Abnormalities of spatial discrimination in focal and generalized dystonia

F. M. Molloy, T. D. Carr, K. E. Zeuner, J. M. Dambrosia and M. Hallett

1Human Motor Control Section, Medical Neurology Branch, and 2Biostatistics Branch, National Institute of Neurological Disorders and Stroke, Bethesda, MD, USA

Correspondence to: Mark Hallett, M.D., NIH, NINDS, Building 10, Room 5N226, 10, Center Drive, MSC 1428, Bethesda, MD 20892–1428, USA
E-mail: hallettm@ninds.nih.gov

Summary

Sensory processing is impaired in focal hand dystonia (FHD), with most previous studies having evaluated only the symptomatic limb. The purpose of this study was to establish whether the sensory system is affected in other types of dystonias and whether the contra-lateral hand is also involved in FHD. We used a spatial acuity measure (Johnson–Van Boven–Phillips domes) to evaluate sensory spatial discrimination in both hands of patients with different forms of dystonias including primary generalized DYT1 dystonia (associated with a unique deletion in the DYT1 gene) (n = 13), FHD (n = 15), benign essential blepharospasm (n = 9), cervical dystonia (n = 10) and in age-matched controls. Clinical evaluation included the Fahn dystonia scale for the focal dystonia groups and the Marsden–Burke–Fahn scale for the generalized dystonia group. Spatial discrimination was normal in patients with DYT1 dystonia, despite all of these patients having hand dystonia. However, spatial discrimination thresholds were significantly increased in both hands in the focal dystonia groups (thresholds were similar for each group) and did not correlate significantly with either severity or duration of dystonic symptoms. Thresholds were significantly increased in the dominant hand compared with the non-dominant hand only within the FHD group. Our observations demonstrate involvement of both the dominant and non-dominant somatosensory cortices, and suggest that abnormal sensory processing is a fundamental disturbance in patients with focal dystonia. These findings of altered sensory processing in idiopathic focal but not generalized DYT1 dystonia suggest both a primary pathophysiological role for the phenomenon in focal dystonia and divergent pathophysiological processes in the two conditions.

Keywords: focal dystonia; generalized dystonia; spatial discrimination

Abbreviations: BEB = benign essential blepharospasm; CD = cervical dystonia; FHD = focal hand dystonia; SDT = spatial discrimination threshold; SEP = sensory evoked potential

Introduction

Dystonia is characterized by involuntary sustained muscle contractions resulting in twisting and repetitive movements of affected body parts (Fahn et al., 1988). Primary torsion dystonia is a heterogeneous disorder with a broad clinical spectrum ranging from early onset generalized disorder to later onset focal dystonias. Early onset of this form is inherited as an autosomal dominant condition with reduced penetrance, and in most cases is due to a unique deletion in the DYT1 gene (Ozelius et al., 1989; Kramer et al., 1990; Bressman et al., 1994a). Unlike early-onset dystonia, the genetic contribution to late-onset focal dystonia is not yet clearly established. Several systematic family studies of patients with late onset focal dystonia have been reported (Waddy et al., 1991; Stojanovic et al., 1995; Munchau et al., 2000). The conclusion from these studies is that the pattern of inheritance is consistent with autosomal dominant transmission with very reduced penetrance. Furthermore, different forms of focal dystonia may present in the same family (Waddy et al., 1991; Stojanovic et al., 1995), suggesting that focal dystonias may share a common aetiology.

Of all movement disorders putatively associated with basal ganglia dysfunction, dystonia is the least understood in terms of underlying pathophysiology. Although perceived as a motor disorder, several clinical and neurophysiological observations suggest that sensory dysfunction may also be implicated in focal dystonia (Hallett, 1995). For example,
sensory symptoms may precede the appearance of dystonia (Leis et al., 1992), sensory tricks (geste antagonist) can relieve dystonic postures (Hallett, 1995; Berardelli et al., 1998; Naumann et al., 2000) and sensory training using Braille reading can improve impaired spatial acuity in patients with focal hand dystonia (FHD) (Zeuner et al., 2002). Tonic vibration of the tendon or belly of a given muscle can induce dystonia in patients with hand cramp and peripheral blockade can alleviate dystonic posturing (Kaji et al., 1995; Grunewald et al., 1997). These sensory phenomena are not surprising because the sensory system provides the major drive to the motor system and the basal ganglia play an important role in the central processing of somatosensory input (Hallett, 1998).

Further evidence for sensory system involvement in focal dystonia comes from neurophysiological and behavioural studies which have demonstrated sensory dysfunction in patients with FHD: abnormal graphaesthesia and stereognosis (Byl et al., 1996a), impaired spatial and temporal discrimination of somaesthetic stimulation (Tinazzi et al., 1999a, 2002; Bara-Jimenez et al., 2000a, b) and abnormal kinaesthesia (Grunewald et al., 1997). These findings all suggest abnormal sensory processing in focal dystonia. Finally, neuroimaging studies using PET (Tempel and Perlmutter, 1993; Feiwell et al., 1999) and MEG (Meunier et al., 2001) support these studies suggesting impaired sensorimotor integration in focal dystonia.

Animal and cortical mapping studies have suggested that synchronous inputs can lead to a rearrangement of cortical maps (Wang et al., 1995; Byl et al., 1996b; Xerri et al., 1996). The abnormal finger representation in the primary somatosensory cortex (S1) observed in patients with FHD (Bara-Jimenez et al., 1998a; Elbert et al., 1998) has been thought to reflect these enlarged and overlapping receptive fields. This hypersensitivity and expanded cortical representation has raised the question of whether dystonia is actually a sensory disorder produced by an environmental experience. Though a recent MEG study (Meunier et al., 2001) suggests that these sensory changes reflect the intrinsic mechanisms of the dystonia itself, it remains unclear what role the sensory changes have in causing the abnormal posturing. Most studies of dystonia have studied the affected limb and contralateral cortex in patients with idiopathic focal dystonia, and there is a paucity of information regarding the involvement of the ipsilateral cortex in unilateral dystonia. With the exception of a recent study using [18F]-fluorodeoxyglucose and PET which demonstrated metabolic overactivity of direct inhibitory projections from the putamen to the globus pallidus interna (Eidelberg et al., 1998), the pathophysiology of DYT1 dystonia is unclear.

This study was performed to establish whether sensory processing is altered in DYT1 generalized dystonia and among different subgroups of focal dystonia, and to establish if the contralateral hand is involved in unilateral dystonia.

**Subjects and methods**

**Subjects**

Patients were recruited from the Human Motor Control Clinic at the National Institute of Neurological Disorders and Stroke (NINDS), USA. Two case-control studies were performed with two separate control groups: one group for the younger generalized DYT1 dystonia patients and another group for comparison with the focal dystonia group. The DYT1 dystonia group comprised nine males and four females, average age and SD were 28.90 ± 15.1 years; the average age of the normal controls for this group (three males and five females) was 28.90 ± 15.1 years. The focal dystonias included: FHD (nine males and six females, average age 54.8 ± 10.6 years); cervical dystonia (CD) (ten females, average age 54.7 ± 13.4 years); and benign essential blepharospasm (BEB) (three males and six females, average age 62.8 ± 10.2 years). The average age and SD of all subjects in the focal dystonia groups was 57.4 ± 4.7 years; the average age of the normal controls (seven females and four males) for the focal dystonia group was 53.3 ± 14.3 years. In the FHD group, 13 of the 15 patients had writer’s cramp (simple writer’s cramp) whereas, in two patients, dystonia was present at rest or during more than one action (dystonic writer’s cramp) (Sheehy and Marsden, 1982); two patients were left-handed and the dominant hand was affected in each case. Patients with BEB and CD were all right-handed. Some of the DYT1 patients were taking medication (Table 2) at the time of the study but, for all groups of patients, botulinum toxin injections were not administered for at least 3 months prior to the study. The effect of medications on spatial discrimination threshold (SDT) has not been investigated, but it is unlikely that the medications outlined in Table 2 decrease the SDT. Patients with a history of peripheral neuropathy, entrapment neuropathies or Raynaud’s phenomenon were ineligible for the study. The diagnosis of dystonia was made by standard medical history and neurological examination.

The Fahn–Burke–Marsden scale which scores for both disability and severity was used for the DYT1 group (Burke et al., 1985). In all groups of focal dystonia, a dystonia disability score was measured (Fahn, 1989). For the BEB and CD group a severity score for the dystonia was also considered (Fahn, 1989). Patients and normal controls gave informed verbal and written consent for this study protocol, which was approved by the NINDS Institutional Review Board.

**Sensory testing**

SDT was evaluated with the Grating Orientation Task as described in other studies (Johnson and Phillips, 1981; Van Boven and Johnson, 1994; Sanger et al., 2001; Zeuner et al., 2002). The Grating Orientation Task consists of a commercially available set of eight hemispheric plastic Johnson–Van Boven–Phillips (JVP) domes (Stoelting, Wood Dale, IL,
controls (dominant and non-dominant hands for the combined group of patients). The clinical characteristics and severity and disability scores on spatial acuity were evaluated using the Wilcoxon signed rank tests, with Bonferroni corrections for the multiple comparisons made. Finally, within the patient groups, Cox proportional hazards models evaluated the relationships between disease duration, Fahn severity and disability scales on spatial acuity.

Results

The clinical characteristics and severity and disability scores for the dystonia subjects are shown in Table 1. As expected, a significant association between increases in SDTs and age was observed; the SDTs increased with increasing age in both dominant and non-dominant hands for the combined group of controls \(P = 0.046\) and \(P = 0.040\), respectively). However, this age-related relationship was not observed in the four patient groups.

The clinical characteristics of the DYT1 dystonia group are outlined in Table 2. Of particular note, all 13 patients in this group had dystonia when writing, and seven of them also had bilateral hand dystonia.

All control subjects had an SDT of <2.2 mm for either hand. However, some patients were unable to detect a gap of 3 mm with either hand. For the DYT1 dystonia group, there was no significant difference in SDTs between patients and age-matched controls for either their dominant or non-dominant hand (Fig. 1A and B). SDTs were significantly greater for the focal dystonia compared with the control group \((P < 0.001\) for both hands); SDTs did not significantly differ within the focal dystonia sub-groups (FHD, CD and BEB). For both hands, the focal dystonia groups differed significantly from their controls even when controlling for the effects of age (Fig. 2A and B).

SDTs were similar between dominant and non-dominant hands in both the DYT1 group and their controls. Within the focal dystonia sub-groups, a significant difference in SDTs was observed between dominant and non-dominant hands in FHD (corrected Wilcoxon signed rank test \(P = 0.02\), but not in the other dystonic groups nor within their normal control group. In each of the dystonia subgroups, neither disease duration nor dystonia scale scores had a significant effect on SDTs.

Discussion

The study’s most notable finding is that of normal spatial discrimination in patients with DYT1 dystonia, but decreased discrimination in subjects with a range of focal dystonias compared with normal controls. Although the genetic abnormality has been well described for the autosomal dominant condition of DYT1 dystonia, there is a relative paucity of knowledge regarding its underlying pathophysiology. While focal and generalized dystonia have been assumed to share a common pathophysiology, our findings could suggest otherwise. Most neurophysiological studies to date have focused on focal dystonias. Despite some shared clinical characteristics, primary generalized and focal dystonias differ in many respects. Generalized dystonia is less prevalent than later onset focal dystonia (Nutt et al., 1988). DYT1 dystonia usually presents in childhood with single limb involvement, which subsequently progresses to involve other regions (Bressman et al., 1994b) whereas focal dystonia has a later onset (older than 28 years, with a median onset of 45 years), which usually starts in cervical, cranial or brachial muscles and tends to remain localized in distribution (Fahn et al., 1987). If a common pathophysiology is assumed, then patients with DYT1 dystonia might reasonably be expected to have as marked if not greater sensory discrimination impairment than those with focal dystonia. This was not the observation in this study.

Sensory abnormalities have been well described for focal (Hallett, 1995; Byl et al., 1996a), but not for DYT1 dystonia. A number of interpretations can be proposed to explain our findings of normal SDT in DYT1 dystonia. One possibility is that sensorimotor integration is intact in DYT1 dystonia, whilst another possibility is that sensory function is initially altered but early adaptive or compensatory changes may take place in the sensorimotor system. Of note, two of the
13 patients in the DYT1 group were censored. These patients were older than other patients in this group (54 and 59 years, respectively), one had a disease duration of 46 years and another of 15 years (Table 2). This finding cannot be explained on the basis of both patients having hand dystonia, as all 13 patients with DYT1 dystonia had involvement of at least one hand. One possible explanation is that an interaction between disease state and age occurs; more specifically, as the disease process progresses, either the sensory-motor integration becomes abnormal or the early ‘adaptation’ process of the sensory-motor system breaks down.

SDTs were increased across a range of focal dystonias and these differences remained after adjusting for age. Furthermore, no significant associations were observed between spatial discrimination thresholds and duration, severity and disability of disease. These findings confirm previous reports of abnormal spatial acuity in dominant (Sanger et al., 2001; Bara-Jimenez et al., 2000b) and non-dominant (Sanger et al., 2001) hands of patients with idiopathic focal dystonia. In our study, a higher threshold is seen in the dominant hand in FHD. A possible explanation for this finding could be that this represents a secondary phenomenon resulting from plasticity changes in the sensorimotor cortex induced by the dystonic hand movements. Alternatively, repetitive activity of the dominant hand

### Table 1 General characteristics in controls and patients with dystonia

<table>
<thead>
<tr>
<th>Group (n)</th>
<th>Age (years)</th>
<th>Gender (M/F)</th>
<th>Dominant hand (R/L)</th>
<th>Onset age (years)</th>
<th>Duration (years)</th>
<th>Severity score</th>
<th>Disability score (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal dystonia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC (11)</td>
<td>53 (14.3)</td>
<td>4/7</td>
<td>10/1</td>
<td>N/A</td>
<td>N/A</td>
<td>0.0 (0.0)</td>
<td>*100 (0.0)</td>
</tr>
<tr>
<td>FHD (15)</td>
<td>55 (10.6)</td>
<td>9/6</td>
<td>13/2</td>
<td>41.7 (15.9)</td>
<td>13.1 (9.9)</td>
<td>N/A</td>
<td>53.2 (19.1)</td>
</tr>
<tr>
<td>CD (10)</td>
<td>54 (13.4)</td>
<td>0/10</td>
<td>10/0</td>
<td>44.8 (13.7)</td>
<td>9.9 (6.1)</td>
<td>23.7 (5.6)</td>
<td>32.8 (22.7)</td>
</tr>
<tr>
<td>BEB (9)</td>
<td>65 (10.2)</td>
<td>3/6</td>
<td>9/0</td>
<td>54.7 (9.4)</td>
<td>8.2 (4.9)</td>
<td>19.1 (4.6)</td>
<td>36.8 (12.5)</td>
</tr>
<tr>
<td>DYT1 dystonia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC (8)</td>
<td>29 (15.1)</td>
<td>5/3</td>
<td>6/2</td>
<td>N/A</td>
<td>N/A</td>
<td>0.0 (0.0)</td>
<td>100 (0.0)</td>
</tr>
<tr>
<td>DYT1 (13)</td>
<td>35 (16.1)</td>
<td>9/4</td>
<td>12/1</td>
<td>14.5 (10.8)</td>
<td>20.9 (14.1)</td>
<td>32.8 (13.7)</td>
<td>6.3 (2.4)</td>
</tr>
</tbody>
</table>

*100% = unaware of any disability; NC = normal controls; N/A = not available. Values given as means with SDs (in brackets).

### Table 2 Clinical characteristics of patients with DYT1 dystonia

<table>
<thead>
<tr>
<th>Patient no.</th>
<th>Age (years)</th>
<th>Symptom duration (years)</th>
<th>Distribution of dystonia</th>
<th>Medication</th>
<th>Severity score</th>
<th>Disability score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>6</td>
<td>Neck, trunk, UEs</td>
<td>nil</td>
<td>36</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>6</td>
<td>LE, UE</td>
<td>trihexyphenidyl</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>57</td>
<td>45</td>
<td>UEs, LE, neck</td>
<td>L-dopa, primidone</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>10</td>
<td>Neck, speech, trunk, UEs, LEs</td>
<td>clonazepam</td>
<td>29</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>10</td>
<td>LEs, UE</td>
<td>nil</td>
<td>24</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>14</td>
<td>LEs, UEs</td>
<td>BTX</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>19</td>
<td>8</td>
<td>Neck, torso, LEs, UEs</td>
<td>Baclofen, BTX, clonazepam, trihexyphenidyl</td>
<td>64</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>37</td>
<td>25</td>
<td>UEs</td>
<td>nil</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>39</td>
<td>32</td>
<td>LEs, UEs</td>
<td>nil</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>54</td>
<td>46</td>
<td>LEs, UEs, speech</td>
<td>carbamazepine</td>
<td>38</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>59</td>
<td>15</td>
<td>LEs, UEs</td>
<td>nil</td>
<td>40</td>
<td>6</td>
</tr>
<tr>
<td>12</td>
<td>35</td>
<td>30</td>
<td>LEs, UEs</td>
<td>nil</td>
<td>21</td>
<td>6</td>
</tr>
<tr>
<td>13</td>
<td>53</td>
<td>25</td>
<td>LEs, UEs</td>
<td>nil</td>
<td>40</td>
<td>7</td>
</tr>
</tbody>
</table>

BTX = botulinum toxin; LE = lower extremity; UE = upper extremity.

### Table 3 SDTs in controls and patients with dystonia

<table>
<thead>
<tr>
<th>Group (n)</th>
<th>Censored (D/N)</th>
<th>SDTs (mm)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dominant hand</td>
<td>Non-dominant hand</td>
<td></td>
</tr>
<tr>
<td>Focal dystonia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC (11)</td>
<td>0/0</td>
<td>1.46 (0.40)</td>
<td>1.49 (0.36)</td>
<td></td>
</tr>
<tr>
<td>FHD (15)</td>
<td>4/3</td>
<td>2.61 (0.38)</td>
<td>2.40 (0.51)</td>
<td></td>
</tr>
<tr>
<td>CD (10)</td>
<td>4/1</td>
<td>2.53 (0.55)</td>
<td>2.35 (0.60)</td>
<td></td>
</tr>
<tr>
<td>BEB (9)</td>
<td>2/5</td>
<td>2.69 (0.55)</td>
<td>2.70 (0.54)</td>
<td></td>
</tr>
<tr>
<td>DYT1 dystonia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC (8)</td>
<td>0/0</td>
<td>1.27 (0.26)</td>
<td>1.36 (0.44)</td>
<td></td>
</tr>
<tr>
<td>DYT1 (13)</td>
<td>2/2</td>
<td>1.70 (0.71)</td>
<td>1.64 (0.77)</td>
<td></td>
</tr>
</tbody>
</table>

NC = normal controls; D = dominant hand; N = non-dominant hand. Mean SDTs are presented with SDs (in brackets).
could lead to worsening of an intrinsic cortical derangement and consequently to the dystonia. The latter hypothesis is supported by a report that some patients with FHD who change hand dominance subsequently develop dystonia in the previously unaffected hand (Sheehy and Marsden, 1982). Patients with symptoms remote from the site of testing were equally impaired in their performance on spatial discrimination testing. In patients with CD and BEB, thresholds were similarly increased for both hands. These findings and reports of abnormal blink reflexes in patients with spasmodic dysphonia (Cohen et al., 1989) and torticollis (Nakashima et al., 1990) would support the hypothesis that dystonia may result from a localized abnormality superimposed upon a more widespread dysfunction of sensorimotor processing. This hypothesis is further supported by a study that reported an inability to track vibration-induced illusions of arm movement in patients with torticollis (Grunewald et al., 1997) and by Mazzini et al. (1994), who reported abnormalities of median nerve sensory evoked potentials (SEPs) in torticollis.

Furthermore, our findings of impaired SDT in both hands of patients with focal dystonia suggest bilateral involvement of the somatosensory cortices in this condition. This observation is consistent with other reports of bilateral cortical sensory changes such as abnormal blood flow in the sensorimotor cortex (Tempel and Perlmutter, 1990) and supplementary motor area (Tempel and Perlmutter, 1993) in response to vibration of the hand and impaired graphaesthesia (Byl et al., 1996a) and dedifferentiation of sensory finger representations in patients with focal hand dystonia (Meunier et al., 2001). Additionally, transcranial magnetic stimulation studies have shown bilateral changes in intracortical inhibition from both motor cortices in patients with FHD (Ridding et al., 1995; Rona et al., 1998) and EMG studies have revealed co-contraction of agonists and antagonists on both the affected and unaffected sides in patients with focal dystonia (Cohen and Hallett, 1988; Rothwell et al., 1988). Furthermore, bilateral abnormal perception of the illusion of vibration-induced movement is described in idiopathic focal dystonia but not in dystonia secondary to Parkinson’s disease (Rome and Grunewald, 1999). This finding supports our results suggesting that focal dystonia is a distinct clinical entity.

Abnormalities of SEPs in dystonia have been described (Reilly et al., 1992; Mazzini et al., 1994; Kanovsky et al., 1997; Tinazzi et al., 1999b; Frasson et al., 2001) and results are conflicting. Some authors have reported a decreased amplitude of the N30 in focal dystonia (Mazzini et al., 1994; Grissom et al., 1995), whereas others have found an increased N30 amplitude in FHD (Reilly et al., 1992; Kanovsky et al., 1997, 1998). These apparently divergent results may reflect methodological differences (Hallett, 1995). The diagnostic heterogeneity of the groups studied may also contribute to these apparently conflicting results. For example, in one study (Reilly et al., 1992) patients with hand dystonia were selected from both generalized and focal dystonia groups. Spatially
separated somatosensory inputs have a reduced inhibition in idiopathic dystonia (Tinazzi et al., 2000). Moreover, the recovery function of the SEP after paired median nerve stimulation shows an impaired inhibition at the spinal and cortical level (Frasson et al., 2001). These findings of inefficient inhibitory integration of afferent inputs are probably due to altered surround inhibition and could result in an abnormal motor output and co-contraction in idiopathic dystonia. Thus, our findings support the hypothesis that abnormal motor output and co-contraction in idiopathic dystonia may result in impaired sensorimotor integration and impaired sensory perception in patients with idiopathic focal dystonia. Therefore, our results are consistent with the hypothesis that abnormal sensory processing could possibly cause a motor disorder, the use of sensory training has been used for treating focal hand dystonia (Byl and Melnick, 1997; Byl et al., 1997; Zeuner et al., 2002). Thus, our findings may also have therapeutic implications for other forms of focal dystonia including cervical dystonia and blepharospasm. More studies are required to evaluate sensory system function in DYTI dystonia and these could include SEPs, MEG and kinaesthetic studies. In addition, serial neurophysiological tests over the course of the disease process may help define the underlying pathophysiology of this disorder. Furthermore, the study of other primary dystonias with known genetic defects (for example DYTI and DYTI dystonia) may further facilitate our understanding of this group of disorders.

Acknowledgements
We wish to thank the patients for their participation and Drs Mitchell F. Brin, Cynthia L. Comella, Steven E. Grill, Joseph J. Jankovic and Stephen G. Reich for referring patients with DYTI dystonia. We also wish to thank Devera G. Schoenberg, MSc, for skilful editing.

References


Received November 14, 2002. Revised April 24, 2003. Accepted April 26, 2003