Introduction to Vestibular Anatomy and Physiology

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±
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• Associations/Affiliations:
  – University of Miami Ear Institute
    • Employer
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    • Past-Chair-Outreach Counsel

Extension of Gratitude

• Anna Marie Jilla, AuD/PhD
  – Co-creator/shared mind trust for presentation slides
Learner Objectives

1. List and describe the 3 systems used for balance.
2. List and describe the 5 peripheral vestibular structures and which types and axes of movement for which they are most sensitive.
3. Explain how differences in the sensory structures of the semicircular canals and otolith organs work differently to activate the vestibular hair cells.
4. Describe how the central vestibular integrator is the “peacekeeper” for balance.
5. Describe each of 3 vestibular reflexes (i.e., VOR, VCR, VSR) and their importance for maintaining balance.

Balance and Equilibrium

• 3 systems
  – Proprioceptive
  – Visual
  – Vestibular
• Correct input from sensory modalities

Peripheral Vestibular Structures
5 Structures Per Ear

- Semi-circular canals (3)
  - Angular acceleration
- Otolith organs (2)
  - Linear/translational acceleration
- Mode of stimulation
  - Change in acceleration, not movement

Semi-Circular Canals (SCC)

- Sensors for angular acceleration
- Three for each ear
  - Lateral/Horizontal
  - Posterior
  - Anterior/Superior

Axes of rotation
- Posterior
  - Think Cartwheel
- Horizontal/lateral
  - Think Pirouette
- Anterior/superior
  - Think Somersault
**Sem i-Circular Canals (SCC)**

Fluid-filled with endolymph (Hi K, Lo Na)

- **kinocilium**
- **stereocilia**

Diagram showing various components of the semicircular canals and their interactions with head movements and the vestibular system.
Semi-Circular Canals (SCC)

- Nerve impulses
  - Steady state
  - Excitation (toward kinocilium)
  - Inhibition (away from kinocilium)
- Coplanar pairs

Otolith Organs

- Sensors for linear/translational acceleration
- Two per ear
  1. Saccule
     -- vertical (think elevator)
     -- up-down
     -- stuck to the wall
  2. Utricle
     -- horizontal (think car)
     -- forward-backward
     -- on the floor
Otolithic Membrane = Gelatinous matrix
Otoliths

*GRAVITATIONAL FORCES*

Central Vestibular Structures
Vestibular Portions of CN VIII

- Superior Vestibular Nerve Branch
  - Lateral SCC, Superior SCC, and Utricle
- Inferior Vestibular Nerve Branch
  - Posterior SCC and Saccule

This isn’t the junction at County Road 12. It’s a superhighway.

- Specialized nerve fibers
  - Type I-irregular
  - Type II-regular
- Inhibition & Excitation
  - Excitation up to 400 spikes/s
  - Inhibition (contra SCC) 0 spikes/s
  - Ewald’s Laws

Central Integrator

- Primary afferent projections
  - Communicate ipsilaterally and contralaterally to the cerebellum and vestibular nuclei in the medulla
- Secondary afferent projections
  - Receive sensory information from the eyes, central visual system, and neck proprioceptive systems
- Vestibulo-cerebellum
  - Informs postural responses
  - Guides movement
  - Mediates vestibular compensation after insult

Want more?
- Central Vestibular Pathways
- Vestibular Nerve Activity
Central Integrator
Vestibulo-cerebellum (the “peacekeeper”)

- Receives information from:
  - Proprioceptive
  - Visual
  - Vestibular systems
- Informs eye movements
- Informs postural responses
- Guides movement

Vestibular Reflexes

- **Vestibulo-ocular reflex (VOR)**
  - Stabilizes vision during rotational head movement in various planes through utilization of extraocular muscles
- **Vestibulo-spinal reflex (VSR)**
  - Makes automatic, postural adjustments to upright stance and stability of head and body during various conditions/activities
- **Vestibulo-colic reflex (VCR)**
  - Stabilizes head during body movements (e.g., ambulation)
Vestibular Reflex Orientation within Vestibulo-Cerebellum

Vestibulo-Ocular Reflex (VOR)
Vestibulo-Colic Reflex (VCR)
Vestibulo-Spinal Reflex (VSR)

Other Vestibular Reflexes to Consider
Frequency, Velocity, and Acceleration. OH MY!

- Normal activities
  - <1 to 20 Hz—frequency of head motion (Das et al 1995; Crossman et al 1988)
  - 530°/s=head velocity (time rate of change)
  - 6000°/s²=head acceleration (time rate of change of velocity)
- The vestibular system is the only detector for this range (Waespe & Henn 1987)
- VOR latency is only about 5-7 ms (Huterer & Cullen 2002; Minor et al 1999)

Cognitive and Gross Motor Development from Birth to 5 Years

Learner Objectives

1. List and describe the 4 primary domains of development
2. Identify age-appropriate milestones specific to cognition and movement/physical development in children from birth to 5 years of age
3. Describe “red flags” and what they indicate
4. Explain what steps may be recommended should parental concerns for development arise and/or should “red flags” be identified
Developmental Milestones

- Functional skills/age-specific tasks achievable within a certain age range.
- Achieved through play, active/passive learning, speaking, various behaviors, and movement.
- Milestones are met when a child is able to perform a task/set of tasks independently.
- Unachieved milestones can raise concerns about developmental disorders, underlying health conditions, or other factors that may negatively impact a child’s development.

Developmental Domains

Social/Emotional

- Whole Child
- Cognitive
- Language
- Social Emotional
- Physical
Quick Review: Vestibular Reflexes

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  - Stabilizes vision during rotational head movement in various planes through utilization of extraocular muscles

- **Vestibulo-spinal reflex (VSR)**
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- **Vestibulo-colic reflex (VCR)**
  - Stabilizes head during body movements (e.g., ambulation)

2 Months: Cognitive

- Pays attention to faces
- Begins to follow objects with eyes and recognize faces from a distance
- Begins to act bored if activity doesn’t change
2 Months: Movement/Physical

- Holds head up and begins to push up when lying prone
- Can make smooth movements with extremities

2 Months: Typical/Atypical Side By Side Comparison

- Typical: 2 Months Pull to Sit
- Atypical: Difficulty to use his shoulder to assist the maneuver

4 Months: Cognitive

- Lets you know if he/she is happy or sad
- Responds to affection
- Reaches for a toy with 1 hand
- Uses hands and feet together (e.g., seeing a toy & reaching for it)
- Follows moving objects with eyes from side to side
- Watches faces intently/closely
- Recognizes familiar people/objects at a distance
4 Months: Movement/Physical

- Holds head steady when unsupported
- Pushes down on legs when feet are on a firm surface
- May roll prone to supine
- Can hold/shake a toy and swing at dangling toys
- Brings hands to mouth
- Pushes up on elbows when lying prone

4 Months: Typical/Atypical Side By Side Comparison

- Typical
  - 4 Months Pull to Sit
    - Pulls forward with both arms and abdominals in action
- Atypical
  - Does not pull with arms and abdominals in action

6 Months: Cognitive

- Looks around at nearby objects
- Brings objects to mouth
- Shows curiosity about objects and attempts to retrieve objects out of reach
- Begins to pass objects between hands
6 Months: Movement/Physical
- Rolls prone to supine and supine to prone
- Begins to sit independently
- When standing, supports weight on legs and may bounce
- Rocks to and fro, at times, crawling before moving forward

6 Months: Typical/Atypical Side By Side Comparison

9 Months: Cognitive
- Watches path of an object as it falls
- Looks for objects she/he sees caretaker hide
- Plays peek-a-boo
- Transfers objects from one hand to the other
- Picks up objects (e.g., food) using pincer grasp (thumb and index finger)
9 Months: Movement/Physical

- Stands while holding onto object
- Begins to get into a sitting position independently
- Sits independently
- Pulls to stand
- Crawls

A Baby at 9 Months

12 Months: Cognitive

- Explores in different ways (e.g., shaking, banging, throwing)
- Finds hidden things easily
- Begins to use items correctly (e.g., brush, cup, etc.)
- Places and removes items in a container
- Lets items go without help
- Pokes with index finger
- Follows simple directions
- Looks at the right picture or item when it’s named
12 Months: Movement/Physical

- Gets into a sitting position independently
- Pulls to stand and then walks while holding on to furniture
- May take a few steps without holding on
- May stand alone

A Child at 12 Months

18 Months: Cognitive

- Knows what ordinary items are for (e.g., spoon, phone, etc.)
- Points to get attention
- Shows interest in a doll or stuffed animal by pretending to feed it
- Scribbles independently
- Can follow 1-step verbal commands without gestures (e.g., “sit down”)
18 Months: Movement/Physical

- Ambulates independently
- May walk up steps and run
- Pulls toys/objects during ambulation
- Can help undress
- Drinks from cup
- Eats with spoon

A Child at 18 Months

2 Years: Cognitive

- Finds items, even when hidden
- Begins to sort shapes/colors
- Completes sentences and rhymes in familiar books
- Plays simple, make-believe games
- Builds towers of 4 or more blocks
- May begin to show hand preference
- Follows 2-step instructions (e.g., “pick up your coat and hand it by the door”)
- Names items in a picture book
2 Years: Movement/Physical

- Stands on tip-toe
- Kicks a ball
- Begins to run
- Climb onto and down from furniture with minimal (if any) assistance
- Ascends/descends stairs while holding onto railing
- Throws ball overhead
- Makes/copies straight lines/circles

A Child at 2 Years

3 Years: Cognitive

- Can manipulate toys with moving parts
- Plays make-believe with dolls, animals, and people
- Can complete basic puzzles (i.e., 3-4 pieces)
- Understands what "two" means
- Copies circles with pencil/crayon
- Turns book pages 1-by-1
- Builds towers of 6 or more blocks
3 Years: Movement/Physical

- Climbs well
- Runs easily
- Can pedal a tricycle
- Ascends/descends stairs with proper weight transfer (i.e., one foot on each step)
- Can screw/unscrew lids and turn door handles

A Child at 3 Years

4 Years: Cognitive

- Names some colors and numbers
- Understands idea of sequencing/counting
- Begins to understand time
- Can recall parts of story
- Understands idea of same/different
- Can draw a person with 2-4 body parts
- Can use scissors
- Starts to copy some capital letters
- Can play simple board/card games
- Can relay what he/she predicts might happen next in a book
4 Years: Movement/Physical

- Can hop and stand on 1 foot for up to 2 seconds
- Can catch a bounced ball most of the time
- Pours, cuts, and mashes own food

A Child at 4 Years

5 Years: Cognitive

- Can count 10 or more items
- Can draw person with at least 6 body parts
- Can write some letters and/or numbers
- Can copy a triangle and other geometric shapes
- Knows about items used daily (e.g., food, money, etc.)
5 Years: Movement/Physical

- Can stand on 1 foot for >10 seconds
- Hops and may be able to skip
- Can do a somersault
- Can use a fork, spoon, and sometimes a knife
- Can use the restroom independently
- Swings and climbs

A Child at 5 Years

Red Flags

- Behaviors/signs/delays that signal a possible problem with development, supporting need for referral for more in-depth screening and/or diagnostic evaluation.
**Taking Action**

- Refer to Pediatrician
- Provide contact/scheduling information for state early intervention program
- Provide and/or direct families to resources to better track/monitor milestones
- Perform screening yourself

**Ages and Stages Questionnaire (ASQ-3)**

- Validated developmental and emotional/social screening tool for children birth to 5.5 years
- Takes 10-15 minutes for the family to complete and 5 minutes for the clinician to score
- Draws on family's in-depth observation of the child to pinpoint developmental progress and catch any underlying delays
  - Scores include "monitoring zone" to help identify children that may be borderline and require routine follow-up/monitoring to track progress
- Available in 6 languages (English, Spanish, Arabic, French, Vietnamese, and Chinese)
- Can be completed in clinic/waiting room, at home, or via phone

**Sample Questionnaire**
Ages and Stages Questionnaire (ASQ-3)

Free Screening through Easter Seals

"...the first 5 years of life lay the foundation for a child’s long-term well-being and overall success.”
- Easter Seals

Content Sources
- Center for Disease Control (CDC)
- Easter Seals
- Ages and Stages
Reference Framework:
A Woman Who Dared to Dream

JCIH, EDHI, and NBHS: Acronyms

- Consequences of hearing loss:
  - Delayed speech/language development
  - Increased risk for cognitive and academic delay and significant psycho/social/emotional consequences

- Joint Committee on Infant Hearing (JCIH) endorses early detection of and intervention for infants with hearing loss (EDHI)
  - Aimed to maximize speech/language and literacy development given increased aforementioned risks for delays as a result of underlying hearing loss
    - Ideal: Screened by 1 month, diagnosed by 3 months, and received intervention by 6 months (1-3y)

- Newborn Hearing Screening (NBHS)
  - Aimed to identify newborns who were likely to have hearing loss and who require further evaluation to confirm

As a Result of NBHS...

- ~96% of children born in the United States were screened for hearing loss before 1 month of age (NICHD, 2016)
- ~98% of children born in the United States received NBHS (NICHD, 2018)
- Increased focus on early auditory development in children
- As a result of earlier intervention, impacts hearing loss would otherwise cause are significantly reduced, allowing most children to excel on par with normal hearing peers
Audiology’s Disregarded Stepsisters: So, what about early identification of vestibular/balance dysfunction in children...
Applied Prevalence

- Li et al., 2016 and Brodsky et al., 2019
  - Nationally-weighted prevalence of vestibular dysfunction in children: 5.6%

- University of Miami Ear Institute-Children’s Hearing Program (UMEI-CHP)
  - ~4,000 children in 2018
  - ~200 (5.3% of 4,000) of which likely had vestibular dysfunction

- Nicklaus Children’s Hospital (NCH)
  - 10,600 inpatients, 221,800 outpatients, 288,000 throughout all satellites (510,400 in total) seen in 2017
  - ~25,520 (5.3% of 510,400) of which likely had vestibular dysfunction

Risk Factors Associated with Vestibular Dysfunction in Children

- Sensory/Neural Hearing Loss (SNHL)
- Delayed Gross Motor Milestones
- Otitis Media with Effusion (OME)
- Migraine
- Head Trauma (Concussion and TBI)
- Cochleovestibular Anomalies and/or Syndromic Etiologies
- Congenital and/or Acquired Infectious Diseases
- Vestibulotoxicity

Other Possible Indicators of Vestibular Dysfunction in Children

- Reading Deficits
- Math Deficits
- Poor Spatial/Body Awareness
  - Clumsy/lack of coordination
- Anxiety/depression
- Poor Attention
- Acute or chronic headache/migrai ne
- Hyper/hyposensitivity
  - Hyper/hypotonicity
Additional Considerations
(RE: Case Hx)

Birth History
- NICU
  - Seizure(s)?

Medical History
- Torticollis in infancy/toddlerhood
- Hx motion intolerance
- Hx staring spells
- Fam. hx imbalance/dizziness
- Fam. hx headache/migraine
- Recent vision examination
  - W/i last 6 months=ideal

Audiologic History
- Recent hearing evaluation
  - W/i last 6 months=ideal

Academic and Social History
- Delayed/slow learning
- Academic strengths/weaknesses
  - Excell in area most challenged by
- Behavioral concerns
- Concerns for attention/focus
- Sensory concerns
  - Avoiding/seeking/both
- Socialization concerns

Achievement of Developmental Milestones

1. Any concerns with your child's balance and/or development?

2. Has your child achieved the following gross motor milestones at/prior to the age listed below?

<table>
<thead>
<tr>
<th>MILESTONE</th>
<th>IN PLACE BY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response to Tilt (&gt;36 months)</td>
<td>Should right within seconds</td>
</tr>
<tr>
<td>Head Control</td>
<td>4 months of age</td>
</tr>
<tr>
<td>Sitting Unassisted</td>
<td>9 months of age</td>
</tr>
<tr>
<td>Walking</td>
<td>18 months of age</td>
</tr>
</tbody>
</table>

*Table: Milestone Benchmarks (McCaskill, 2016)*

Per Janky et al, 2018, a diagnostic vestibular evaluation may be warranted for children with SNHL who:

1. PTA > 66 dBHL
2. Sit later than 7.25 months
3. Walk later than 14.5 months
4. Whose parents express concerns with gross motor development
Screening Measures for Bedside Evaluation

**What We Know...**
- Ocular motility
- High frequency head shake
- Fukuda step test
- Romberg
- Dix-Hallpike maneuver

**“New” Considerations...**
- Head thrust/impulse test
- Single leg stance
- Lay man’s rotary chair
- DVA w/ Snellen eye chart
- Gans SOP Test/mCTSIB
- Physioball
- Subjective observation of gait
- 4 Mountains Test

Head Thrust/Impulse Test

Single Leg Stance
Layman’s Rotary Chair

DVA with Snellen Eye Chart

Gans SOP Test/mCTSIB
Physioball

Subjective Observation of Gait

4 Mountains Test

Ages and Stages Questionnaire (ASQ-3)

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- Available in 6 languages (English, Spanish, Arabic, French, Vietnamese, and Chinese).
- Can be completed in clinic/waiting room, at home, or via phone.

Sample Questionnaire

Free Screening through Easter Seals
Take Aways

• Screenings are quick and easy to administer and interpret.
• Increases/enhances your level of service and value as a provider.
• Screenings can be easily incorporated into standard hearing evaluation appointment slots (i.e., amidst billable services).

AND...

Take Aways Cont.

Children with vestibular dysfunction cannot adequately navigate the world around them, much in the same way children with HL struggle to interact and engage with the world around them.

Why is this any less important?

Future Aspirations...

• Development/growth of vestibular (and research) component within current/future Audiology Programs
  – Provoke interest, increased specialization, and provider scope of competency
  – Identify/train current/prospective mentors within the field to facilitate expanding knowledge
  – Provide greater opportunity for us to contribute to our own evidence base
• Expand “web of influence” beyond the realms of audiology
• Increase public/provider awareness of vestibular dysfunction in children
• Joint Committee on Infant/Toddler Vestibular Development
  – Hey, a boy can dream...
Meanwhile, in Belgium...

**Vestibular Infant Screening-Flanders (VIS-Flanders)**

- Objective:
  - Aims to implement and refine a vestibular screening protocol for all children diagnosed with neonatal hearing loss in Flanders, Belgium to limit the impact of vestibular dysfunction on motor, cognitive, and physical development of hearing impaired children.

**VIS-Flanders Protocol**

- **Tools and Resources**
  - Parent and/or child self-report measures
    - Pediatric Dizziness Handicap Inventory for Patient Caregivers (pDHI-PC) and/or the Dizziness Handicap Inventory (DHI)
    - Pediatric Vestibular Symptom Questionnaire (PVSQ)
    - Pediatric Visually-Induced Dizziness Questionnaire (PV-ID)
    - Questionnaire for Dizziness, Eye, and Balance Function for Children and Adolescents (Q-DEB)-Norgett

- **Pediatric Vestibular Screening Tool (PVST)**

- **Pediatric Vestibular Epidemiological Monitoring System (PVEMS)**
Remember Sara?

Vestibular screening completed in March 2019 indicated the following:

- **Reflexes** mediating vestibular function are under-developed
- Under-reactive vestibular system
- Notable fall risk/increased propensity for head injury
- Poor activation of vestibulo-limbic interactions

Sara 5 Months Later (August 2019)

References

References Cont.


Reference Framework: A Man Who Dared to Dream

VESTIBULAR TESTING IN CHILDREN
DAVID C. CHU, MA
Omaha, Nebraska

Vestibular evaluation in the pediatric population has been the focus of this study. The challenges faced by pediatric vestibular evaluation have been highlighted in this research. The study aimed to address the difficulties encountered in pediatric vestibular assessment, including the need for specialized equipment, the need for specialized testing, and the need for standardized testing protocols.

Objectives

1. Describe challenges to objective quality objective measures of vestibular function in children
2. List which tests of vestibular function are appropriate for children based on their age
3. Describe modifications that can be made to each test to adequately accommodate children

Challenges

• Equipment unavailable
• Lack of pediatric-sized goggles
• Limited attention-span/focus
• Lack of normative data
• Lack of provider knowledge/specialization in pediatric vestibular assessment
• Limited awareness of prevalence of vestibular dysfunction in children
• Poor subjective report from patient
Ocular Vestibular-Evoked Myogenic Potential (oVEMP)

Pediatric Modifications for c/oVEMP

<table>
<thead>
<tr>
<th>Test Procedure/Characteristic</th>
<th>Modification</th>
</tr>
</thead>
</table>
| Shorten testing time           | – Perform bilateral, simultaneous cVEMP and oVEMP  
                                – Use a bone conduction stimulus |
| Increase attention span        | – Use interesting toys, stickers, or images to distract and engage |
| Improve sustained muscle contraction | oVEMP:  
                                – Rotate the head and stimulate rooting reflex for newborns  
                                – Sit child on parent’s lap or have him/her lie on a table with head turned toward a target |
                                – Use eye-closed testing for small children who cannot perform testing with eyes open |
| Utilize EMG monitoring          | – Use an animated cartoon that plays when contraction level is met |
| Improve electrode tolerance    | – Use one reference electrode (e.g., chin)  
                                – Put oVEMP active electrodes on after cVEMP testing |
| Improve safety for air-conduction VEMP | Present at 20–200 dB (held at the ears)  
                                – Use a 500 Hz tone burst stimulus  
                                – Use an ascending threshold search approach  
                                – Use a bone conduction stimulus |

VEMP Administration
Pediatric Modifications for vHIT

<table>
<thead>
<tr>
<th>Test Procedure Characteristic</th>
<th>Modification</th>
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</table>
| Poor goggle fit secondary to small head size | - Insert foam block between band and back of child’s head to increase tension/tighten fit  
- Consider remote video system for children 3 months-3 years |
| Increase attention span | - Use interesting toys, stickers, or videos as distractors and targets and feel free to change frequently between impulses |
### Pediatric Modifications for RVT

<table>
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</tr>
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</table>
| Poor goggle fit secondary to small head size | - Insert foam block between band and back of child's head to increase tension/tighten fit  
  - Consider remote video system for children 3 months-3 years. |
| Inability to sit independently         | - May sit in parent's lap, who may then assist with maintaining head position/stability and/or goggle placement throughout rotation. |
| Child afraid of dark/enclosure         | - Door may remain open if remote video system is being utilized and/or if gogles are light-tight  
  - Consider singing nursery rhymes/familiar songs, allowing the child to talk about an interesting topic (e.g., dinosaurs), or have them name their favorite cartoon/Disney characters. |
Caloric Irrigations

Pediatric Modifications for Caloric Irrigations

<table>
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<tr>
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<tr>
<td>Poor goggle fit secondary to small head size</td>
<td>Insert foam block between band and back of child's head to increase tension/tighten fit</td>
</tr>
<tr>
<td>Fearful of testing/afraid of dark</td>
<td>Reinforce/reassurance of safety from clinician/parent. Child may hold/squeeze clinician/parent's hand during irrigation/data collection</td>
</tr>
<tr>
<td>Maintaining alertness/tasking</td>
<td>Consider singing nursery rhymes/familiar songs, allowing the child to talk about an interesting topic (e.g., dinosaurs), have them name their favorite cartoon/Disney characters, and/or ask them to take you through all the toys in their playroom/bedroom. Consider monothermal vs. bithermal irrigations. Reduce irrigations from 30 sec to 15-20 sec</td>
</tr>
</tbody>
</table>

Caloric Administration
Take Aways

• Evaluation aim:
  – To comprehensively assess functional output of the vestibular system across entire dynamic range of operation
• Vestibular function testing by age:
  – 0-2 years (RVT, cVEMP, and *vHIT)
  – 3-7 years (vHIT, c/o VEMP)
  – 8+ years (vHIT, *calorics, and c/o VEMP)

More comprehensive the assessment, the better our diagnostic power becomes.

THANK
Joshua.Huppert@med.miami.edu