment of the lateral pterygoid muscle. It was concluded that a prosthesis cannot take over function of a healthy joint and therefore does not have to be an anatomic copy. Wolford et al\textsuperscript{5,13} noted that lateral and protrusive function of the mandible were 2 mm or less (right or left) following total TMJ replacement prosthesis; and reattaching the lateral pterygoid muscle to the prosthetic condyle did not improve the movements significantly. van Loon et al\textsuperscript{9} concluded the loss of lateral jaw movement as a great disadvantage to total TMJ prosthesis replacement; therefore, a future prosthesis must allow the anterior movement of the mandible on the operated side when the mouth is opened and also allow some mediolateral (lateral) translation. They recommended optimizing the shape of the articulating surfaces based on wear tests, and confirmation of good clinical performance on long-term follow-up studies.

Mercuri et al\textsuperscript{14} showed a 24% improvement in mouth opening 2 years post total TMJ replacement; at the 10 year follow-up a 30% increase was noted. On the other hand, at 2 years postimplantation there was a 14% decrease in left lateral excursion and a 25% decrease in right lateral excursion from the preimplantation data. At 9 years, the decrease in left lateral excursion and right lateral excursion was 31% and 30%, respectively. They described that the unilaterally reconstructed patient will exhibit greater lateral excursion to the reconstructed side than to the nonreconstructed side. This is attributable not only to the loss of lateral pterygoid muscle function on the implanted side but also to the formation of periarticular scar tissue on the operated side. Bilaterally reconstructed rheumatoid arthritis patients and patients who underwent 2 or fewer prior TMJ operations (in contrast to multioperated patients), often display greater postimplantation lateral excursion. This may be attributed to recruitment of suprahypoid, masseter, and medial pterygoid muscle function as well as the lack of periarticular scarring in the minimally operated patients.

Recently, Collins et al\textsuperscript{15} reported that reattachment of the lateral pterygoid muscle to the condylar stump during total joint reconstructive surgery may provide the patient with greater interincisal opening, lateral excursions, and protrusive movement. However, this observation was not quantitated.

Although favorable results have been reported following TMJ reconstruction using the partial or total TMJ replacement systems,\textsuperscript{3,14,16,18} most data to evaluate the results have been collected by subjective surveys or mandibular incisor motion rather than condylar motion. Our kinematic method tracks both the condyle and incisors path of motion. This method allows the clinician and research scientist a better analysis of the functional surgical outcome.

In the present study, the authors obtained postoperative subjective data from a patient group that received reconstruction with the metal hemi-joint fossa-eminence TMJ prostheses. The patient questionnaires in this study documented significant improvement in all clinical outcome measures including pain experience, pain intensity, chewing ability, jaw opening, and joint noise. Importantly, mean satisfaction with the surgical result was 25.7 on a scale of 1 to 30.

In addition, kinematic measurements of the TMJ of healthy volunteers and surgical TMJ patients (unilateral hemi-joint replacement) were obtained using the electromagnetic tracking device and custom dental appliance. We did not match age and genders in our control group with those of the patients group, which is a limitation of our study. This should be done for future studies. In our operated group, the condyle and associated lateral pterygoid muscle attachments were preserved intraoperatively by minimal condylar recontouring or performing a selective (1 to 3 mm) condylotomy.

The amount of mandibular incisel and condylar movement was good after surgery. We hypothesize that this outcome is partly related to the more conservative surgical management (hemi- vs total joint reconstruction) where the condyle and lateral pterygoid muscle are preserved. However, there was a significant difference in the amount of mandibular incisal and condylar motion during opening, protrusive, and lateral movements between postoperative patients and healthy subjects. This showed less than ideal postsurgical condylar motion (anterior and lateral) because of postsurgical (current and previous) muscular or peri-articular scarring morbidity.

Post TMJ arthroplasty patients showed significant antero-posterior and lateral condylar motion, indicating preservation of functional masticatory function (including lateral pterygoid muscle) following TMJ hemi-joint replacement with fossa-eminence metal prosthesis; however, when compared with normal subjects, this motion was still less than normal.

A prospective study for the comparison between preoperative and postoperative condylar motion results on the same patient population is necessary and ongoing at our medical center.

We theorize preservation of the condyle in osteoarthritic patients undergoing reconstructive TMJ surgery is an important functional goal.

In this study, patients showed significant improvement in functional (jaw motion, joint noise) and qual-
ity of life (pain reduction, overall satisfaction) issues following hemi-joint reconstruction with a hemi-joint fossa-eminence metal prosthesis.

References